Belize Blue Carbon: Establishing a National Carbon Stock Estimate for Mangrove Ecosystems

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Abbreviations: TECS, Total Ecosystem Carbon Stock; NDC, Nationally Determined Contribution; LOI, Loss on Ignition; GHG, Greenhouse Gas; IPCC, Intergovernmental Panel on Climate Change; NGO, Non-governmental organization; UNFCCC, United Nations Framework Convention on Climate Change; AGB, Aboveground Biomass; BGB, Belowground Biomass; DBH, Diameter at Breast Height.

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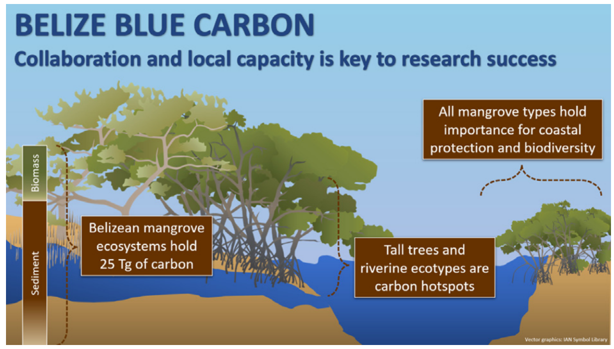
HIGHLIGHTS

- We conducted the first national mangrove carbon stock assessment for Belize.
- Mangrove ecosystems of Belize currently store 25.7 Tg of carbon.
- Higher total carbon stock is found in riverine, healthy, tall mangrove ecosystems.
- Collaboration, knowledge sharing, and local buy-in is key for mangrove conservation.
- Results inform nationally determined contributions to preserve blue carbon ecosystems.

GRAPHICAL ABSTRACT



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ABSTRACT

Mangrove ecosystems are among the most economically and ecologically valuable marine environments in the world. Mangroves are effective at long-term carbon storage within their sediments and are estimated to hold 12 billion metric tons of carbon worldwide. These ecosystems are therefore vitally important for carbon sequestration and, by extension, climate change mitigation. As part of the Paris Agreement, participating countries agree to provide plans to reduce their carbon emissions, or nationally determined contributions (NDCs). However, despite mangroves being recognized as important nature-based solutions, many countries still lack national data on carbon stocks and must use global or regional averages, which may not be sufficiently accurate. Here, we present the national carbon stock estimate of mangrove ecosystems for the NDC of Belize, acquired through a collaborative approach involving government agencies and NGOs. We conducted a comprehensive sampling of mangroves across the country, including a range of mangrove ecotypes. The mean total ecosystem carbon stock (TECS) for the nation was 444.1 ± 21.0 Mg C ha^{-1}, with 74.4 ± 6.2 Mg C ha^{-1} in biomass stocks, and 369.7 ± 17.7 Mg C ha^{-1} in sediment stocks. Combining these data with a recent mapping effort, we provide the first national comprehensive mangrove carbon stock estimate of 25.7 Tg C. The national mean from this study varies from previous global analyses, which can under- or overestimate TECS by as much as 0.6 Tg C and 16.5 Tg C, respectively, depending on the study. These data supported the NDC update of Belize, and can be used to inform the country's mangrove protection and restoration commitments. The collaborative approach of this work should serve as a blueprint for other countries seeking to conserve natural blue carbon sinks as a strategy to achieve their climate targets.

1. Introduction

Blue carbon refers to carbon sequestered and stored long-term by ocean and coastal ecosystems, thus removing CO_2 from the atmosphere and contributing to climate change mitigation (Laffoley and Grimsditch, 2009; Nellemann et al., 2009). Coastal wetlands, namely mangroves, seagrasses, and tidal marshes, are prime examples of these blue carbon ecosystems; mangroves alone being 4–5 times more effective at sequestering carbon than tropical terrestrial forests (Donato et al., 2011; Macreadie et al., 2021). These ecosystems are therefore recognized as natural climate solutions (Duarte et al., 2013; Serrano et al., 2019), while also simultaneously providing a range of ecosystem services such as coastal protection, pollution control, and fisheries habitat (Barbier et al., 2011; Himes-Cornell et al., 2018; Menéndez et al., 2020). They are currently the only marine ecosystems with established methodologies for estimating national inventories of greenhouse gas (GHG) fluxes (Christianson et al., 2022; IPCC, 2019). For countries with one or more of these ecosystems, the conservation and/or restoration of these ecosystems can lead to an overall reduction in country GHG emissions (Bindoff et al., 2019).

Despite their importance, blue carbon ecosystems continue to be lost across the globe. Driven primarily by anthropogenic activities, mangrove ecosystems alone are estimated to have lost 35–86 % of their original global extent (Duke et al., 2007; Sippo et al., 2018), and seagrasses 19 % of their extent since the late 1800s (Dunic et al., 2021). Significant anthropogenic threats remain, such as eutrophication of coastal waters (Halpern et al., 2019; Simpson et al., 2021; Berger et al., 2022), clearing for development (Romañach et al., 2018), and aquaculture (Thomas et al., 2017). These systems are also vulnerable to effects of climate change, such as El Niño Southern Oscillation events (Kulp and Strauss, 2019), sea level rise (Jevrejeva et al., 2012; Saintilan et al., 2020), and more frequent, intense hurricane events (Krauss and Osland, 2020; Emanuel, 2021; Vecchi et al., 2021).

Mangroves are perhaps the most effective blue carbon system, storing 11.7 Pg of carbon globally, largely in their soils (Kauffman et al., 2020). As a result, their continued loss and degradation has significant implications for established carbon stocks and rates of burial (de Oliveira Gomes et al., 2021), including remobilization of carbon in the surrounding environments, creating a net loss of carbon for that ecosystem instead of a traditional sink when mangroves are healthy and intact (Brodersen et al., 2019; Friess et al., 2020a; Lovelock et al., 2017). More recently, however, rates of mangrove loss have decreased, and while there may be some cause for optimism, there is need for improved management, protection, and restoration of these critical ecosystems (Friess et al., 2019; Friess et al., 2020b). To address the loss of mangroves and their ecosystem services, ambitious protection and restoration targets are required (Buelow et al., 2022). For such actions to be successful, both governmental and community support and involvement are essential to each effort (Aswani et al., 2012; Kadaverugu et al., 2021; UNEP, 2014). Various initiatives have been developed that aim to both protect and restore mangroves, including grassroots efforts such as the Global Mangrove Alliance (https://www.mangrovealliance.org/) - an international group of scientists and policy makers that collectively works to improve management and facilitate restoration of mangroves.

The United Nations Framework Convention on Climate Change's (UNFCCC, 2015) Paris Agreement provides a unique opportunity for countries to advance the restoration and protection of nature to meet climate objectives. Signatories to the agreement can put forward coastal wetland protection and restoration targets as part of their emission reduction and climate adaptation pledges known as nationally determined contributions, or NDCs (The Blue Carbon Initiative, 2020; IPCC, 2014). As of October 2021, seventy-one (71) countries have mentioned marine or coastal nature-based solutions in their new or updated NDCs (Lecerf et al., 2021), and several countries that included coastal solutions emphasized mangrove ecosystems as a potential tool towards the reduction of their own emissions and risk factors (GoB, 2021; UNFCCC, 2021).

Nevertheless, significant challenges exist in informing and operationalizing NDCs. First, valid and current maps of mangrove extent have proved historically difficult to produce throughout much of the world, although many local and regional examples now exist thanks to remote sensing applications. Second is the need for local- or region-specific values for carbon storage across different pools (e.g., aboveground biomass, soils) and species. The Intergovernmental Panel on Climate Change (IPCC) guidelines suggest as a first approach to use global averages (i.e., a Tier I approach), although there are significant deviations from these numbers depending on the location and identity of the blue carbon ecosystem. Generating more localized values (i.e., Tier II) can prove challenging across entire coastlines and requires coordinated methods and surveys. Finally, derivation and incorporation of carbon stock estimates into NDCs requires cooperation across multiple sectors, including academic institutions, multiple local, state, and federal resource management agencies, and stakeholder groups, such as non-governmental organizations (NGOs). As NDCs are designed to be iterative and continually updated, facilitating the capacity to continue measurements into the future is a key goal in providing timely and relevant assessments of blue carbon.

