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TECHNICAL ADVANCE

The Coastal Carbon Library and Atlas: Open source soil data and tools supporting blue carbon research and policy

James R. Holmquist[1] | David Klinges[1,2] | Michael Lonneman[1] | Jaxine Wolfe[1] | Brandon Boyd[3] | Meagan Eagle[4] | Jonathan Sanderman[5] | Kathe Todd-Brown[2] | E. Fay Belshe[2] | Lauren N. Brown[6] | Samantha Chapman[7] | Ron Corstanje[8] | Christopher Janousek[9] | James T. Morris[10] | Gregory Noe[11] | André Rovai[12] | Amanda Spivak[13] | Megan Vahsen[14] | Lisamarie Windham-Myers[15] | Kevin Kroeger[4] | J. Patrick Megonigal[1]

[1]Smithsonian Environmental Research Center, Edgewater, Maryland, USA

[2]University of Florida, Gainesville, Florida, USA

[3]Army Corps of Engineers, Washington, DC, USA

[4]USGS, Woods Hole, Massachusetts, USA

[5]Woods Hole Research Center, Woods Hole, Massachusetts, USA

[6]Bowling Green State University, Bowling Green, Ohio, USA

[7]Villanova University, Villanova, Pennsylvania, USA

[8]Cranfield University, Cranfield, UK

[9]Oregon State University, Corvallis, Oregon, USA

[10]University of South Carolina, Columbia, South Carolina, USA

[11]USGS, Wetland Ecosystem Ecology and Biogeochemistry Laboratory, Reston, Virginia, USA

[12]Louisiana State University, Baton Rouge, Louisiana, USA

[13]University of Georgia, Athens, Georgia, USA

[14]Notre Dame University, Notre Dame, Indiana, USA

[15]USGS, Water Missions Area, Menlo Park, California, USA

Correspondence
James R. Holmquist, Smithsonian Environmental Research Center, 647 Contees Wharf Road, Edgewater, MD 21037, USA.
Email: holmquistj@si.edu

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Abstract

Quantifying carbon fluxes into and out of coastal soils is critical to meeting greenhouse gas reduction and coastal resiliency goals. Numerous 'blue carbon' studies have generated, or benefitted from, synthetic datasets. However, the community those efforts inspired does not have a centralized, standardized database of disaggregated data used to estimate carbon stocks and fluxes. In this paper, we describe a data structure designed to standardize data reporting, maximize reuse, and maintain a chain of credit from synthesis to original source. We introduce version 1.0.0. of the Coastal Carbon Library, a global database of 6723 soil profiles representing blue carbon-storing systems including marshes, mangroves, tidal freshwater forests, and seagrasses. We also present the Coastal Carbon Atlas, an R-shiny application that can

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be used to visualize, query, and download portions of the Coastal Carbon Library. The majority (4815) of entries in the database can be used for carbon stock assessments without the need for interpolating missing soil variables, 533 are available for estimating carbon burial rate, and 326 are useful for fitting dynamic soil formation models. Organic matter density significantly varied by habitat with tidal freshwater forests having the highest density, and seagrasses having the lowest. Future work could involve expansion of the synthesis to include more deep stock assessments, increasing the representation of data outside of the U.S., and increasing the amount of data available for mangroves and seagrasses, especially carbon burial rate data. We present proposed best practices for blue carbon data including an emphasis on disaggregation, data publication, dataset documentation, and use of standardized vocabulary and templates whenever appropriate. To conclude, the Coastal Carbon Library and Atlas serve as a general example of a grassroots F.A.I.R. (Findable, Accessible, Interoperable, and Reusable) data effort demonstrating how data producers can coordinate to develop tools relevant to policy and decision-making.

KEYWORDS
blue carbon, carbon sequestration, coastal wetland, open data, sea-level rise, soil organic carbon, synthesis

1 | INTRODUCTION

Globally, wetland soils are estimated to contain 500–680 Petagrams of carbon (Poulter et al., 2021), equivalent to 60%–82% of all carbon present in the atmosphere (Ciais et al., 2014). Coastal wetlands such as tidal marshes, tidal freshwater forests, referred to throughout as swamps, mangroves, and seagrasses are known to sequester carbon on decadal to millennial time scales (Chmura et al., 2003; Howard et al., 2017; Mcleod et al., 2011; Ouyang & Lee, 2014). So-called blue carbon habitats have been garnering attention in recent years because of the capacity for management interventions to avoid greenhouse gas emissions by conserving wetlands or re-establish greenhouse gas removals by restoring them (Eagle et al., 2022; Kroeger et al., 2017; Lovelock & Duarte, 2019; Wylie et al., 2016).

Coastal wetland soils are unique in that they store carbon in situ as a dynamic response to sea-level rise (Morris et al., 2002) via mineral trapping and organic soil mass production (Morris et al., 2002; Turner et al., 2006). These dynamics mean that factors such as relative sea-level rise (Rogers et al., 2019), plant community (Doughty et al., 2015; Schile et al., 2017), and elevation (Callaway et al., 2012; Peck et al., 2020b), are of great importance to predicting carbon stocks and burial rates. Given the fact that tidal wetlands were underrepresented in previous efforts (Holmquist et al., 2018b), the requirements of specialist and interdisciplinary knowledge represented in tidal wetland datasets, and their distinctness from terrestrial soils, we propose that soils from blue carbon habitats require their own dedicated synthesis effort for disaggregated data.

Data syntheses for coastal wetland ecosystems have been undertaken previously. An original synthesis by Chmura et al. (2003) established coastal wetland carbon storage as a major carbon sink. A subsequent expansion by Ouyang and Lee (2014) documented covariates associated with carbon burial. These foundational studies provided data reported or estimated from literature values but did not present original disaggregated information, original measurements rather than summary statistics, limiting their reuse for other purposes. Later synthesis datasets greatly expanded the available disaggregated carbon stocks data available for seagrasses (Fourqurean et al., 2012), tidal marshes (Holmquist et al., 2018b), tidal swamps (Krauss et al., 2018), and mangroves (Donato et al., 2011; Sanderman, 2017). These studies have many elements that a comprehensive database would require, but none were designed to be a living resource for the communities they helped establish.

Sharing of disaggregated data is vital to discovery in coastal carbon studies. Morris et al. (2016) documented a relationship between soil organic content and density which limits vertical accretion capacity. Holmquist et al. (2018b) independently validated soil carbon stock mapping strategies, uncovering an overestimate in carbon stock when relying on conventional maps. Rogers et al. (2019) utilized an earlier version of the database presented herein to show that the geography of relative sea-level rise explained variability in carbon density at a global scale. All of these important studies would not be possible without the sharing of disaggregated data from researcher to researcher. However, data sharing between researchers is much rarer in practice than is implied through data availability statements in academic peer-reviewed journal articles (Tedersoo et al., 2021).

In this paper, we describe the creation and implementation of a set of standards and introduce the Coastal Carbon Library v1.0.0. This database is unique from previous efforts in that it spans multiple

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habitats, pays special attention to gathering site characteristics and methodological meta-data required to re-interpret data for new uses, and it contains disaggregated data, rather than summary statistics. We then present the Coastal Carbon Atlas (https://shiny.si.edu/coastal_carbon_atlas), a web tool for visualizing, querying, and downloading the Coastal Carbon Library. We also discuss the strengths of this database in the face of rapidly changing coastal ecosystems. Finally, we discuss potential future directions and proposed best practices.

2 | METHODS

Belowground carbon studies use soil depth series data to quantify belowground carbon stocks and estimate carbon burial rates (Chmura et al., 2003; Needelman et al., 2018; Ouyang & Lee, 2014). Typically cores are extracted using a tube or auger, and sub-sectioned into multiple depth increments (Smeaton et al., 2020). Organic matter density or carbon density is usually assessed as the product of dry bulk density (Blake, 1965), the organic matter fraction using loss-on-ignition (Dean, 1974) and/or fraction organic carbon (Callaway et al., 2012; Craft et al., 1991; Poppe & Rybczyk, 2018). Multiple methods are also employed for creating models of the accumulation or accretion rate of the profile including lead-210 (^{210}Pb; Appleby & Oldfield, 1978; DeLaune et al., 1987), radiocarbon (^{14}C; Redfield, 1972), radiocesium (^{137}Cs; DeLaune et al., 1978), as well as tying traces of pollution (Gerlach et al., 2017), pollen (Gerlach et al., 2017; Kearney & Ward, 1986), or sediment quality (Abbott, Elsey-Quirk, & DeLaune, 2019; Drexler et al., 2019) to dated historical events.

2.1 | Goals and scope

F.A.I.R. (Findable, Accessible, Interoperable, and Reusable) data principles are a set of best practices, seeking to maximize the re-usability of data. To meet goals of F.A.I.R. data, the goals of the data structure were four-fold, and grounded in best practices for data management (Wilkinson et al., 2016; Wilson et al., 2017). First, we preserved data in as much detail as is practical to maximize versatility. Second, we were transparent, relying on stable repositories. Third, we explicitly connect individual datasets within the synthesis to their original sources through one more associated citations. Fourth, we emphasized simplicity.