Here, we report the first country-wide evaluation of mangrove blue carbon for the Central American Caribbean nation of Belize through a unique, internationally collaborative model involving local stakeholders, including protected area managers, government and NGOs, academic institutions, and research organizations. Forty percent of the population in Belize resides within what is considered the coastal zone (SIB, 2010), so existing threats to mangrove ecosystems are inherent threats to much of the nation. Belize was also one of the few countries to mention mangrove conservation in their first NDC, and one of the first to include robust time-bound targets for mangrove protection and restoration within their updated NDC (GoB, 2021). As a result, the primary goal of this study is to support the implementation of Belize's updated NDC commitment to protect 12,000 ha of mangroves and restore 4,000 ha by 2030 (GoB, 2021), by informing priority areas for the efforts based on carbon sequestration value combined with important ecosystem services by region. A secondary goal is to report on a novel model to build capacity in the region and strengthen local research by engaging key stakeholders in all decisions from site-selection to data reporting through open knowledge sharing and training.

2. Methods

2.1. Site locations

Site selection was performed as an iterative, collaborative process that focused on choosing sampling locations that fit the needs and priorities of the Belizean government and local environmental NGOs. Ten sites were chosen out of a list of over 50 potential locations, selected to represent a wide range of geographical, biophysical, and morphological characteristics of mangrove systems across the Belizean coastline from 16.182 to 18.342 N latitude (Fig. 1, Supplemental Table A). Overall health of each site was assessed in the field and classified by expert researchers as healthy (minimal disturbance with good mangrove growth), disturbed (objectively healthy sites with signs of anthropogenic influence such as tree harvesting), or degraded (sites with mostly dead or dying mangroves).

2.2. Field sampling

Fieldwork was conducted on all sites, except for Turneffe Atoll, by a team of 14 national and international organizations and over 35 individuals during September of 2021. Turneffe Atoll was surveyed in March 2022, due to inaccessibility caused by inclement weather during the initial surveys, by a completely Belizean team. We followed the methods in Kauffman and Donato (2012) and the Coastal Blue Carbon Manual (Howard et al., 2014) to align with other total ecosystem carbon stock (TECS) research efforts, including estimates of above- and belowground living biomass, standing and downed dead wood, and soil carbon. At each site, we established two transects separated by a minimum of 100 m. Transects commenced 15 m from the shoreline running 125 m perpendicular to the coast into the mangrove ecosystem (Fig. 2). At 25 m intervals along each transect, we established six plots, inside which we initially recorded conditions of overall health, depth of standing water, and other notable defining characteristics. This was repeated at each site, except for Hicks Caye, where only a single transect was conducted during initial training, and at New River, where lack of standing mangroves farther inshore led to a shorter second transect of only 75 m. The second transect at Big Creek was also divided into two 75 m transects due to the presence of a creek that prevented running a single continuous transect.

2.3. Mangrove biomass

Mangrove height, canopy width, and diameter at breast height (DBH) for all mangroves with a DBH ≥ 5 cm and within a 7 m radius of the plot center were censused. Within a nested 2 m radius plot, the team further measured all plants with a DBH < 5 cm and counted all seedlings (Fig. 2). If the dominant mangrove ecotype was dwarf, the entire plot had a 3 m radius due to high tree density, with all plants being measured within the entire plot. At each plot within each transect, we conducted a survey of woody debris by establishing four 12 m subtransects running at 90-degree angles from the center of the plot. Along these intersections, we identified coarse woody debris to species (where possible) and graded according to decay class, following Howard et al. (2014). Allometric equations (Komiyama et al., 2005; Smith and Whelan, 2006) and carbon conversion factors outlined in Howard et al. (2014) were used to calculate the above- (AGB) and below-ground biomass (BGB) estimates for this study (Supplemental Table B).

2.4. Soil carbon

A sediment core was collected from the center of each plot using a 1 m long, 6.35 cm diameter open-faced gouge auger (AMS Inc.). The Eijkelkamp-type auger was chosen for portability and its popularity in wetlands for retrieving undisturbed and uncompacted volumetric soil samples, with the caveat that the bottom of the soil sample can sometimes be lost, as the end of the auger is open (Howard et al., 2014). Total length sampled of each core was recorded to note this occurrence when present. After being inserted fully into the sediment perpendicular to the surface, the corer was twisted several times in place to sever the roots and then continuously twisted while lifted straight out of the ground to retrieve a sediment sample. The auger was extended in increments of 1 m as needed and reinserted into the existing hole until depth of refusal or a maximum depth of 3 m, at which point the total length of the core was recorded. The core was cut lengthwise along the auger opening to reveal the interior and the soil color was recorded using a soil color chart (Munsell), as well as the relative root density and water content, and any other notable features (such as the presence of shell material). For the top 50 cm of soil, the core was sectioned in 5 cm increments, removed, and placed into pre-weighed tins. From 50 cm to the maximum depth, a 5 cm section was removed from the midpoint of every subsequent 50 cm section (i.e., 72–77 cm sample from 50 to 100 cm section). Finally, we measured the pH and oxidation reduction potential of the pore water (or as close to the pore water as possible, if standing water was present at the site) using a handheld combo tester (Hanna Instruments), and salinity (in PSU) using a handheld refractometer (Extech).

2.5. Laboratory processing

After collection, soil sample tins were immediately transported back to the laboratory and placed into drying ovens at 70 °C for 36–48 h until they

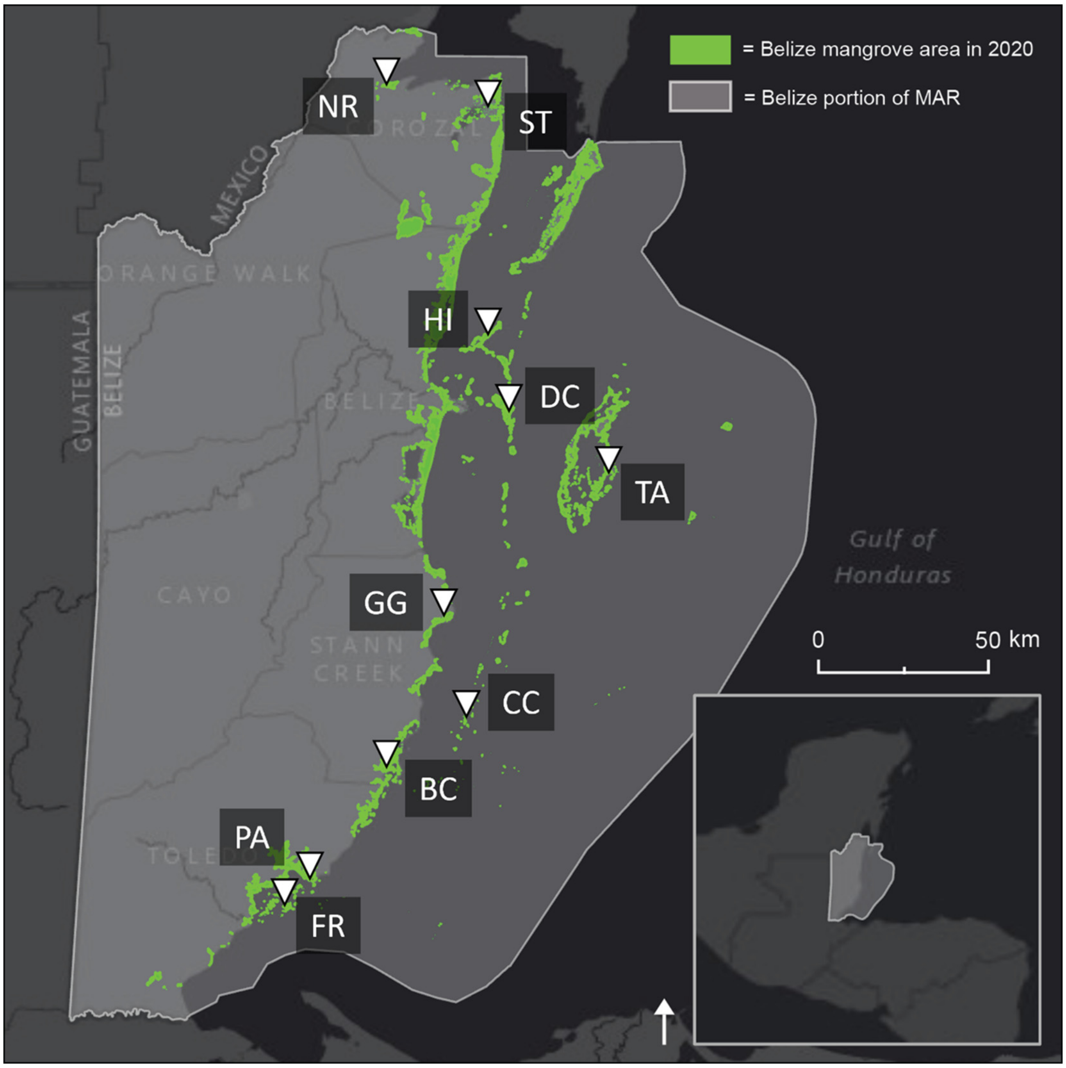

Fig. 1. Distribution of mangroves within Belize (Cissell et al., 2021), and the sampling locations of the Belize Blue Carbon field collection effort. HI = Hicks Caye, DC = Drowned Caye Range, ST = Shipstern Lagoon, NR = New River, GG = Gra Gra Lagoon, CC = Channel Caye, BC = Big Creek, PA = Payne's Creek, FR = Frenchman Caye, TA = Turneffe Atoll.