For scope, we focused on vegetated coastal tidal wetlands. We focused on emergent vegetation (marsh), scrub/shrub, and forested wetlands including mangroves and tidal swamps. We included seagrasses and tidal flats, but not kelp beds, coral reefs, or oyster reefs (Howard et al., 2017). These included saltwater, brackish, and freshwater ecosystems in the tidal zone and subtidal seagrasses. In addition to current tidal wetlands, we also included former tidal wetlands that had been modified by human impact and uplands or non-tidal wetlands if that comparison was a key aspect of the original study. Finally, while we did classify datasets based on their completeness or utility, we did not exclude any datasets based on methods used, origins, or lack of attributes beyond a few key requirements such as basic positional and depth information, as well as at least one relevant measured depth series attribute (Data S1).

2.2 | Data structure

Coastal Carbon Library data formatting (Holmquist et al., 2023) follows practices (Wilson et al., 2017) for maximizing data reuse such as descriptive attribute names, consistently formatted 'no data' values, multiple quality control attributes with consistent formatting, and multiple places for explanatory comments written in prose. Data files are long rather than wide, designating each row as a single observation, each column as a single variable, and each table as a set of observations and variables (Wickham, 2014). Data files are 'flat', all information is stored as simple, uniform, text. The structure consists of seven data tables (Figure 1):

1. Site: contains site-level information (Table 1).
2. Cores: contains core-level information (Table 2).
3. Depth series: provides the disaggregated information collected across depth increments of each soil profile (Table 3).
4. Methods: contains information about the methodology used for a collection of sampling and measurement events (Table 4).
5. Species: provides the plant species observed proximal to the sampling location (Table 5).
6. Impacts: provides a controlled classification of anthropogenic impacts associated with the sampling location (Table 6).
7. Bibliography: associated information of sources associated with datasets (Table 7).

All tables are relational with common linking variables study_id, site_id, methods_id, core_id, and bibliography_id. The site, core, depth series, species, impacts, and methods tables are hierarchical. Depth increments are nested within cores. Cores are nested within sites. Species and impacts are nested within cores, or within sites, if site-level data are the highest resolution provided by the study (Figure 1). Categorical variables have defined vocabulary listed in Table 8.

2.3 | Data sourcing

Data entered the Coastal Carbon Library through two tracks, with and without curatorial assistance by Coastal Carbon Network personnel. If a data source was already available through a data publication then the original data and associated metadata were downloaded to the Library repository (Figure 2). Ingestion scripts were then written in R code (R Core Team, 2021) to reshape, and reformat so that datasets could be merged (Figure 2).

If a dataset was unpublished, Coastal Carbon Network personnel first assisted the data submitter in creating a data publication on Figshare (Figure 2). Data releases included a title, abstract, keywords, authors, associated publications, acknowledgment of funding sources, data files, and ecological meta-data language (EML)-style metadata, an HTML version of the metadata, and a

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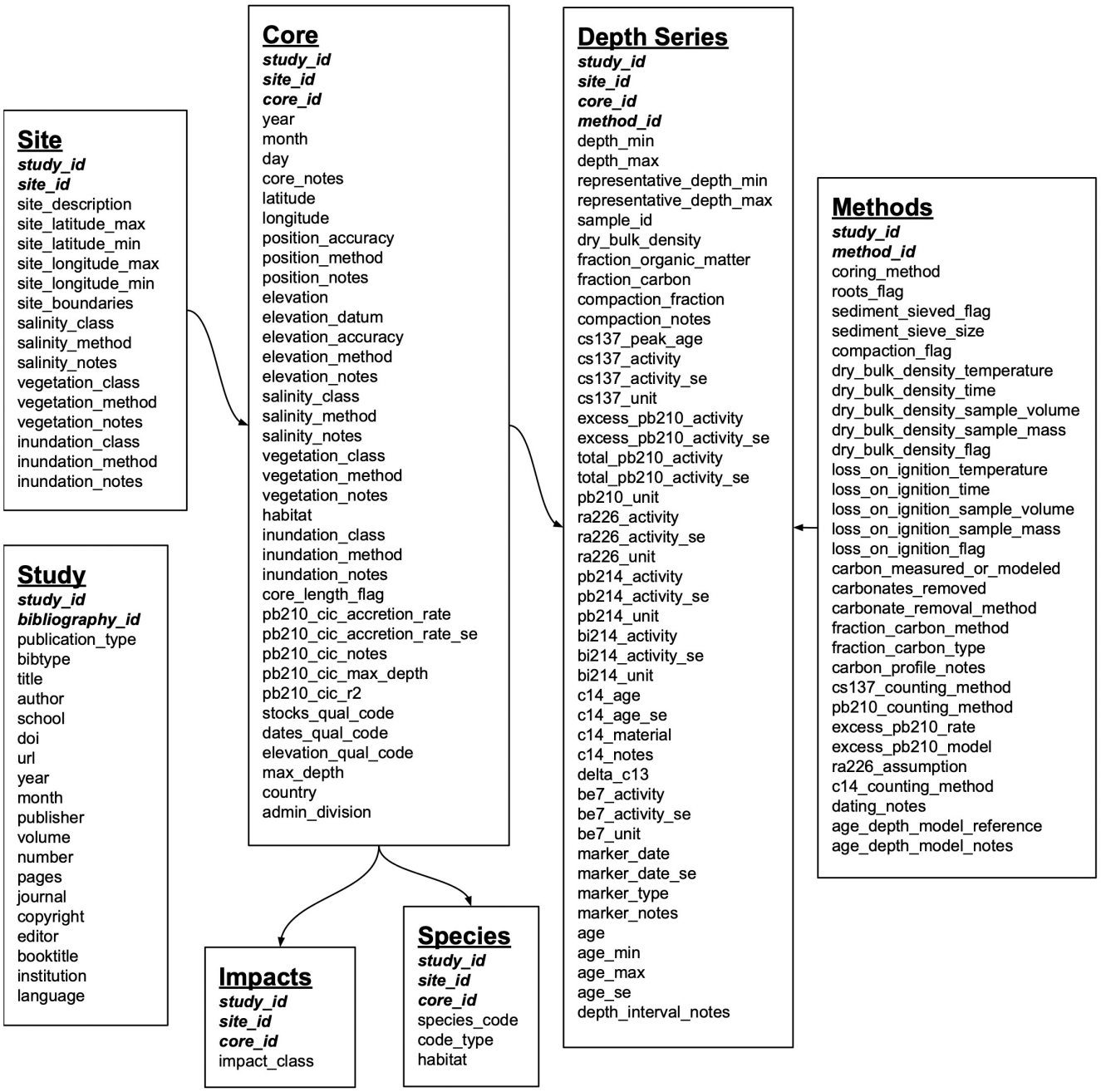

FIGURE 1 Relationships between the tables that make up the Coastal Carbon Library. Attributes tracked in each table are listed. Bold and italicized text indicates common attributes that can be used to join tables. The structure of the library is mostly hierarchical (a site contains multiple cores, and a core contains multiple depth increments in a series). One coring location can also have multiple anthropogenic impacts and plant species associated with it. A methods table links directly to depth increments as more than one set of methods may be used to analyze depth increments within a core.

citable digital object identifier (DOI). We published 27 datasets in this way (Abbott, Quirk, & Delaune, 2019; Allen et al., 2022; Arias-Ortiz, Masqué, et al., 2021; Belshe et al., 2019b; Boyd et al., 2019; Breithaupt et al., 2019, 2020; Buffington et al., 2020; Callaway et al., 2019; Carlin et al., 2021; Doughty et al., 2019; Ensign et al., 2021; Fell et al., 2021; Kauffman et al., 2020b; Kemp et al., 2020; Keshta et al., 2020; Lagomasino et al., 2020; McTigue et al., 2020; Messerschmidt & Kirwan, 2020; Nolte, 2020; Peck et al., 2020a; Poppe & Rybczyk, 2019; Sanbor & Darwyn, 2020; St. Laurent et al., 2020b; Thom, 2019; Vaughn et al., 2021; Weston et al., 2022).

2.4 | Data quality control and quality assessment

Data were quality-controlled using automated and visual checks. Automated quality tests were performed at both the individual study and whole synthesis levels and included (but were not limited to):

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TABLE 1 Attribute information for site table.

Attribute name	Definition	Data type	Unit
study_id	Unique identifier for the study made up of the first author's family name, as well as the second author's family name or et al. if more than three, then publication year separated by underscores	Free text	
site_id	Site identification code unique to each study	Free text	
site_description	Site description includes relevant study details and political geographic units. Some of these descriptions can be automated by the ingestion code.	Free text	
site_latitude_max	Maximum latitude defining a bounding box for the site in decimal degree World Geodedic System of 1984 (WGS84)	Numeric	Degree
site_latitude_min	Minimum latitude defining a bounding box for the site in decimal degree WGS84	Numeric	Degree
site_longitude_max	Maximum longitude defining a bounding box for the site in decimal degree WGS84	Numeric	Degree
site_longitude_min	Minimum longitude defining a bounding box for the site in decimal degree WGS84	Numeric	Degree
site_boundaries	As an alternative to submitting or automatically generating a bounding box, submitters can include a shapefile (.shp) or keyhole markup language (.kml) documenting the geographic boundaries of the site. This can be converted to and stored in well-known text format.	Free text	
salinity_class	Code based on submitter field observation or measurement indicating average annual salinity	Categorical	
salinity_method	Indicate whether salinity_class was determined using a field observation or a measurement	Categorical	
salinity_notes	Any relevant submitter-generated notes on how salinity_class was determined	Free text	
vegetation_class	Code based on submitter field observations or measurements indicating dominant wetland vegetation type	Categorical	
vegetation_method	Indicate whether vegetation_class was determined using a field observation or a measurement	Categorical	
vegetation_notes	Any relevant submitter-generated notes on how vegetation_class and/or dominant species were determined	Free text	
inundation_class	Code based on submitter field observation or measurement indicating how often the coring location is inundated	Categorical	
inundation_method	Indicate whether inundation_class was determined using a field observation or a measurement	Categorical	
inundation_notes	Any relevant submitter-generated notes on how inundation was determined	Free text	

- checking that the controlled attributes and variable names match guidelines.
- checking for the presence of mandatory and conditionally mandatory attributes (Data S1).
- verifying the uniqueness of core identifiers for a site and study.
- verifying the uniqueness of core locations in the overall database.
- verifying numeric attributes expressed as fractions were bound between 0 and 1.
- enforcing consistent spelling of taxonomic names using a global name resolver (Chamberlain & Szöcs, 2013).

During visual checks, Coastal Carbon Network personnel mapped the provided coordinates of sampling locations, the relationship between dry bulk density and organic matter, organic matter and organic carbon (Callaway et al., 2012; Craft et al., 1991; Morris et al., 2016), as well as depth-series of any depth profiles of soil measurements or radioisotope values (Arias-Ortiz et al., 2018).

2.5 | Data post-processing

We built a post-processing workflow that added geography attributes, detailed habitat classifications, and classified profiles based on the data's utility, completeness, and quality. Following initial processing, cores were assigned geographic units, using spatial joins in the sf package (Pebesma, 2018) in R. Geographic units include countries (ESRI Data and Maps, 2015b), internationally recognized exclusive economic zones (Flanders Marine Institute, 2019) and level-1 administrative districts such as states and provinces (ESRI Data and Maps, 2015a).

Explicit habitat classification was not a part of the initial versions of this database, only descriptions of vegetation type (emergent, scrub/shrub, and forested) and salinity, as is compatible with the U.S. National Wetlands Inventory (FGDC Wetlands Subcommittee, 2009). In response to community demand, we provided a consistent classification of coastal ecosystems (e.g., marshes, mangroves, swamps, seagrasses, and scrub-shrub wetlands). This information was typically present but spread across multiple linked tables such as the core and species table, and multiple attributes such as vegetation_class, salinity_class, core_id, or site_id within the core table. For the version of the Library presented herein, we improved the classification of blue carbon habitats by writing a decision-making workflow to classify each core based on contextual study-specific information, salinity and vegetation descriptions, presence of indicator species, and author-provided core and site descriptions:

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TABLE 2 Attribute information for the core table.

Attribute name	Definition	Data type	Unit
study_id	Unique identifier for the study made up of the first author's family name, as well as the second author's family name or et al. if more than three, then publication year separated by underscores	Free text	
site_id	Site identification code unique to each study	Free text	
core_id	Core identification code unique to each site	Free text	
year	Year of collection	Numeric	Numerical year
month	Numeric month of year of collection	Numeric	Numerical month of year
day	Numeric day of month of collection	Numeric	Numerical day of month
core_notes	Any other relevant submitter-generated notes on how cores were collected.	Free text	
latitude	Positional latitude of the core in decimal degree WGS84	Numeric	Degree
longitude	Positional longitude of the core in decimal degree WGS84	Numeric	Degree
position_accuracy	Accuracy of latitude and longitude measurement, if determined and recorded	Numeric	Meter
position_method	Code indicating how latitude and longitude were determined	Categorical	
position_notes	Any relevant submitter generated notes on how latitude and longitude were determined	Free text	
elevation	Surface elevation of the core relative to defined datum	Numeric	Meter
elevation_datum	The datum relative to which the core elevation was measured against (For a complete list of datum names and aliases please refer to the ISO Geodedic Registry_https://iso.registry.bespire.eu/register/geodetic/VerticalDatum)	Categorical	
elevation_accuracy	Accuracy of elevation measurement, if determined and recorded	Numeric	Meter
elevation_method	Code indicating how elevation was determined	Categorical	
elevation_notes	Any relevant submitter-generated notes on how elevation was determined	Free text	
salinity_class	Code based on submitter field observation or measurement indicating average annual salinity	Categorical	
salinity_method	Indicates whether salinity_class was determined using a field observation or a measurement	Categorical	
salinity_notes	Any relevant submitter-generated notes on how salinity_class was determined	Free text	
vegetation_class	Code based on submitter field observations or measurement indicating dominant wetland vegetation type	Categorical	
vegetation_method	Indicates whether vegetation_class was determined using a field observation or a measurement	Categorical	
vegetation_notes	Any relevant submitter-generated notes on how vegetation_class and/or dominant species were determined	Free text	
habitat	Habitat classification of the sampled location based on description or dominant vegetation	Categorical	
inundation_class	Code based on submitter field observation or measurement indicating how often the coring location is inundated	Categorical	
inundation_method	Indicates whether inundation_class was determined using a field observation or a measurement	Categorical	
inundation_notes	Any relevant submitter-generated notes on how inundation was determined	Free text	
core_length_flag	Indicates whether or not the coring team believes they recovered a full sediment profile, down to bedrock, or other non-marsh interface	Categorical	
stocks_qual_code	Code indicating the quality of information present for a core containing data relevant for carbon stock assessment	Categorical	

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TABLE 2 (Continued)

Attribute name	Definition	Data type	Unit
dates_qual_code	Code indicating the quality of information present for a core containing dated stratigraphy	Categorical	
elevation_qual_code	Code indicating the quality of information present for a dated core that contains elevation data	Categorical	
max_depth	Maximum depth of the sampled soil profile	Numeric	Centimeter
country	Country in which data were collected	Free text	
admin_division	Administrative division in which data were collected	Free text	

1. We detected whether the entry originates from a habitat-specific synthesis for mangroves (Sanderman, 2017) or seagrasses (Fourqurean et al., 2012).
2. Non-forested wetlands were classified into marshes, seagrasses, or tidal flat based on vegetation_class.
3. If the vegetation class was not descriptive, then we cross-referenced species present at the coring location with the USDA Plants database (USDA, NRCS, 2022) to determine the growth form of the plant. If multiple growth forms were reported for a species, then we classified it based on the tallest reported. We used habitat-specific lists of taxa (Larkum et al., 2006; Tomlinson, 2016) to determine whether or not a species had any special designation as seagrass or mangrove. Any graminoids, forbs, or ferns not otherwise classified as seagrasses were classified as marshes. Any trees not otherwise classified as mangroves were classified as swamps.
4. If previous steps were inconclusive, we used partial string matching to detect whether any descriptive language such as 'mangrove' or 'seagrass' was present in site_id or core_id.
5. A small number of estuarine forested wetland locations from the United States (Nahlik & Fennessy, 2016) could not be sorted into swamps and mangroves using the previously outlined methods, We assumed sites were mangrove if they occurred south of 29.75° latitude, the maximum northern extent of mangroves observed on the U.S. Atlantic coast of the U.S. (Cavanaugh et al., 2014). Conversely, we assumed estuarine forested sites north of this threshold were tidal swamps.

We developed an automated workflow to classify cores based on the type of study the data can be used for, including carbon stock assessments, calculation of carbon burial rates, and fitting of models of future carbon sequestration and wetland resilience. If dry bulk density and either organic matter or organic carbon were present in-depth series, then the core meets the minimal inclusion criteria for carbon stocks (C). If the core was confirmed to reach the bottom of the profile then it was considered a high-quality core (C1). If not, it was classified as of lower utility (C2). Here, the wetland sediment profile is considered complete if the contact point between wetland sediment and bedrock or non-wetland sediment is reached.

If any profile age-related or disaggregated data associated with these techniques were present in a core, then the core met the minimal inclusion criteria for calculating carbon burial rates (B). If any radioisotope activity levels were reported, then we required that the associated instrument error be reported for dating information to be considered complete (B1). This included ^{137}Cs, total ^{210}Pb, excess ^{210}Pb, ^{14}C, as well as any isotopes used to estimate supported ^{210}Pb, ^{226}Ra via its proxies ^{214}Bi and/or ^{214}Pb in gamma analysis. If the depth of ^{137}Cs peaks were reported, then we required a ^{137}Cs activity depth profile for completeness. If excess ^{210}Pb was reported, then we required that total ^{210}Pb be reported as well for the dataset to be considered complete. For ^{14}C ages, the material dated needed to be specified for the dataset to be considered complete. Any missing radioisotope errors or conditional attributes resulted in the dataset being classified as having incomplete data reporting (B2).

Cores with any age-depth data and elevation data met the minimum inclusion criteria for accretion modeling (A; Schile et al., 2014). We differentiated between elevations that were interpolated from remotely sensed or spatially interpolated digital elevation models (A3) and those that were directly measured using precise real-time kinematic GPS data or better (A1 or A2), which typically only have errors of a few centimeters. Cores with both a full suite of dating information and precise elevation were classified as the highest utility for data-model integration (A1), and cores with precise elevation but some missing dating information were graded lower (A2).

2.6 | Versioning, data use policy, and citation

The version of the database presented herein is v.1.0.0. and current as of January 12, 2023 (Coastal Carbon Network, 2023). Preliminary versions of this database were summarized in previous publications (Malhotra et al., 2019; Todd-Brown et al., 2022). New versions of this database will adopt standardized semantic versioning with the first digit indicating major changes to database structure, the second minor changes and additions of new datasets, and the third, backward-compatible changes. We anticipate regular updates to the Coastal Carbon Library as new datasets are submitted, approximately quarterly. It has a digital object identifier and a web link that will automatically route to the most up-to-date version.