reached a constant weight, at which point the dry weight was recorded for the calculation of bulk density. Dried and weighed samples were then packaged and transported back to the Smithsonian Environmental Research Center for further laboratory processing. There, sediments were ground and homogenized with a SamplePrep 8000D grinding mill (Spex), and each was tested for the presence of inorganic carbon via 1 N hydrochloric acid (HCl). A 3–5 g subsample of each original dry, ground, sample was combusted in a Isotemp muffle furnace (Fisher Scientific) at 450 °C for 6 h to obtain loss on ignition (LOI). Combustion via LOI burns off present organic material, therefore, pre-LOI samples were considered as having total carbon, and post-LOI samples were assumed to have inorganic carbon (Schulte and Hopkins, 1996). For samples that did not test positive for the

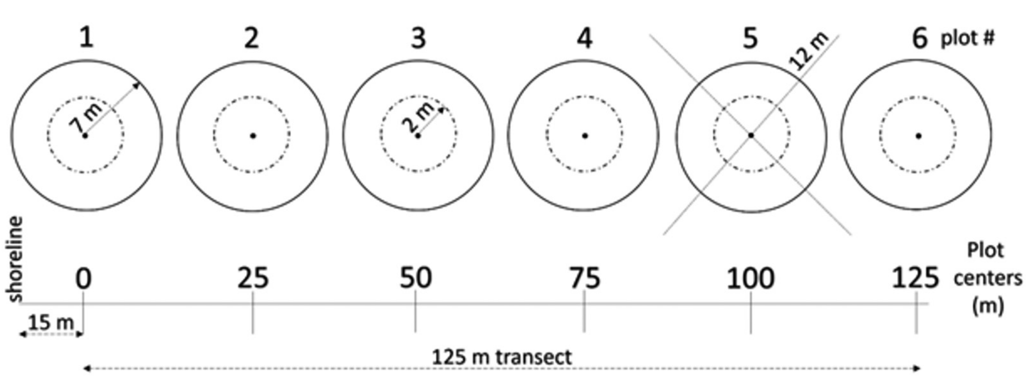

Fig. 2. Methods for constructing mangrove carbon stock assessment transects.
Adapted from Kauffman and Donato (2012).

presence of carbonates via HCl, it was assumed that total carbon equaled organic carbon for those sediments. The final step in this process was elemental analysis, for which we weighed and tinned thoroughly mixed representative subsamples to be analyzed at the Blue Carbon Analysis Lab at Florida International University, following methods detailed in Fourqurean et al. (2012). For samples which comprised of only organic carbon, a single original subsample (pre-LOI) was sent for analysis, whereas for samples which contained carbonates, both an original pre-LOI subsample (total carbon) and post-LOI subsample (inorganic carbon) were sent for analysis. Elemental analysis yielded percent total carbon values for each sample, which equaled (a) %TC = %OC for samples containing only organic carbon, and (b) %TC − %IC = %OC for samples where carbonates were present.

2.6. Data preparation

For each plot, we estimated the amount of AGB, BGB, and dead biomass with previously mentioned allometric equations (Supplemental Table B) and carbon conversion factors. Those values were then summed per area and converted to Mg C ha^{-1}. Total organic carbon for each core was calculated following Howard et al. (2014). Values were converted from g cm^{-2} to Mg C ha^{-1} for each plot. Total carbon per plot was then extrapolated out by the average core organic carbon multiplied by the plot area with the biomass carbon for the same area. After which a national value was achieved by using a 2020 mangrove cover baseline conducted at 10 m resolution (Cissell et al., 2021).

The mangrove stands of each site location were separated into biophysical classes based on the surrounding geomorphology and ecotype. Following Adame et al. (2013), mangroves were classified by height: tall (>5 m), medium (2–5 m), and dwarf (<2 m). Based on sampling site location, the mangroves were separated into categories of riverine/coastal, lagoonal, and island/caye (offshore) ecosystems.

Since LOI and soil organic carbon have previously been found to have a discernible positive relationship (Howard et al., 2014; Kauffman et al., 2011), this study calculated a new equation to predict soil organic carbon as a function of LOI that is applicable to Belize, specifically. This could reduce costs of future carbon stock efforts, as determining the carbon content of each sediment sample is the most expensive (yet critical) step of laboratory analyses, and Belize does not currently have the capacity to complete these measurements in-country.

2.7. Statistical analysis

Data was not normally distributed using the Shapiro-Wilk test for normality, even after transformation. Therefore, statistical significance was tested via the unpaired two-samples Wilcoxon test (two sample sets) or the Kruskal-Wallis test (pairwise Wilcoxon test; three or more sample sets).

3. Results

3.1. National mangrove carbon stocks

Across all sites and times, we estimate the mean TECS for Belize at 444.05 ± 21.0 Mg C ha^{-1}, with the nationwide average for sediment carbon stock at 369.70 ± 17.7, and the average biomass per plot estimated at 74.35 ± 6.2 Mg C ha^{-1}. Using 57,854 ha of mangrove cover (Cissell et al., 2021) and the aforementioned mean, the nationwide mangrove TECS was estimated to be 25.69 ± 1.2 Tg C when constraining soil depth to 1 m, as is IPCC standard. The carbon stocks for each of the 111 plots sampled were calculated for aboveground live biomass, aboveground dead biomass, belowground biomass, sediment, and the sum of all four to estimate TECS (Fig. 3; Supplemental Tables E.1 & E.2). Sediment organic carbon stocks varied widely, ranging from 5.80 to 773.36 Mg C ha^{-1}. The biomass portion of the TECS had a plot minimum of 2.56 (excluding plots with no biomass) and maximum of 371.29 Mg C ha^{-1}. Plot TECS ranged from 28.97 to 996.07 Mg C ha^{-1} within the individual plots, leading to an approximate sediment to biomass ratio throughout the plots of 4:1.

Physical parameters of each site ranged drastically, with salinity ranging from 3 to 57 PSU (average of 24 PSU), oxidation reduction potential (ORP) ranging from −377 to +142 mV, pH ranging from slightly acidic (6.29) to slightly alkaline (8.30), and depth to refusal measuring from a minimum of 41 cm to below 300 cm depth (mean of 140.6 ± 6.1 cm; maximum depth attempted for coring was 3 m; Supplemental Table C). Three species of mangroves are present in Belize- *Rhizophora mangle*, *Avicennia germinans*, and *Laguncularia racemosa* - with dominance calculated as 77.4 %, 17.5 %, and 4.5 % of the 111 plots, respectively (Supplemental Table D). Analysis into the effect of these measurements on carbon stock will not be reported here, for brevity, but will be produced separately (Morrissette et al., *in prep*).