The Coastal Carbon Library is licensed under CC-BY-4, meaning that it can be used without restriction other than attribution. Full attribution of the Coastal Carbon Library requires three things, first, citing the original primary datasets, papers or data publications, when they are reused for other purposes. In cases which an original

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TABLE 3 Attribute information for depth-series table.

Attribute name	Definition	Data type	Unit
study_id	Unique identifier for the study made up of the first author's family name, as well as the second author's family name or et al. if more than three, then publication year separated by underscores	Free text	
site_id	Site identification code unique to each study	Free text	
core_id	Core identification code unique to each site	Free text	
method_id	Unique identification code used to distinguish cores or sampling intervals that were collected or processed using different methods	Free text	
depth_min	Minimum depth of a sampling increment	Numeric	Centimeter
depth_max	Maximum depth of a sampling increment	Numeric	Centimeter
representative_depth_min	Minimum depth of a soil horizon of which the sample is representative	Numeric	Centimeter
representative_depth_max	Maximum depth of a soil horizon of which the sample is representative	Numeric	Centimeter
sample_id	This is a sample identification unique to the core. This should be used in the case that there are relevant lab specific sample codes, or in the case that there are multiple replicate samples.	Free text	
dry_bulk_density	Dry mass per unit volume of a soil sample This does not include ash-free bulk density	Numeric	Grams per cubic centimeter
fraction_organic_matter	This is the mass of organic matter relative to sample dry mass. Ash-free bulk density should not be used here but should be expressed as a loss on ignition fraction.	Numeric	Dimensionless
fraction_carbon	Mass of carbon relative to sample dry mass	Numeric	Dimensionless
compaction_fraction	Fraction of the sample depth interval reduced due to compaction	Numeric	Dimensionless
compaction_notes	Any submitter generated notes on compaction	Free text	
cs137_peak_age	Age of documented radiocesium (^{137}Cs) peak	Numeric	Year
cs137_activity	Radioactivity counts per unit dry weight for ^{137}Cs	Numeric	Specified in ^{137}cs unit
cs137_activity_se	1 standard error of uncertainty associated with cs137_activity	Numeric	Specified in ^{137}cs unit
cs137_unit	Reported unit for sample interval's ^{137}Cs activity measurements	Free text	Specified in ^{137}cs unit
excess_pb210_activity	Excess radioactivity counts per unit dry weight for excess lead 210 (^{210}Pb)	Numeric	Specified in ^{210}pb unit
excess_pb210_activity_se	1 standard error of uncertainty associated with excess_pb210_activity	Numeric	Specified in ^{210}pb unit
total_pb210_activity	Total radioactivity counts per unit dry weight for excess ^{210}Pb	Numeric	Specified in ^{210}pb unit
total_pb210_activity_se	1 standard error of uncertainty associated with total_pb210_activity	Numeric	Specified in ^{210}pb unit
pb210_unit	Reported unit for sample interval's ^{210}Pb activity measurements	Free text	
ra226_activity	This is the total radioactivity counts per unit dry weight for Radium-226 (^{226}Ra), also referred to as supported ^{210}Pb. This can be measured either using the proxy lead-214 (^{214}Pb), bismuth-214 (^{214}Bi), or the two of them averaged. Authors also have the option to report ^{214}Pb and ^{214}Bi in separately under pb214_activity and bi214_activity respectively.	Numeric	Specified in ^{226}ra unit
ra226_activity_se	1 standard error of uncertainty associated with ra226_activity	Numeric	Specified in ^{226}ra unit
ra226_unit	Reported unit for sample interval's ^{226}Ra activity measurements	Free text	Specified in ^{226}ra unit
pb214_activity	This is the rdioactivity counts per unit dry weight for lead-214 (^{214}Pb), a proxy for Radium-226 (^{226}Ra), also referred to as supported ^{210}Pb. Radioactivity should be reported here, rather than ra226_activity, either if the author also measures bismuth-214 and ra226_activity is a composite of the two measurements, or if they want to specify the proxy used for ^{226}Ra.	Numeric	Specified in ^{214}pb unit
pb214_activity_se	Estimated uncertainty in pb214_activity	Numeric	Specified in ^{214}pb unit
pb214_unit	Reported unit for sample interval's ^{214}Pb activity measurements	Free text	

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TABLE 3 (Continued)

Attribute name	Definition	Data type	Unit
bi214_activity	This is the radioactivity counts per unit dry weight for bismuth-214 (^{214}Bi), a proxy for Radium-226 (^{226}Ra), also referred to as supported ^{210}Pb. Radioactivity should be reported here, rather than ra226_activity, either if the author also measures lead-214 and ra226_activity is a composite of the two measurements, or if they want to specify the proxy used for ^{226}Ra.	Numeric	Specified in ^{214}bi unit
bi214_activity_se	Reported standard error for radioactivity counts per unit dry weight for ^{214}Bi	Numeric	Specified in ^{214}bi unit
bi214_unit	Reported unit for sample interval's ^{214}Bi activity measurements.	Free text	
c14_age	Radiocarbon (^{14}C) age as estimated from AMS measurements	Numeric	Radiocarbon year
c14_age_se	Estimated uncertainty in c14_age	Numeric	Radiocarbon year
c14_material	Description of the material selected for ^{14}C dating	Free text	
c14_notes	Any relevant submitter generated notes on ^{14}C dating process	Free text	
delta_c13	The isotopic signature of ^{13}C, oftentimes measured along with ^{14}C age and can be useful for analyzing carbon lability and provenance	Numeric	Parts per million
be7_activity	Radioactivity counts per unit dry weight for beryllium-7 (^{7}Be)	Numeric	Specified in ^{7}be unit
be7_activity_se	Estimated uncertainty in be_7_activity	Numeric	Specified in ^{7}be unit
be7_unit	Reported unit for sample interval's ^{7}Be activity measurements	Free text	
marker_date	The age of any other dated depth horizon such as an artificial marker, pollen horizon, pollution horizon, etc.	Date	Numerical year
marker_date_se	The standard error of the age of any other dated depth horizon such as an artificial marker, pollen horizon, pollution horizon, etc.	Date	
marker_type	Code indicating the type of marker	Categorical	
marker_notes	Any other submitter-generated notes about the origin of the marker	Free text	
age	Most likely, median, or mean age of the depth interval from submitter generated age-depth model	Numeric	Numerical year
age_min	Minimum age of the depth interval from submitter generated age-depth model	Numeric	Numerical year
age_max	Maximum age of the depth interval from submitter generated age-depth model	Numeric	Numerical year
age_se	Standard error of age estimate from submitter generated age-depth model	Numeric	Numerical year
depth_interval_notes	Any other submitter-generated notes specific to the depth interval	Free text	

source entered the Coastal Carbon Library via another synthesis for example, Sanderman et al. (2018) and Fourqurean et al. (2012), both the original source and synthesis should be cited. Second and third, the Coastal Carbon Library itself (Coastal Carbon Network, 2023) and, this manuscript should be cited in addition to primary and synthesis sources. Importantly, when data are downloaded and analyzed for new purposes, original primary sources need to always be cited to comply with the policy; citation of the Coastal Carbon Library and this paper alone would not be sufficient.

Because relationships between original data sources and the Coastal Carbon Library are complex, we include a relational table connecting study_id's to bibliographic information (Figure 1). The Coastal Carbon Altas (Figure 3), automatically formats bibliographic information based on the subset of datasets downloaded.

2.7 | Quantification of data coverage

We compared the makeup of cores in the Coastal Carbon Library to the global allocation of blue carbon area based on habitat and countries. For habitats, we reference literature for global area estimates for seagrasses, tidal marshes, and mangroves (Bunting et al., 2022; McKenzie et al., 2020; Murray et al., 2022; Table 9). For countries, we used a probabilistic map of intertidal area (Murray et al., 2022), counting tidal wetland pixels with greater than a 50% chance of being classified as tidal flat, tidal marsh, or mangrove in 1999. Country borders included both the land borders (ESRI Data and Maps, 2015b) and exclusive economic zones (Flanders Marine Institute, 2019).

3 | ACCESSING DATA VIA THE COASTAL CARBON ATLAS

The Coastal Carbon Atlas (https://shiny.si.edu/coastal_carbon_atlas; Figure 3) is an R-shiny web application that interfaces with the Coastal Carbon Library allowing users to explore, query, and directly download data. This tool has been adapted to suit user needs through community feedback. The Coastal Carbon Atlas consists of a map interface (Figure 3a) displaying sampling locations. The tabular view allows for a direct visual review of the site, core, and depth series tables (Figure 3b). The Coastal Carbon Atlas allows for the sub-setting of datasets by habitat type, geography, data availability,

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TABLE 4 Attribute information for methods table.