While the IPCC standard reporting for sediment carbon stock values restrain values to a depth of 1 m, there is an overall consensus that constraining stocks to 1 m significantly underestimates sediment carbon (Kauffman et al., 2020); as such, this study sampled down to 3 m when possible. Including the deeper sediments led to a significantly higher sediment carbon stock ($p < 0.005$), with the mean across all plots increasing to 528.49 ± 27.7 Mg C ha^{-1} and the mean TECS increasing by 36 % to 602.84 ± 30.7 Mg C ha^{-1}. Maximum TECS in a single plot grew to 1396 Mg C ha^{-1} in deep stands of peat. The national TECS of mangroves when sediments down to 3 m were included was estimated as 34.9 Tg C, an increase of 9.2 Tg C. When this is delineated into mainland and offshore

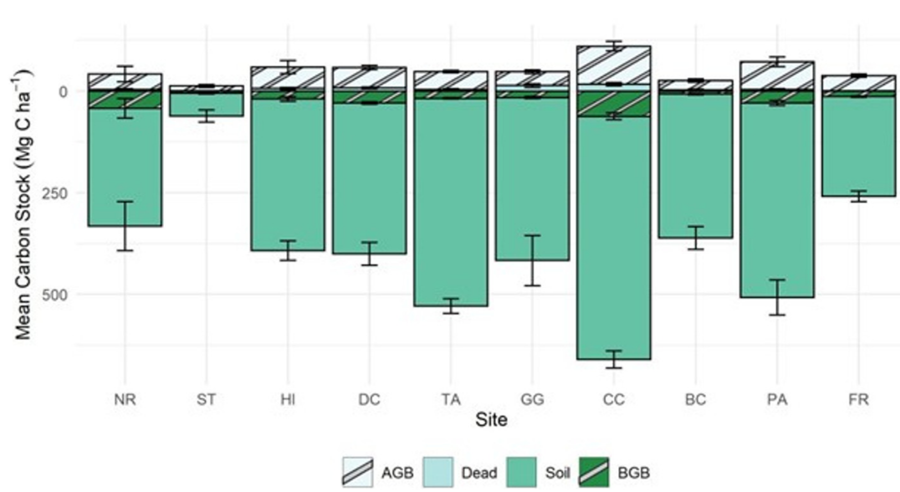

Fig. 3. Average carbon stock pool (AGB, BGB, Dead biomass, Soil) per sampling site within Belize. Striped bars are live biomass pools.

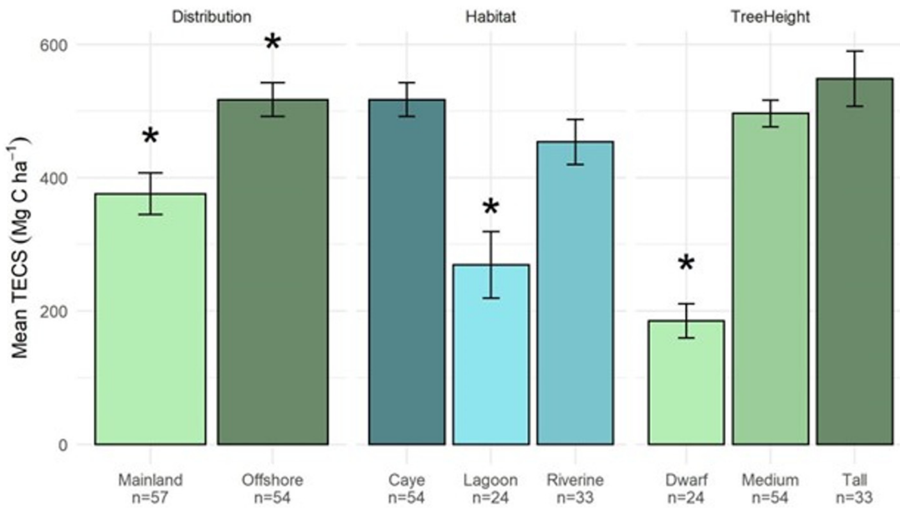

Fig. 4. Mean mangrove total ecosystem carbon stocks (TECS) per classification of three different subsets of sampling locations: (a) distribution, (b) habitat, and (c) tree height. Asterisks indicate significant differences between the other classes of the qualifying group ($p < 0.005$).

carbon stocks the stocks increased to 21.4 and 13.0 Tg C, respectively. Explored under- and overestimates of the national mangrove carbon stock can be found in Supplemental Table F.

3.2. Importance of the study and future assessments

Through a stepwise analysis of the data, three major classifications were identified as important for determining variations in TECS (Fig. 4, Supplemental Tables E.1 & E.2). Data was analyzed in the subsets of (a) mainland versus offshore distribution, (b) lagoonal, riverine/coastal, and caye ecotypes, and (c) dwarf, medium, and tall tree height.

Separating the 111 sampled plots between mainland and offshore distribution, offshore site locations had a significantly higher mean TECS (515.96 ± 25.0 Mg C ha^{-1}, $p < 0.005$) than the plots sampled on the mainland (375.92 ± 31.0 Mg C ha^{-1}). Cissell et al. (2021) distinguished the separation of mainland versus offshore mangrove cover, so this study used the values of 37,204 and 20,650 ha respectively to scale up to 13.99 Tg of estimated mainland TECS and 10.65 Tg of estimated offshore TECS.

This study further separated out the distribution into three ecotypes; mainland lagoon, riverine/coastal, and the offshore cayes (Fig. 5). Lagoonal systems had a significantly lower average carbon stock than both riverine and caye ecosystems ($p < 0.005$ each), while riverine and caye carbon stock averages were not significantly different ($p = 0.06$).

A third dominant pattern emerged from the average tree height of each plot, classified as dwarf (<2 m), medium (2–5 m), and tall (>5 m) stands (Fig. 5). Dwarf locations had a significantly lower average carbon stock than either the medium or tall plots ($p < 0.005$ each), and while the tall stands have a slightly larger mean TECS, they are not significantly different from the medium height trees ($p = 0.26$). Although the pattern of dwarf stands having less total carbon is present, there is no discernable significant relationship between aboveground biomass and sediment stock across all sites, with an R^2 of 0.196, which was also the case in Kauffman et al. (2020).

A general equation for estimating the percent organic carbon of mangrove sediments from their percent LOI was tested on these data in order to determine the accuracy of the generic equation to the region. The equation,

a. % Organic Carbon = 2.89 + 0.42 ∗ % LOI (Kauffman et al., 2011)

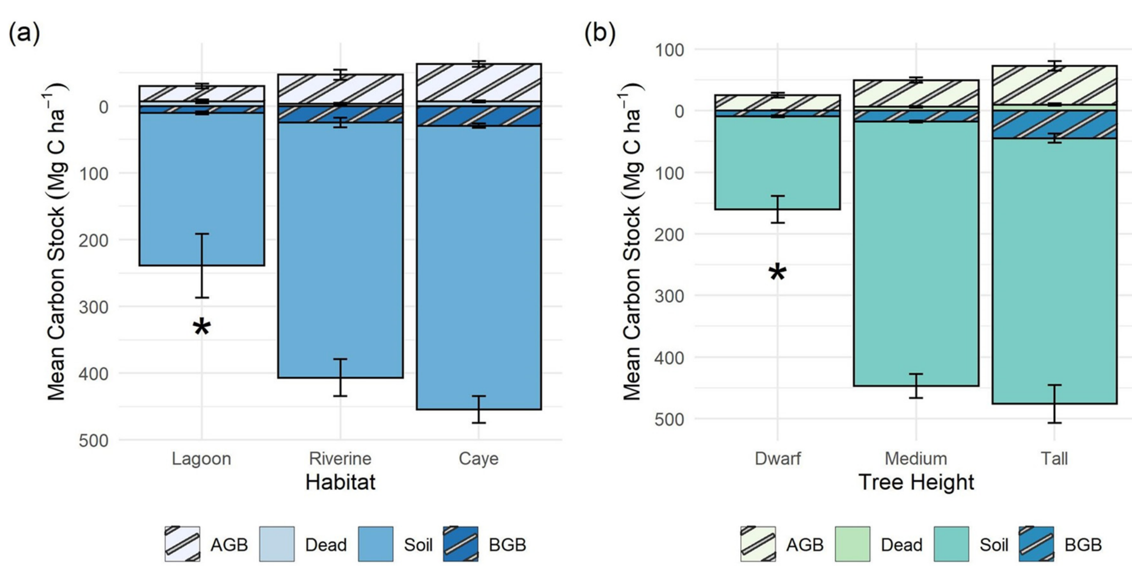

Fig. 5. Average carbon stock pools (AGB, BGB, Dead biomass, Soil) per classification sampled, for (a) habitat and (b) tree height. Striped bars are live biomass pools. Asterisks indicate significant differences between the other classes of the qualifying group ($p < 0.005$).

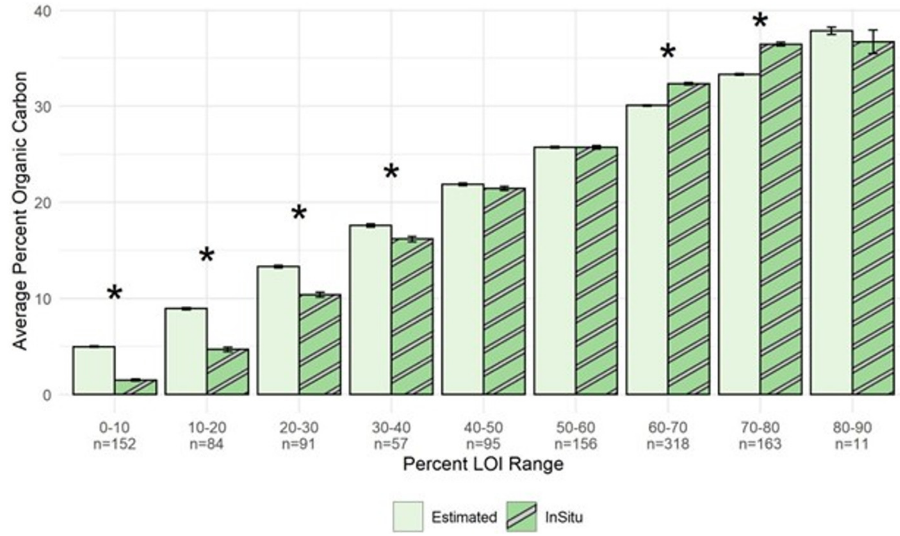

Fig. 6. Comparison between percent organic carbon values from collected in situ samples (dark green, striped) and percent organic carbon values estimated with a loss on ignition (LOI) relationship (light green, solid). Significant differences ($p < 0.005$) between the two sets of samples are designated with an asterisk. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

is shown below (Fig. 6) to have overestimated the organic carbon values for Belize's mangrove sediments when a sample had low LOI, and slightly underestimated when the sample had high LOI.

We provide a Belize-specific equation to estimate the percent carbon within a sediment sample (either total carbon (b) or organic carbon (c)), to reduce over- and underestimations of soil carbon stocks. This was accomplished by fitting a linear equation to the graphed percent carbon values (calculated from elemental analysis results) versus LOI values, binned in 10 % ranges (Fig. 7), with reported R^2 values of 0.89 and 0.95, respectively.

b. % Total Carbon $= 4.2 + 0.42 * \%$ LOI
c. % Organic Carbon $= -1.8 + 0.51 * \%$ LOI

4. Discussion

4.1. National mangrove carbon stocks

Following the IPCC Wetlands Supplement (IPCC, 2014) we were able to provide the first comprehensive mangrove carbon stock assessment for the country of Belize, which we estimate at 25.7 ± 1.2 Tg C to the top 1 m of soils. The availability of these region-specific data now allows Belize to transition from Tier I to Tier II reporting, and strengthens the government's commitment to reduce carbon emissions and progress towards being carbon neutral. We also provide guidance on priority areas for future conservation to meet the goals outlined in Belize's current NDC, namely targeting carbon-rich offshore cayes and riverine sites with medium to tall (>2 m) stands of mangroves. With no significant difference being observed between medium and tall mangrove sediment carbon stocks, the results indicate a threshold for height influence on TECS. Mangroves located offshore on the network of islands and cayes were observed to have significantly higher mean TECS (restricted to 1 m sediment depth) compared to mangroves located on the Belizean mainland, being approximately one-third (~36 %) of Belize's mangroves are located offshore (Cissell et al., 2021), thus representing an important contribution of the TECS budget of the country, 10.7 Tg C (~42 %). Currently ~13 % of Belizean mangroves are within protected areas (Canty et al., 2018), and assessing which mangrove ecosystems are to be included in protected areas, under the NDC commitment, will need to balance carbon stocks with other ecosystem services, such as coastal protection and fisheries habitat.

As many nations are not yet in a position to derive region-specific Tier II assessments of carbon, it is valuable to compare the values presented here with existing assessments to emphasize the importance of more refined estimates. Our findings have a lower mean TECS than regional estimates from Central America (473.6 Mg C ha^{-1}; Kauffman et al., 2020), but are more comparable with estimates of the general Americas (433.6 Mg C ha^{-1}; Kauffman et al., 2020). This is mostly likely due to the inclusion of Pacific coast sites within the Central American estimate, as they have more riverine stands and more likely higher carbon stocks. If regional estimates from Central America or the IPCC mean (511 Mg C ha^{-1}; IPCC, 2014) had been used to estimate the TECS of Belize, this would have overestimated the carbon stocks of the country by 1.7 Tg C (total 27.4 Tg C) or 3.9 Tg C (total 29.6 Tg C), respectively. Using the general Americas mean listed above, which is the closest estimate, there still would have been a slight underestimate of 0.6 Tg C (total 25.1 Tg C). The discrepancy between regional means and national data underline the importance of and investment in national data collection for mangrove carbon accounting, to ensure accurate reporting under NDC guidelines or other carbon inventories.

Mangrove sediment depths can be much >1 m and researchers regularly sample to 3 m depth (Kauffman et al., 2020). Within Belize's mangroves, for example, peat deposits have been recorded at 10–12 m on offshore cayes (Macintyre et al., 2009). Our sampling strategy included coring to a maximum depth of 3 m, and using the deeper mean sediment depth, we found a 26 % increase of approximately 9.2 Tg C in nationwide TECS, all of which is stored within mangrove sediment stocks. Riverine ecosystems also become the dominant accumulators of carbon when including these deeper sediments, demonstrating the complexity of each mangrove ecosystem type. This shows that many TECS values are underestimated globally by restraining the reporting to 1 m depth, and that restoration and sequestration potential may shift importance with in-situ measurements, thus better understanding the carbon stocks within mangrove systems and ensuring the safeguarding of these ecosystems to prevent significant carbon emissions from long-term storage.

The categorization of mangroves by specific ecotypes can influence the overall TECS value, and can be estimated using data layers such as biophysical typologies of mangroves (Worthington et al., 2020). Additionally, attributing carbon values to mangrove cover to species or genus may increase resolution, as *Rhizophora* spp. are associated with greater mean TECS than *Avicennia* spp. (Kauffman et al., 2020), however such maps are not widely available.

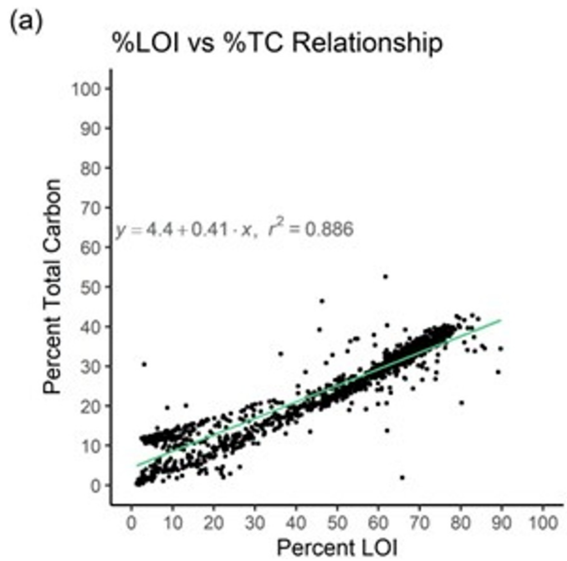

Fig. 7. Relationship between percent loss on ignition (LOI) and (a) percent total carbon (TC) or (b) percent organic carbon (OC) in the sediment samples, with the fitted linear equation in green. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4.2. Importance of the study and future assessments

A critical part of this project was the sharing of ecosystem and methodology knowledge between individuals from Belizean and international organizations. These exchanges were key in the co-development of a comprehensive and representative sampling strategy to encompass the various ecotypes of Belize's mangroves, as sites were chosen based on local and regional importance for management. During the field effort, 35 + individuals from government departments, academic institutions, and national NGOs were trained in the various methods of mangrove blue carbon assessments during an intensive field season in September 2021, which included the successful completion of nine of the ten chosen sampling locations. In March 2022 the tenth sampling site, which could not be conducted in 2021 due to a passing storm, was completed by a purely Belizean field team, highlighting the effectiveness of the knowledge-sharing model and in-person training for implementation of future projects. We suggest that this model can be adapted for other projects, and by including a focus on knowledge sharing and co-development, projects like these can foster a more diverse and equitable representation in the sciences. It will also help stem the undesirable consequences of “parachute science” where international scientists conduct valuable research in other countries but fail to work or connect the output with the local stakeholders who are most in need of that information (Stefanoudis et al., 2021).