Attribute name	Definition	Data type	Unit
study_id	Unique identifier for the study made up of the first author's family name, as well as the second author's family name or et al. if more than three, then publication year separated by underscores	Free text	
method_id	Unique identification code used to distinguish cores or sampling intervals that were collected or processed using different methods	Free text	
coring_method	Code indicating what type of device was used to collect soil depth profiles	Categorical	
roots_flag	Code indicating whether live roots were included or excluded from carbon assessments	Categorical	
sediment_sieved_flag	Code indicating whether or not sediment was sieved prior to carbon measurements	Categorical	
sediment_sieve_size	If sediment was sieved, the size of sieve used	Numeric	Millimeters
compaction_flag	Code indicating how the authors qualified or quantified compaction of the core	Categorical	
dry_bulk_density_temperature	This is the temperature at which samples were dried to measure dry bulk density. This can include either samples that were freeze dried or oven dried.	Numeric	Degree celsius
dry_bulk_density_time	Time over which samples were dried to measure dry bulk density	Numeric	Hour
dry_bulk_density_sample_volume	Sample volume used for bulk density measurements, if held constant	Numeric	Cubic centimeter
dry_bulk_density_sample_mass	Sample mass used for bulk density measurements, if held constant	Numeric	Gram
dry_bulk_density_flag	Any notable codes regarding how the authors quantified dry bulk density	Categorical	
loss_on_ignition_temperature	Temperature at which samples were combusted to estimate fraction organic matter	Numeric	Degree celsius
loss_on_ignition_time	Time over which samples were combusted to estimate fraction organic matter	Numeric	Hour
loss_on_ignition_sample_volume	Sample volume used for loss on ignition, if held constant	Numeric	Cubic centimeter
loss_on_ignition_sample_mass	Sample mass used for loss on ignition, if held constant	Numeric	Gram
loss_on_ignition_flag	Common codes regarding loss on ignition methodology	Categorical	
carbonates_removed	Whether or not carbonates were removed prior to calculating fraction organic carbon	Categorical	
carbonate_removal_method	The method used to remove carbonates prior to measuring fraction carbon	Categorical	
fraction_carbon_method	Code indicating the method for which fraction carbon was measured	Categorical	
fraction_carbon_type	Code indicating whether fraction_carbon refers to organic or total carbon	Categorical	
carbon_profile_notes	Any other submitter-defined notes describing methodologies for determining dry bulk density, organic matter fraction, and carbon fraction	Free text	
pb210_counting_method	Code indicating the method used for determining lead 210 activity	Categorical	
excess_pb210_rate	Code indicating the mass or accretion rate used in the excess_pb_210_model	Categorical	
excess_pb210_model	Code indicating the model used to estimate accumulation rates and/or age-depth chronologies	Categorical	
ra226_assumption	Code indicating the assumption used to estimate the core's supported radium-226-specific activities	Categorical	
c14_counting_method	Code indicating the method used for determining radiocarbon activity	Categorical	
dating_notes	Any submitter defined notes elaborating on the process of dating the core not yet made clear by the coding	Free text	
age_depth_model_reference	Code indicating the reference or 0 year of the age depth model	Categorical	
age_depth_model_notes	Any submitter defined notes on how the age depth model was created	Free text	

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TABLE 5 Attribute information for species table.

Attribute name	Definition	Data type
study_id	Unique identifier for the study made up of the first author's family name, as well as the second author's family name or et al. if more than three, then publication year separated by underscores	Free text
site_id	Site identification code unique to each study	Free text
core_id	Core identification code unique to each site	Free text
species_code	Code associated with a species or a vegetation assemblage	Free text
code_type	Defines whether the code refers to a description, or level of plant taxonomy	Categorical
habitat	Habitat classification of the sampled location based on description or dominate vegetation	Categorical

TABLE 6 Attribute information for impacts table.

Attribute name	Definition	Data type
study_id	Unique identifier for the study made up of the first author's family name, as well as the second author's family name or et al. if more than three, then publication year separated by underscores	Free text
site_id	Site identification code unique to each study	Free text
core_id	Core identification code unique to each site	Free text
impact_class	Code indicating any major anthropogenic impacts historically and currently affecting the coring location	Categorical

core depth, study, human impacts, plant species present, and salinity descriptor. Finally, the Coastal Carbon Atlas provides options for limited post-processing and for downloading the data (Figure 3c). The user can specify custom depth intervals to download quantitative attributes summarized as depth-weighted averages of the depth increments specified.

Data downloads (Figure 3d) are accompanied by a bibliography of original sources and associated publications, metadata, and a text file that outlines the data use policy. To facilitate data users in providing credit to original sources, bibliographic information is included in a text file with formatted citations, a BibTex file that can be imported into reference management software, and a comma-separated value file with disaggregated reference information.

4 | CURRENT STATE OF THE COASTAL CARBON LIBRARY

The Coastal Carbon Library synthesis contained 6723 coastal wetland soil profiles from around the globe. These represent 48,870 depth increments, and 126,629 individual measurements, from 64 countries (Figures 3 and 4). Overall there were 305 studies represented in the database, related to 299 bibliographic entities (Abbott, Elsey-Quirk, & DeLaune, 2019; Abbott, Quirk, & Delaune, 2019; Abed-Navandi & Dworschak, 2005; Abino et al., 2014; Adame et al., 2013, 2015; Agawin et al., 1996; Ajonina et al., 2014; Allen et al., 2007, 2021, 2022; Alongi, 1996; Alongi et al., 1999, 2001, 2004, 2005; Alongi, Tirendi, Clough, 2000; Alongi, Tirendi, Trott, et al., 2000; Alongi, Trott, Rachmansyah, et al., 2008; Alongi, Trott, Undu, et al., 2008; Al-rousan et al., 2005; Amon & Herndl, 1991; Andreetta et al., 2014, 2016; Arias-Ortiz, Masqué, et al., 2021; Arias-Ortiz, Oikawa, et al., 2021; Arriola & Cable, 2017; Ashton & Macintosh, 2002; Banerjee et al., 2012; Barrón et al., 2004; Baustian, Stagg, Perry, Moss, & Carruthers, 2021; Baustian, Stagg, Perry, Moss, Carruthers, et al., 2021; Belshe et al., 2019a, 2019b; Bernhardt et al., 2018; Borg et al., 2010; Boschker et al., 2000; Bouillon et al., 2003; Boyd, 2012; Boyd et al., 2017, 2019; Boyd & Sommerfield, 2016; Breithaupt et al., 2014, 2017, 2019, 2020; Brunskill et al., 2002, 2004; Buffington et al., 2020; Bukoski et al., 2017; Bulmer et al., 2016; Burden et al., 2018, 2019; Burns & Swart, 1992; Buzzelli, 1998; Cahoon & Lynch, 1997; Callaway et al., 1997, 2012, 2019; Calleja et al., 2007; Campbell et al., 2014; Cardona & Botero, 1998; Carlin et al., 2021; Carruthers et al., 2005; Chambers et al., 2019; Chanda et al., 2013; Chen et al., 2010, 2012, 2014, 2016; Chen & Twilley, 1999; Chmura et al., 2003; Coastal Protection and Restoration Authority, 2015; Cochran et al., 1998; Cotner et al., 2004; Craft, 2007; Crooks et al., 2014; da Silva et al., 2009; Danovaro, 1996; Danovaro et al., 1994; Danovaro & Fabiano, 1995; Danovaro & Gambi, 2002; De Falco et al., 2006; de Iongh et al., 1995; De Troch et al., 2006; DelVecchia et al., 2014; Devereux et al., 2011; Dissanayake & Chandrasekara, 2014; Donato et al., 2011, 2012; Doughty et al., 2015, 2019; Drake et al., 2015; Drexler et al., 2009, 2013, 2019; Dung et al., 2016; Dutta et al., 2013; Elsey-Quirk et al., 2011; Ensign et al., 2015, 2021; EPA, 2016a, 2016b; Erftemeijer & Middelburg, 1993; Eyre & Ferguson, 2002; Ezcurra et al., 2016; Fell et al., 2021; Ferreira et al., 2007; Fonseca et al., 2011; Fourqurean et al., 2010, 2012; Fujimoto et al., 1999; Gacia et al., 2002; Gerlach et al., 2017; Giblin et al., 2018; Gillis et al., 2017; Gleason & Ewel, 2002; Gomes et al., 2016; Gonneea et al., 2004, 2018; Grady, 1981; Grenz et al., 2003; He et al., 2002; Hebert et al., 2006; Hemminga et al., 1994; Hill & Anisfeld, 2015; Holmer et al., 2001, 2006, 2009; Holmer & Duarte, 2003; Holmer & Frederiksen, 2007; Holmquist et al., 2018a; Howe et al., 2009; Iacono et al., 2008; Isaksen & Finster, 1996; Jennerjahn & Ittekkot, 2002; Johnson et al., 2007; Jones et al., 2016, 2017; Kairis & Rybczyk, 2010; Kamp-Nielsen et al., 2002; Kao et al., 2002; Kauffman et al., 2020a,

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TABLE 7 Attribute information for bibliography table.