One of the more expensive steps of this project was the soil elemental analyses, for which we ran a total of 1806 samples (including reruns) via a third-party commercial laboratory. While it is unlikely that future assessments will have as many samples, there is currently no capacity in Belize to complete these analyses, and therefore all future samples would be required to be outsourced. One way to combat this is the use of relationships between LOI and percent carbon within the sediments, and we provide here a Belize-specific equation between LOI and percentage carbon in mangrove sediments. Upon request, utilizing our current extensive dataset, the relationships can be further defined by region, ecotype, etc., depending on the needs of stakeholders. The availability of new parameters for these regional relationships decreases the future requirement for outsourced elemental analysis for percent carbon values, reducing costs and improving subsequent data acquisition. Having the regionally specific suite of equations will ensure a higher level of accuracy when determining future estimates for NDC updates and analyzing gains and losses due to development or restoration.

4.3. Conclusions

Within Belize's updated NDC, the government committed to protect an additional 12,000 ha of mangrove and restore 4000 ha of mangrove by 2030 (GoB, 2021). We identified potential hotspots of mangrove carbon stocks, with tall mangroves located on coastal rivers and offshore cayes associated with higher mean TECS. Protecting these areas will be key for the country, especially as the coastal and offshore caye areas are threatened by coastal development, particularly for tourism (Macintyre et al., 2009; Sweetman et al., 2018). Between 1980 and 2017, an estimated 4081–7232 ha of mangrove were lost due to various stressors in Belize, however a total area of 6522 ha has been identified as potentially suitable for restoration (Cherrington et al., 2020; Worthington and Spalding, 2018). Identifying potential areas for restoration in proximity to mangrove blue carbon hotspots could be a useful way to prioritize efforts with the caveat that protection and restoration should not only focus on blue carbon, but balance other ecosystem services and the needs of local communities. Similarly, deeper investigation of potential sources and drivers of carbon delivery and burial, including watershed loadings, hydrology, precipitation, salinity, and other environmental covariates, will be valuable to further aid in identifying and validating potential sites for both conservation and restoration.

Layering of different ecosystem services will be critical for a seascapes approach to management and conservation actions. Additionally, a socio-ecological approach should be considered as part of a robust measurement of management implementation and success. It is essential to understand how communities utilize their resources in order to assess their management needs and levels of engagement (Dencer-Brown et al., 2022), as climate change mitigation and adaptation may be critical needs. Garnering local support and having community-led initiatives have been proven to be highly successful not only for this study but also for marine resource protection and restoration efforts globally (Lovelock and McAllister, 2013).

CRediT authorship contribution statement

Hannah K. Morrissette: Data curation, Formal analysis, Methodology, Investigation, Resources, Software, Supervision, Validation, Visualization, Writing – original draft. **Stacy K. Baez:** Conceptualization, Investigation, Project administration, Supervision, Writing – original draft. **Lisa Beers:** Investigation, Methodology, Supervision, Writing – original draft. **Nadia Bood:** Conceptualization, Investigation, Writing – original draft. **Ninon**

D. Martinez: Data curation, Formal analysis, Investigation, Resources, Visualization, Writing – original draft. **Kevin Novelo:** Data curation, Formal analysis, Investigation, Resources, Visualization, Writing – original draft. **Gilbert Andrews:** Investigation, Writing – review & editing. **Luis Balan:** Investigation, Writing – review & editing. **C. Scott Beers:** Investigation, Writing – review & editing. **Sumeet A. Betancourt:** Investigation, Writing – review & editing. **Reynel Blanco:** Investigation, Writing – review & editing. **Eeryn Bowden:** Investigation, Writing – review & editing. **Virginia Burns-Perez:** Investigation, Writing – review & editing. **Mercedes Carcamo:** Investigation, Writing – review & editing. **Luis Chevez:** Investigation, Writing – review & editing. **Stephen Crooks:** Conceptualization, Investigation, Methodology, Writing – review & editing. **Ilka C. Feller:** Conceptualization, Writing – review & editing. **Galento Galvez:** Investigation, Writing – review & editing. **Kent Garbutt:** Investigation, Writing – review & editing. **Ronny Gongora:** Investigation, Writing – review & editing. **Edalmi Grijalva:** Investigation, Writing – review & editing. **Jonathan Lefcheck:** Investigation, Writing – review & editing. **Alwyn Mahung:** Investigation, Writing – review & editing. **Colin Mattis:** Conceptualization, Writing – review & editing. **Tre McKoy:** Investigation, Writing – review & editing. **Daniel McLaughlin:** Investigation, Writing – review & editing. **Johan Meza:** Investigation, Writing – review & editing. **Edwardo Pott:** Investigation, Writing – review & editing. **Genevieve Ramirez:** Investigation, Writing – review & editing. **Vivian Ramnarace:** Investigation, Writing – review & editing. **Anthony Rash:** Investigation, Writing – review & editing. **Samir Rosado:** Investigation, Writing – review & editing. **Honorio Santos:** Investigation, Writing – review & editing. **Leomir Santoya:** Investigation, Writing – review & editing. **Wilson Sosa:** Investigation, Writing – review & editing. **Gabriela Ugarte:** Investigation, Writing – review & editing. **Jose Viamil:** Investigation, Writing – review & editing. **Arlene Young:** Conceptualization, Writing – original draft. **Jayron Young:** Investigation, Writing – review & editing. **Steven W.J. Canty:** Conceptualization, Formal analysis, Funding acquisition, Methodology, Project administration, Supervision, Visualization, Writing – original draft.

Data availability

The Coastal Carbon Atlas (https://ccrcn.shinyapps.io/CoastaCarbonAtlas/) houses the associated dataset for this publication, which can be found online and downloaded at: doi.org/10.25573/serc.21298338.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary information

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References

Adame, M.F., Kauffman, J.B., Medina, I., Gamboa, J.N., Torres, O., Caamal, J., Reza, M., Herrera-Silveira, J.A., 2013. Carbon stocks of tropical coastal wetlands within the karstic landscape of the Mexican Caribbean. PLoS ONE 8, e56569. https://doi.org/10.1371/journal.pone.0056569.

Aswani, S., Christie, P., Muthiga, N.A., Mahon, R., Primavera, J.H., Cramer, L.A., Barbie, E.B., Granek, E.F., Kennedy, C.J., Wolanski, E., Hacker, S., 2012. The way forward with ecosystem-based management in tropical contexts: reconciling with existing management systems. Mar. Policy 36 (1), 1–10. https://doi.org/10.1016/j.marpol.2011.02.014.

Barbier, E.B., Hacker, S.D., Kennedy, C., Koch, E.W., Stier, A.C., Silliman, B.R., 2011. The value of estuarine and coastal ecosystem services. Ecol. Monogr. 81, 169–193. https://doi.org/10.1890/10-1510.1.

Berger, M., Canty, S.W.J., Tuholske, C., Halpern, B.S., 2022. Sources and discharge of nitrogen pollution from agriculture and wastewater in the Mesoamerican Reef region. Ocean Coast. Manag. 227, 106269. https://doi.org/10.1016/j.ocecoaman.2022.106269.

Bindoff, N.L., Cheung, W.W., Kairo, J.G., Arístegui, J., Guinder, V.A., Hallberg, R., et al., 2019. Changing ocean, marine ecosystems, and dependent communities. In: Pörtner, H.-O., Roberts, D.C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., et al. (Eds.), IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 447–587 https://doi.org/10.1017/9781009157964.007.

Brodersen, K.E., Trevathan-Tackett, S.M., Nielsen, D.A., Connolly, R.M., Lovelock, C.E., Atwood, T.B., Macreadie, P.I., 2019. Oxygen consumption and sulfate reduction in vegetated coastal habitats: effects of physical disturbance. Front. Mar. Sci. 6, 14. https://doi.org/10.3389/fmars.2019.00014.

Buelow, C.A., Connolly, R.M., Turshwell, M.P., Adame, M.F., Ahmadiyya, G.N., Andradi-Brown, D.A., Bunting, P., Canty, S.W.J., Dunic, J.C., Friess, D.A., Lee, S.Y., Lovelock, C.E., McClure, E.C., Pearson, R.M., Sievers, M., Sousa, A.I., Worthington, T.A., Brown, C.J., 2022. Ambitious global targets for mangrove and seagrass recovery. Curr. Biol. 32, 1641–1649. https://doi.org/10.1016/j.cub.2022.02.013.