Attribute name	Definition	Data type
study_id	Unique identifier for the study made up of the first author's family name, as well as the second author's family name or et al. if more than three, then publication year separated by underscores	Free text
bibliography_id	Bibliography identification code unique to each study	Free text
publication_type	Code indicating the type of publication the study originates from	Categorical
bibtype	BibTeX entry type	Free text
title	The title of the work	Free text
author	The author(s) of the publication	Free text
school	The school where the thesis was written	Free text
doi	Digital object identifier associated with the work	Free text
url	Permanent web address where the work can be located	Free text
year	The year of publication or, if unpublished, the year of creation	Free text
month	The month of publication (or, if unpublished, the month of creation)	Free text
publisher	The publisher's name	Free text
volume	The volume of a journal or multi-volume book	Free text
number	The (issue) number of a journal, magazine, or tech-report, if applicable (most publications have a volume, but no number field)	Free text
pages	Page numbers, separated either by commas or double-hyphens	Free text
journal	The journal or magazine the work was published in	Free text
copyright	The intellectual rights of the publication	Free text
editor	The name(s) of the editor(s)	Free text
booktitle	The title of the book, if only part of it is being cited	Free text
institution	The institution that was involved in the publishing, but not necessarily the publisher	Free text
language	The language a publication was written in	Free text

2020b; Kemp et al., 2012, 2020; Kenig et al., 1990; Keshta et al., 2017, 2020, 2021; Keuskamp et al., 2013; Koch & Madden, 2001; Koepfler et al., 1993; Krause-Jensen et al., 2011; Krauss et al., 2018; Kristensen et al., 1992, 2000; Kulawardhana et al., 2015; Lacerda et al., 1995; Lagomasino et al., 2013, 2020; Lallier-Verges et al., 1998; Lang et al., 2014; Larned, 2003; Leduc & Probert, 2010; Lee et al., 2005; Lee & Baker, 1972; Leopold et al., 2013; Lewis et al., 2007; Lillebø et al., 2006; Liu et al., 2008, 2014; Livesley & Andrusiak, 2012; Loi & Ni, 2015; Lovelock et al., 2010; Luk et al., 2020, 2021; MacKenzie et al., 2016; Maher & Eyre, 2010; Mao et al., 2011, 2012; Marchand et al., 2003, 2004; Marchio et al., 2016; Mateo et al., 1997; Mateo & Romero, 1997; Matsui and Naohiro, 1998; McClellan, 2021; McClellan et al., 2021; McFadden et al., 2016; McGlathery et al., 2012; McTigue et al., 2019, 2020; Mellors et al., 2002; Merrill, 1999; Messerschmidt & Kirwan, 2020; Mfilinge et al., 2002; Middelburg et al., 1996; Miller et al., 2022; Miyajima et al., 1998; Murdiyarso et al., 2015; Nahlik & Fennessy, 2016; Naidoo, 1980; Naidoo & Raiman, 1982; Nam et al., 2016; Neubauer et al., 2002; Noe et al., 2012, 2016; Nolte, 2020; Nolte et al., 2013; Nsommbo et al., 2016; Nuttle, 1996; Nyman et al., 1993; Oakes & Connolly, 2004; O'keefe Suttles, Eagle, Mann, & Kroeger, 2021; O'keefe Suttles, Eagle, Mann, Moseman-Valtierra, et al., 2021; O'keefe Suttles, Eagle, Mann, Spivak, et al., 2021; O'keefe Suttles, Eagle, Mann, Wang, et al., 2021; O'keefe Suttles, Wigand, Eagle, Branoff, et al., 2021; Ooi et al., 2011; Orem et al., 1999; Orson & Simpson, 1990; Osland, 2017; Osland et al., 2012; Otero et al., 2009; Pastore et al., 2017; Paula et al., 2001; Pazi et al., 2016; Peck et al., 2020a, 2020b; Pedersen et al., 1997; Piazza et al., 2011; Poppe, 2015; Poppe & Rybczyk, 2018, 2019, 2021, 2022; Prentice et al., 2020; Pulich Jr., 1987; Qu et al., 2006; Radabaugh et al., 2017; Rigollet, 2004; Rodriguez & Molly, 2022; Rosenfeld, 1979; Sahu et al., 2016; Saintilan et al., 2013; Sanbor & Darwyn, 2020; Sanderman, 2017; Sanders et al., 2008, 2014; Schile & Megonigal, 2017; Sfriso & Marcomini, 1999; Smith, 2012; Smith et al., 2015; Smoak et al., 2013; Spivak, 2020; Spivak et al., 2009; Spruzen et al., 2007; St. Laurent et al., 2020a, 2020b; Stoner et al., 1998; Stringer et al., 2015; Tam & Wong, 1998; Thimdee et al., 2003; Thom, 1992, 2019; Thompson et al., 2014; Thorne et al., 2018; Townsend & Fonseca, 1998; Trettin et al., 2017; Tue et al., 2014; Twilley et al., 1997; Unger et al., 2016; U.S. Geological Survey and Thorne, 2015; Van Engeland, 2010; Vasconcelos et al., 2014; Vaughn et al., 2020, 2021; Vichkovitten & Holmer, 2005; Volkman et al., 2008; Wang et al., 2013; Ward, 2021; Ward et al., 2021; Watson & Byrne, 2013; Weis et al., 2001; Weis & Anthony, 1999; Weston et al., 2022; White et al., 2020; Wigand et al., 2021; Windham-Myers et al., 2010; Woodroffe, 1985; Wooller et al., 2003; Xia et al., 2015; Xu et al., 2012; Yamamuro et al., 1993; Yando et al., 2016; Yang et al., 2013; Yarbro & Carlson, 2008; Zhang et al., 2012).

The majority of soil profiles came from tidal marsh (43.7%), followed by mangrove (29.5%), and seagrass ecosystems (11.7%). Lower proportions were from unvegetated surfaces (8.5%), not specified

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TABLE 8 Definitions of controlled vocabulary for attributes with categorical data.

Attribute name	Variable name	Definition
corresponding_author	TRUE	The author should be contacted with any further questions.
corresponding_author	FALSE	The author should not be contacted with any further questions.
publication_type	Combined dataset and manuscript	Primary dataset and associated manuscript are from the same source.
publication_type	Primary dataset	Primary published dataset
publication_type	Associated source	Source associated with primary dataset
publication_type	Synthesis dataset	Published dataset associated with the data synthesis
publication_type	Synthesis source	Source associated with data synthesis contribution
coring_method	Cryo core	A technique involving collecting a core by freezing soil using liquid nitrogen to a copper tube
coring_method	Gouge auger	A half cylinder coring device in which the coring section is open, not sealed off by a fin
coring_method	Hargas corer	A large diameter (>10 cm) coring device consisting of a tube, piston, and a cutting head
coring_method	Mcauley corer	A half cylinder coring device with the coring section sealed off by a fin attached to a rotating pivot point
coring_method	Mccaffrey peat cutter	U-shaped blade that extracts a core by cutting down through peat
coring_method	None specified	No coring device was specified
coring_method	Other shallow corer	Any other type of coring device typically taking cores shallower than 30 cm
coring_method	Piston corer	A device that extrudes core into tube upward with a plunger
coring_method	Push core	Any number of coring types involving driving a tube into the sediment to recover a core
coring_method	Pvc and hammer	PVC pipe was driven into the sediment with a hammer to recover a core
coring_method	Russian corer	A half cylinder coring device with the coring section sealed off by a fin attached to a rotating pivot point
coring_method	Vibracore	A technique involving collecting a core by sinking a continuous pipe into sediment attaching a source of vibration, then recovering using a winch and pulley
coring_method	Surface sample	A technique involving collecting a core shallower than ~5 cm using a circular metal cutter
coring_method	Soil pit	A pit is dug from the surface of the soil to the underlying bedrock
roots_flag	Roots and rhizomes included	Roots and rhizomes were included in dry bulk density and or organic matter and carbon measurements
roots_flag	Roots and rhizomes separated	Roots and rhizomes were separated from soil before dry bulk density and or organic matter and carbon measurements
sediment_sieved_flag	Sediment sieved	Sediment was sieved prior to analysis for organics
sediment_sieved_flag	Sediment not sieved	Sediment was not sieved prior to analysis for organics
compaction_flag	Compaction qualified	Compaction was at least qualified and noted by the authors
compaction_flag	Compaction quantified	Compaction was quantified and corrected for in core based measurements
compaction_flag	Corer limits compaction	Authors specified that the coring device's design minimized compaction
compaction_flag	No obvious compaction	Authors observed no obvious compaction
compaction_flag	Not specified	Compaction was not specified
dry_bulk_density_flag	Air dried to constant mass	Methodology specified that samples were air dried to a constant mass
dry_bulk_density_flag	Freeze dried	Bulk density was measured on freeze dried samples
dry_bulk_density_flag	Not specified	No additional details regarding bulk density methodology were provided
dry_bulk_density_flag	Removed non structural water	Bulk density methodology did not specify drying temperature or length, only that non-strucural water was removed
dry_bulk_density_flag	Time approximate	Bulk density time recorded herein is an approximate estimate
dry_bulk_density_flag	To constant mass	Bulk density methodology did not specify drying temperature or length, only that samples were dried to a constant mass

(Continues)

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TABLE 8 (Continued)