Canty, S.W.J., Preziosi, R.F., Rowntree, J.K., 2018. Dichotomy of mangrove management: a review of research and policy in the Mesoamerican reef region. Ocean Coast. Manag. 157, 40–49.

Cherrington, E.A., Griffin, R.E., Anderson, E.R., Hernandez Sandoval, B.E., Flores-Anderson, A.I., Muench, R.E., Markert, K.N., Adams, E.C., Limaye, A.S., Irwin, D.E., 2020. Use of public earth observation data for tracking progress in sustainable management of coastal forest ecosystems in Belize,Central America. Remote Sens. Environ. 245, 111798. https://doi.org/10.1016/j.rse.2020.111798.

Christianson, A.B., Cabre, A., Bernal, B., Baez, S.K., Leung, S., Perez-Porro, A., Poloczanska, E., 2022. The promise of blue carbon climate solutions: where the science supports ocean-climate policy. Front. Mar. Sci. 9, 851448. https://doi.org/10.3389/fmars.2022.851448.

Cissell, J.R., Canty, S.W.J., Steinberg, M.K., Simpson, L.T., 2021. Mapping national mangrove cover for Belize using Google Earth Engine and Sentinel-2 imagery. Appl. Sci. 11, 4258. https://doi.org/10.3390/app11094258.

de Oliveira Gomes, L.E., Sanders, C.J., Nobrega, G.N., Vescovi, L.C., Queiroz, H.M., Kauffman, J.B., Ferreira, T.O., Bernardino, A.F., 2021. Ecosystem carbon losses following a climate-induced mangrove mortality in Brazil. J. Environ. Manag. 297, 113381. https://doi.org/10.1016/j.envman.2021.113381.

Donato, D.C., Kauffman, J.B., Murdiyarso, D., Kurnianto, S., Stidham, M., Kanninen, M., 2011. Mangroves among the most carbon-rich forests in the tropics. Nat. Geosci. 4, 293–297. https://doi.org/10.1038/ngeo1123.

Dencer-Brown, A., Shilland, R., Friess, D.A., Herr, D., Benson, L., Berry, N., Cifuentes-Jara, M., Colas, P., Damayanti, E., Lopez Garcia, E., Gavaldao, M., Grimsditch, G., Hejnowicz, A.P., Howard, J., Islam, S.T., Kennedy, H., Kivugo, R.R., Lang'at, J.K.S., Lovelock, C.E., Malleson, R., Macreadie, P.I., Andrade-Medina, R., Mohamed, A., Pigeon, E., Ramos, J., Rosette, M., Salim, M.M., Schoof, E., Talukder, B., Thomas, T., Vanderklift, M.A., Huxham, M., 2022. Integrating blue: how do we make nationally determined contributions work for both blue carbon and local coastal communities? Ambio 51 (9), 1978–1993. https://doi.org/10.1007/s13280-022-01723-1.

Duarte, C.M., Losada, I.J., Hendriks, I.E., Mazarrasa, I., Marba, N., 2013. The role of coastal plant communities for climate change mitigation and adaptation. Nat. Clim. Chang. 3, 961–968. https://doi.org/10.1038/nclimate1970.

Duke, N.C., Meynecke, J.O., Dittmann, S., Ellison, A.M., Anger, K., Berger, U., Cannicci, S., Diele, K., Ewel, K.C., Field, C.D., et al., 2007. A world without mangroves? Science 317, 41–42. https://doi.org/10.1126/science.317.5834.41b.

Dunic, J.C., Brown, C.J., Connolly, R.M., Turschwell, M.P., Côté, I.M., 2021. Long-term declines and recovery of meadow area across the world's seagrass bioregions. Glob. Chang. Biol. 27, 4096–4109. https://doi.org/10.1111/gcb.15684.

Emanuel, K., 2021. Atlantic tropical cyclones downscaled from climate reanalyses show increasing activity over past 150 years. Nat. Commun. 12, 7027. https://doi.org/10.1038/s41467-021-27364-8.

Fourqurean, J., Duarte, C., Kennedy, H., Marbà, N., Holmer, M., Mateo, M.A., Apostolaki, E.T., Kendrick, G.A., Krause-Jensen, D., McGlathery, K.J., Serrano, O., 2012. Seagrass ecosystems as a globally significant carbon stock. Nat.Geosci. 5, 505–509. https://doi.org/10.1038/ngeo1477.

Friess, D.A., Krauss, K.W., Taillardat, P., Adame, M.F., Yando, E.S., Cameron, C., Sasmito, S.D., Sillanpää, M., 2020a. Mangrove blue carbon in the face of deforestation, climate change, and restoration. Annu.Plant Rev. 3, 427–456. https://doi.org/10.1002/9781119312994.apr0752.

Friess, D.A., Yando, E.S., Abuchahla, G.M.O., Adams, J.B., Cannicci, S., Canty, S.W.J., Cavanaugh, K.C., Connolly, R.M., Cormier, N., Dahdouh-Guebas, F., Diele, K., Feller, I.C., Fratini, S., Jennerjahn, T.C., Lee, S.Y., Ogurcak, D.E., Ouyang, X., Rogers, K., Rowntree, J.K., Sharma, S., Sloey, T.M., Wee, A.K.S, 2020b. Mangroves give cause for conservation optimism, for now. Curr. Biol. 30, R135–R158.

Friess, D.A., Rogers, K., Lovelock, C.E., Kraus, K.W., Hamilton, S.E., Lee, S.Y., Lucas, R., Primavera, J., Rajkaran, A., Shi, S., 2019. The state of the world's mangrove forests: past, present, and future. Annu. Rev. Environ. Resour. 44, 89–115. https://doi.org/10.1146/annurev-environ-101718-033302.

Government of Belize, 2021. Belize Updated Nationally Determined Contribution.

Halpern, B.S., Frazier, M., Afflerbach, J., Lowndes, J.S., Micheli, F., O'Hara, C., Scarborough, C., Selkoe, K.A., 2019. Recent pace of change in human impact on the world's ocean. Sci. Rep. 9 (1), 1–8. https://doi.org/10.1038/s41598-019-47201-9.

Himes-Cornell, A., Pendleton, L., Atiyah, P., 2018. Valuing ecosystem services from blue forests: a systematic review of the valuation of salt marshes, sea grass beds and mangrove forests. Ecosyst. Serv. 30, 36–48.

Howard, J., Hoyt, S., Isensee, K., Telszewski, M., Pidgeon, E. (Eds.), 2014. Coastal Blue Carbon: Methods for Assessing Carbon Stocks and Emissions Factors in Mangroves, Tidal Salt Marshes, and Seagrasses. Conservation International, Intergovernmental Oceanographic Commission of UNESCO, International Union for Conservation of Nature, Arlington, Virginia, USA.

IPCC, 2014. In: Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M., Troxler, T.G. (Eds.), 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands. IPCC, Switzerland.

IPCC, 2019. 2019 refinement to the 2006 IPCC guidelines for national greenhouse gas inventories: wetlands. In: Buendia, C., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., et al. (Eds.), Volume 4: Agriculture, Forestry and Other Land Use. IPCC, Switzerland.

Jevrejeva, S., Moore, J.C., Grinsted, A., 2012. Sea level projections to AD2500 with a new generation of climate change scenarios. Glob. Planet. Chang. 80–81, 14–20.

Kadaverugu, R., Dhyani, S., Dasgupta, R., Kumar, P., Hashimoto, S., Pujari, P., 2021. Multiple values of Bhitarkanika mangroves for human well-being: synthesis of contemporary scientific knowledge for mainstreaming ecosystem services in policy planning. J. Coast. Conserv. 25, 32. https://doi.org/10.1007/s11852-021-00819-2.

Kauffman, J.B., Adame, M.F., Arifanti, V.B., Schile-Beers, L.M., Bernardino, A.F., Bhomia, R.K., Donato, D.C., Feller, I.C., Ferreira, T.O., Jesus Garcia, M.C., MacKenzie, R.A., Megonigal, J.P., Murdiyarso, D., Simpson, L., Hernandez Trejo, H., 2020. Total ecosystem carbon stocks of mangroves across broad global environmental and physical gradients. Ecol. Monogr. 90 (2), e01405. https://doi.org/10.1002/ecm.1405.

Kauffman, J.B., Donato, D.C., 2012. Protocols for the Measurement, Monitoring and Reporting of Structure, Biomass and Carbon Stocks in Mangrove Forests. Working Paper. 86. CIFOR, Bogor, Indonesia.

Kauffman, J.B., Heider, C., Cole, T., Dwire, K.A., Donato, D.C., 2011. Ecosystem C pools of Micronesian mangrove forests: implications of land use and climate change. Wetlands 31, 343–352. https://doi.org/10.1007/s13157-011-0148-9.

Komiyama, A., Poungparn, S., Kato, S., 2005. Common allometric equations for estimating the tree weight of mangroves. J. Trop. Ecol. 21, 471–477. https://doi.org/10.1017/s0266467405002476.

Krauss, K.W., Osland, M.J., 2020. Tropical cyclones and the organization of mangrove forests: a review. Ann. Bot. 125, 213–234. https://doi.org/10.1093/aob/mcz161.

Kulp, S.A., Strauss, B.H., 2019. New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. Nat. Commun. 10, 4844. https://doi.org/10.1038/s41467-019-12808-z.

Laffoley, D.d'A., Grimsditch, G. (Eds.), 2009. The Management of Natural Coastal Carbon Sinks. IUCN, Gland, Switzerland.

Lecerf, M., Herr, D., Thomas, T., Elverum, C., Delrieu, E., Picourt, L., 2021. Coastal and Marine Ecosystems as Nature-based Solutions in New or Updated Nationally Determined Contributions, Ocean & Climate Platform, Conservation International. IUCN, GIZ, Rare, The Nature Conservancy, Wetlands International and WWF.

Lovelock, C.E., Fourqurean, J.W., Morris, J.T., 2017. Modeled CO2 emissions from coastal wetland transitions to other land uses: tidal marshes, mangrove forests, and seagrass beds. Front. Mar. Sci. 4, 143. https://doi.org/10.3389/fmars.2017.00143.

Lovelock, C.E., McAllister, R.R.J., 2013. 'Blue carbon' projects for the collective good. Carbon Manag. 4 (5), 477–479. https://doi.org/10.4155/cmt.13.50.

Macintyre, I.G., Toscano, M.A., Feller, I.C., Faust, M.A., 2009. Decimating mangrove forests for commercial development in the Pelican Cays, Belize: long-term ecological loss for short-term gain? Smithson. Contrib. Mar. Sci. 38, 281–290.

Macreadie, P.I., Costa, M.D.P., Atwood, T.B., Friess, D.A., Kelleway, J.J., Kennedy, H., Lovelock, C.E., Serrano, O., Duarte, C.M., 2021. Blue carbon as a natural climate solution. Nat. Rev. Earth Environ. 2, 826–839.

Menéndez, P., Losada, I.J., Torres-Ortega, S., Narayan, S., Beck, M.W., 2020. The global flood protection benefits of mangroves. Nat. Sci. Rep. 10, 4404. https://doi.org/10.1038/s41598-020-61136-6.

Nellemann, C., Corcoran, E., Duarte, C.M., Valdés, L., De Young, C., Fonseca, L., Grimsditch, G. (Eds.), 2009. Blue Carbon. A Rapid Response Assessment. United Nations Environment Programme, GRID-Arendal . www.grida.no.

Romañach, S.S., DeAngelis, D.L., Koh, H.L., Li, Y., Teh, S.Y., Barizan, R.S.R., Zhai, L., 2018. Conservation and restoration of mangroves: global status, perspectives, and prognosis. Ocean Coast.Manag. 154 (15), 72–82. https://doi.org/10.1016/j.ocecoaman.2018.01.009.

Saintilan, N., Khan, N.S., Kelleway, J.J., Rogers, K., Woodroffe, C.D., Horton, B.P., 2020. Thresholds of mangrove survival under rapid sea level rise. Science 368 (6495), 1118–1121. https://doi.org/10.1126/science.aba2656.

Schulte, E.E., Hopkins, B.G., 1996. Estimation of organic matter by weight loss-on-ignition. In: Magdoff, F.R., et al. (Eds.), Soil Organic Matter: Analysis and Interpretation (SSSA Spec. Publ. 46). SSSA, Madison, Wisc, pp. 21–31.

Serrano, O., Kelleway, J.J., Lovelock, C., Lavery, P.S., 2019. Chapter 28 - conservation of blue carbon ecosystems for climate change mitigation and adaptation. In: Perillo, Gerardo M.E., Wolanski, Eric, Cahoon, Donald R., Hopkinson, Charles S. (Eds.), Coastal Wetlands, Second edition Elsevier, pp. 965–996 https://doi.org/10.1016/B978-0-444-63893-9.00028-9 ISBN 9780444638939.

Smith, T.J., Whelan, K.R.T., 2006. Development of allometric relations for three mangrove species in South Florida for use in the Greater Everglades Ecosystem restoration. Wetl. Ecol. Manag. 14, 409–419. https://doi.org/10.1007/s11273-005-6243-z.

Simpson, L.T., Canty, S.W.J., Cissel, J.R., Steinberg, M.K., Cherry, J.A., Feller, I.C., 2021. Bird rookery nutrient over-enrichment as a potential accelerant of mangrove cay decline in Belize. Oecologia 197, 771–784. https://doi.org/10.1077/s00442-021-05056-w.

Sippo, J.Z., Lovelock, C.E., Santos, I.R., Sanders, C.J., Maher, D.T., 2018. Mangrove mortality in a changing climate: an overview. Estuar. Coast. Shelf Sci. 215, 241–249. https://doi.org/10.1016/j.ecss.2018.10.011.

Statistical Institute of Belize, 2010. Belize Population and Housing Census 2010.

Stefanoudis, P.V., Licuanan, W.Y., Morrison, T.H., Talma, S., Veitayaki, J., Woodall, L.C., 2021. Turning the tide of parachute science. Curr. Biol. 31, R161–R185. https://doi.org/10.1016/j.cub.2021.01.029.

Sweetman, B.M., Cissel, J.R., Rhine, S., Steinber, M.K., 2018. Land cover changes on Ambergris Caye, Belize: a case study of unregulated tourism development. Prof. Geogr. 71 (468), 1–12. https://doi.org/10.1080/00330124.2018.1501710.

The Blue Carbon Initiative, 2020. Blue Carbon and Nationally Determined Contributions. Guidelines on Enhanced Action: A Guide on How Countries May Include Blue Carbon in Their Nationally Determined Contributions.

Thomas, J.-B.E., Nordström, J., Risén, E., Malmström, M.E., 2017. The perception of aquaculture on the Swedish West Coast. Ambio 47, 398–409. https://doi.org/10.1007/s13280-017-0945-3.

UNEP, 2014. In: van Bochove, J., Sullivan, E., Nakamura, T. (Eds.), The Importance of Mangroves to People: A Call to Action. United Nations Environment Programme World Conservation Monitoring Centre, Cambridge 128 pp.

UNFCCC, 2015. Adoption of the Paris Agreement. I: Proposal by the President (Draft Decision). United Nations Office, Geneva (Switzerland) 128 pp.

UNFCCC, 2021. Nationally determined contributions under the Paris Agreement. Synthesis Report by Secretariat. https://unfccc.int/sites/default/files/resource/cma2021_08_adv_1.pdf.

Vecchi, G.A., Landsea, C., Zhang, W., Villarini, G., Knutson, T., 2021. Changes in Atlantic major hurricane frequency since the late-19th century. Nat. Commun. 12, 4054. https://doi.org/10.1038/s41467-021-24268-5.

Worthington, T., Spalding, M., 2018. Mangrove Restoration Potential: A Global Map Highlighting a Critical Opportunity. The Nature Conservancy, IUCN, University of Cambridge.

Worthington, T.A., zu Ermgassen, P.S.E., Friess, D.A., Krauss, K.W., Lovelock, C.E., Thorley, J., Tingey, R., Woodroffe, C.D., Bunting, P., Cormier, N., Lagomasino, D., Lucas, R., Murray, N.J., Sutherland, W.J., Spalding, M., 2020. A global biophysical typology of mangroves and its relevance for ecosystem structure and deforestation. Sci. Rep. 10, 14652. https://doi.org/10.1038/s41598-020-71194-5.