Attribute name	Variable name	Definition
loss_on_ignition_flag	Time approximate	Loss on ignition time recorded herein is an approximate estimate
loss_on_ignition_flag	Not specified	No additional details regarding loss on ignition methodology or time were provided
carbonates_removed	FALSE	Carbonates were not removed before measuring organic carbon
carbonates_removed	TRUE	Carbonates were removed before measuring organic carbon
carbonate_removal_method	Direct acid treatment	Carbonates were removed using direct application of dilute acid
carbonate_removal_method	Acid fumigation	Carbonates were removed by fumigating with concentrated acid
carbonate_removal_method	Low carbonate soil	Organic carbon fraction was measured without removing carbonates assuming carbonate content of the soil type was minimal
carbonate_removal_method	Carbonates not removed	Carbonates were not removed and low carbonate soil was not specified
carbonate_removal_method	None specified	Carbonate removal methodology was not specified
fraction_carbon_method	EA	Each sample presented was measured using Elemental Analysis
fraction_carbon_method	Kjeldahl digestion	Each sample was measured kjeldahl digestion method
fraction_carbon_method	Not specified	No additional details were provided regarding fraction carbon methodologies
fraction_carbon_method	Wet oxidation	Each sample was measured using a wet oxidation method
fraction_carbon_type	Organic carbon	Author specified that fraction carbon measurements were of organic carbon
fraction_carbon_type	Total carbon	Author specified that fraction carbon measurements were of total carbon
pb210_counting_method	Alpha	Alpha counting method was used
pb210_counting_method	Gamma	Gamma counting method was used
excess_pb210_rate	Mass accumulation	Excess ^{210}Pb modeled using mass accumulation rate
excess_pb210_rate	Accretion	Excess ^{210}Pb modeled using vertical accretion rate
excess_pb210_rate	Cumulative mass	Model run as excess ^{210}Pb against cumulative mass
excess_pb210_rate	Depth	Model run as excess ^{210}Pb against depth
excess_pb210_model	CRS	Constant rate of supply model used to estimate mass and/or accretion rates from age profile or chronology
excess_pb210_model	CIC	Constant initial concentration model used
excess_pb210_model	CFCS	Constant flux constant sedimentation model used
ra226_assumption	Each sample	^{226}Ra was measured for each sample
ra226_assumption	Total core	^{226}Ra was measured for the total core
ra226_assumption	At asymptote	^{226}Ra was measured at the asymptote of the ^{210}Pb profile
ra226_assumption	Selected samples	^{226}Ra measured by spectrometry at selected samples along the soil profile
c14_counting_method	AMS	Accelerator mass spectroscopy used
c14_counting_method	Beta	Beta counting used
age_depth_model_reference	YBP	Year zero is defined as years before present, 1960 CE
age_depth_model_reference	CE	Year zero is set according to Common Era and Before Common Era standards
age_depth_model_reference	Core collection date	Year zero is set as the core's collection year

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TABLE 8 (Continued)

Attribute name	Variable name	Definition
salinity_class	Estuarine	0.5–35 ppt
salinity_class	Brine	>50 ppt
salinity_class	Saline	30–50 ppt
salinity_class	Brackish	0.5–30 ppt
salinity_class	Fresh	<0.5 ppt
salinity_class	Mixoeuhaline	30–40 ppt
salinity_class	Polyhaline	18–30 ppt
salinity_class	Mesohaline	5–18 ppt
salinity_class	Oligohaline	0.5–5 ppt
salinity_class	Estuarine C-CAP	5–35 parts per thousand salinity (ppt) according to the coastal change analysis program
salinity_class	Palustrine C-CAP	<5 ppt according to the coastal change analysis program
salinity_method	Field observation	Salinity inferred by field observation such as vegetation
salinity_method	Measurement	Salinity observed from local instrument
vegetation_class	Emergent	Describes wetlands dominated by persistent emergent vascular plants
vegetation_class	Scrub shrub	Describes wetlands dominated by woody vegetation < or equal to 5 m in height
vegetation_class	Forested	Describes wetlands dominated by woody vegetation >5 m in height
vegetation_class	Forested to shrub	Dominated by forested to scrub/shrub biomass
vegetation_class	Forested to emergent	Dominated by forest and underlying marsh
vegetation_class	Seagrass	Describes tidal or subtidal communities dominated by rooted vascular plants
vegetation_method	Field observation	Vegetation inferred by field observation
vegetation_method	Measurement	Vegetation measured by counts or plots.
inundation_class	High	Study-specific definition of an elevation relatively high in the tidal frame, typically defined by vegetation type
inundation_class	Mid	Study-specific definition of an elevation in the relative middle of the tidal frame, typically defined by vegetation type
inundation_class	Low	Study-specific definition of an elevation in relatively low in the tidal frame, typically defined by vegetation type
inundation_class	Levee	Study-specific definition of a relatively high elevation zone built up on the edge of a river, creek, or channel
inundation_class	Back	Study-specific definition of a relatively low elevation zone behind a levee
inundation_method	Field observation	Inundation inferred by field observation such as vegetation
inundation_method	Measurement	Inundation class assessed from elevation and nearby tide gauge or other similar method
position_method	RTK	Real-time kinematic global position system (GPS)
position_method	Handheld	Conventional Commercially available hand-held GPS
position_method	Other high resolution	Any other technique resulting in positional error <1 m
position_method	Other moderate resolution	Any other technique resulting in positional error <30 m
position_method	Other low resolution	Any other technique resulting in positional error >30 m
elevation_datum	NAVD88	A gravity-based geodetic datum, North American Vertical Datum of 1988
elevation_datum	MSL	A tidal datum, Mean Sea Level as measured against a local tide gauge
elevation_datum	MTL	A tidal datum, Mean Tidal Level as measured against a local tide gauge
elevation_datum	MHW	A tidal datum, Mean High Water as measured against a local tide gauge
elevation_datum	MHHW	A tidal datum, Mean Higher High Water as measured against a local tide gauge
elevation_datum	MHHWS	A tidal datum, Mean Higher High Water for Spring Tides as measured against a local tide gauge
elevation_datum	MLW	A tidal datum, Mean Low Water as measured against a local tide gauge

(Continues)

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TABLE 8 (Continued)

Attribute name	Variable name	Definition
elevation_datum	MLLW	A tidal datum, Mean Lower Low Water as measured against a local tide gauge
elevation_datum	NHN	Normaal Amsterdams Peil, a vertical datum used in many areas of Western Europe
elevation_datum	NAP	Normalhoehennull, a vertical datum used in Germany that represents height above mean sea level
elevation_method	RTK	Real-time kinematic GPS
elevation_method	Other high resolution	Any other technique resulting in positional error <5 cm of random error
elevation_method	LiDAR	Handheld GPS matched to lidar-based digital elevation model
elevation_method	DEM	Handheld GPS matched to another digital elevation model
elevation_method	Other low resolution	Any other technique resulting in positional error >5 cm of random error
core_length_flag	Core depth limited by length of corer	The total depth of the core was limited by the length of the coring device
core_length_flag	Core depth represents deposit depth	Authors report that the depth of the core represents the depth of the wetland soil deposit.
core_length_flag	Not specified	Authors did not specify whether or not the depth of the core represents the depth of the wetland soil deposit
marker_type	Artificial horizon	Horizon was added to the surface artificially by using materials such as feldspar, glitter, or rare earth elements
marker_type	Pollen	Pollen analysis was used to tie horizon to the timing of vegetation change such as the arrival of invasives, or the beginning of local agriculture
marker_type	Pollution	Chemical analysis was used to tie the horizon to the timing of a pollution event
marker_type	Tsunami	Sediment analysis was used to tie the horizon to the timing of a tsunami event
impact_class	Tidally restricted	Tidal flow is muted or blocked by built structures
impact_class	Impounded	Water level is raised artificially by a tidal restriction, resulting in ponding of water on the wetland and or upland surface
impact_class	Salt impacted	Wetland has been salinized
impact_class	Natural	No disturbance or management has occurred
impact_class	Managed impounded	Wetland is impounded seasonally, and other times natural or semi natural hydrology occurs
impact_class	Ditched	Tidal hydrology is altered because artificial ditches have been cut to promote tidal flooding and drainage
impact_class	Diked and drained	The wetland has been diked and drained, with or without flapper gates, pumping, or other means
impact_class	Farmed	Managed impoundment or drainage in which wetland has been converted to agricultural land
impact_class	Tidally restored	Tidal flow has been restored by removing an artificial obstruction
impact_class	Revegetated	Wetland vegetation has been reintroduced by replanting on unvegetated surfaces
impact_class	Restored	Some method of restoration (potentially unspecified) has occurred
impact_class	Invasive plants removed	Natural plant communities have been restored by the active removal of invasive plant species
impact_class	Invasive herbivores removed	Tidal wetland vegetation has been managed by the removal of invasive herbivores
impact_class	Sediment added	Elevation has been managed by artificially adding sediment to the site using techniques such as thin layering or sediment diversion
impact_class	Wetlands built	Constructed wetland using sediments such as dredge spoils or other sediment source
habitat	Mangrove	Tropical and dominated by specialized shrubs or trees
habitat	Swamp	Predominantly freshwater and dominated by trees
habitat	Scrub/shrub	Wetland dominated by shrubs

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TABLE 8 (Continued)

Attribute name	Variable name	Definition
habitat	Marsh	Wetland dominated by emergent vegetation, gramminoids or forbs
habitat	Seagrass	Intertidal to subtidal and dominated by specialized predominantly submerged grasses
habitat	Algal mat	Dominated by algae
habitat	Unvegetated	Unvegetated
habitat	Tidal flat	Describes unvegetated areas exposed and flooded by the tides
habitat	Upland	Predominately above sea level and dominated by trees
code_type	Description	Cover description not related to plant taxonomy
code_type	Family	Refers to taxonomic family without indicating a genus or species
code_type	Genus	Refers to a taxonomic genus without indicating a species
code_type	Genus species	Refers to taxonomic Genus and species
stocks_qual_code	C2	Carbon stock data complete, not confirmed to be a complete profile
stocks_qual_code	C1	Carbon stock data complete, confirmed to be a complete profile
dates_qual_code	B2	Dating information present, but not complete
dates_qual_code	B1	Dating information present and complete
elevation_qual_code	A3	Elevation data present but of low quality, dating info present
elevation_qual_code	A2	Elevation data are of high quality, and dating info present but incomplete
elevation_qual_code	A1	Elevation data are of high quality, and dating info is complete

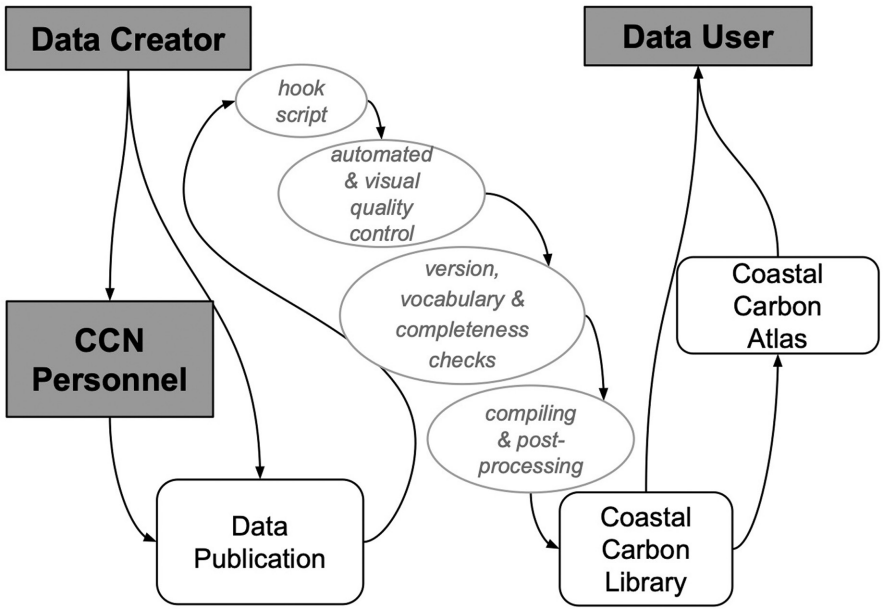

FIGURE 2 A flowchart shows the interactions between people (data creators, project personnel, and data users), products (data publications, the Coastal Carbon Library, and Coastal Carbon Atlas), and processes, outlined in this manuscript. Data creators can publish their data independently or through Coastal Carbon Network. Public data enters the Coastal Carbon Library, a centralized data synthesis, after multiple stages of data reshaping and quality control. Data users can access the library directly or through the Coastal Carbon Atlas.

(2.8%), or swamp ecosystems (1.8%). Algal mat, scrub/shrub, adjacent upland, and tidal flat ecosystems made up <1% of the database. Also, 93.6% of cores in the database are either classified as 'natural' or do not specify any anthropogenic impacts.

The most common types of soils data for marsh, mangrove, seagrass, and swamp ecosystems included dry bulk density, fraction organic matter, and fraction carbon measurements (Figure 4). Soil cores with a suite of basic soil carbon stock information included 4815 profiles (Figure 5). However, 90.4% were not confirmed to reach a contact point between wetland sediment and bedrock or non-wetland sediment. Only 19.5% of cores were greater than or equal to 1 m long, the target depth of soil maps used in some organic carbon stock assessments (Holmquist et al., 2018b).

Of the marsh, mangrove, seagrass, and swamp cores with sufficient data to calculate carbon stocks (4815), a subset of those had data sufficient to calculate carbon accumulation rates (533, Figure 5). Of these, the majority (77.8%) have fully transparent age-depth information traceable back to the original measurements (Figure 5). Of these dated cores, 326 also have associated elevation data, with 317 having both high-quality elevation and age-depth information (Figure 5).

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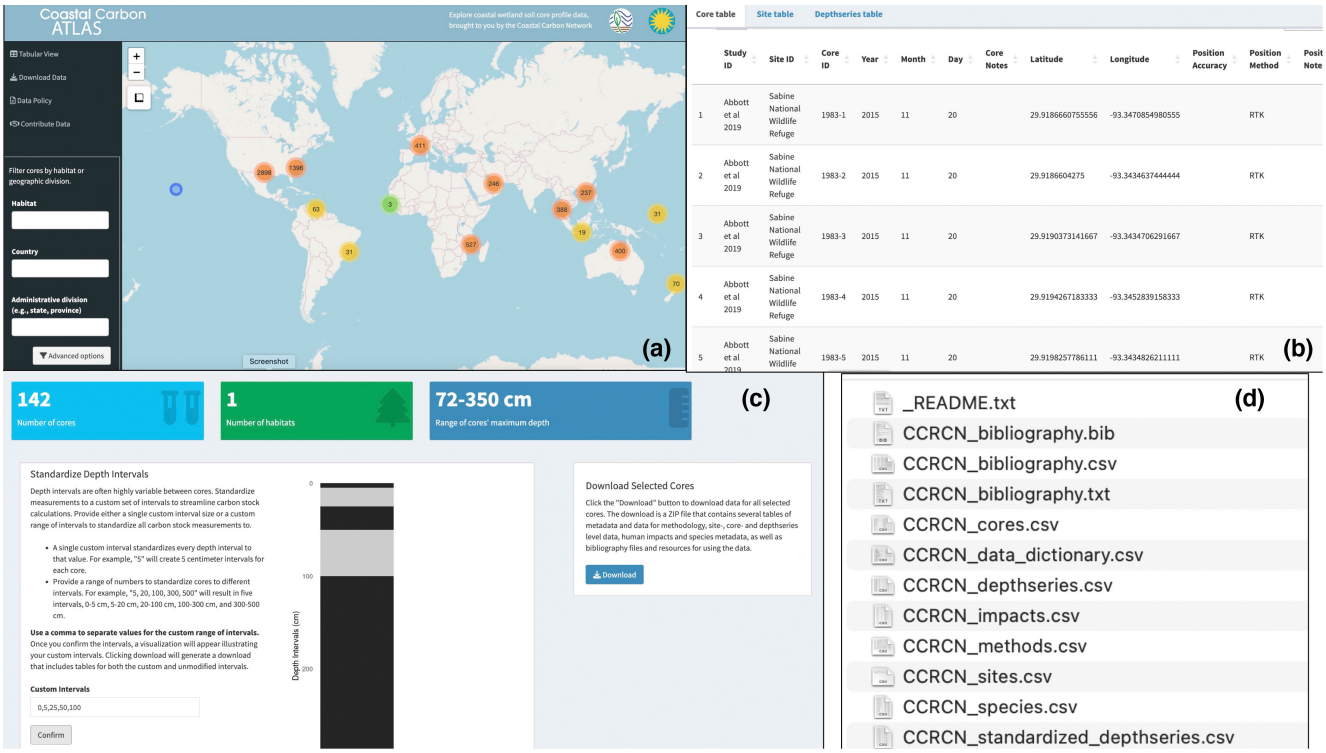

FIGURE 3 The Coastal Carbon Atlas: (a) Shows the map view with warmer colors indicating denser clusters of data. Clusters change and become more detailed as a user zooms in on a particular region or location. When zoomed all the way in users can identify individual coring locations. (b) An example of the Atlas's tabular view, which allows users to browse the raw data stored in the Coastal Carbon Library and accessible for download. (c) Shows the download screen including summary statistics of a query and options of post-processing depth series to output as depth weighted averages. (d) Shows a file tree of downloads including file summary in 'readMe', attribute and variable definitions in the 'data dictionary' file, the bibliographic information in three file formats, the site, core, depth series, methods, impacts, and species table, as well as the derived normalized weighted averages depth series table in the 'standardized depth series' table. The interactive application is available online (https://shiny.si.edu/coastal_carbon_atlas). Map lines do not necessarily depict accepted national boundaries.

TABLE 9 We compared global area estimates for three major blue carbon ecosystems, tidal marshes, mangroves, and seagrasses, compared with the representativeness of data appropriate for carbon stock assessments and burial rates when only the subset of those habitats is considered. Multiple estimates were found, so we present ranges based on the maximal scenario for mangroves and minimal for marshes, as well as maximal for marshes and minimal for mangroves. Despite variation in estimates of areas based on source, the current iteration of the Coastal Carbon Library clearly overrepresents marshes.

	Global area			Coastal carbon library representation	
Habitat	Source	Area estimate (km^2)	Area (%)	Carbon stocks (%)	Carbon burial rate (%)
Marsh	a,b	90,800–152,361	17.0–32.7	61.3	92.9
Mangrove	a,c	152,604–284,803	32.8–53.1	25.2	4.98
Seagrass	a	160,387	30.0–34.5	7.04	2.11

[a]McKenzie et al. (2020).
[b]Murray et al. (2022).
[c]Bunting et al. (2022).

When subsetting the major three habitats, marsh, mangrove, and seagrasses, and comparing to global estimates of area, it is clear that the current database over-represents tidal marshes and under-represents mangroves and seagrasses for carbon stock, but especially for carbon burial rate data (Table 9). Depending on the area estimate used, tidal marshes may represent between 17 and 32% of intertidal area, but tidal marshes dominate ecosystem representation in the database, at 61.3% of the carbon stock data and 92.9% of the carbon burial data. Seagrass and mangrove area are at least equal to, and very likely greater than, tidal marsh area (Table 9).

Data in the Coastal Carbon Library originated from 64 coastal countries, but the majority (59.9%) were from the United States despite the fact that the United States represented 8.6% of global tidal ecosystem extent (Murray et al., 2022; Figure 6). Countries such as

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Indonesia, Canada, Brazil, and Papua New Guinea were undersampled despite having relatively large areas (Figure 6).

Median organic matter density was highest in swamps and marshes, lower in mangroves, and lowest in seagrasses (Table 10). Dry bulk density, organic matter fraction, and their products, organic matter density, were non-normally distributed (Figure 7). All varied significantly based on habitat type according to a non-parametric Kruskal–Wallis rank-sum test ($p < 2.2e\text{-}16$).

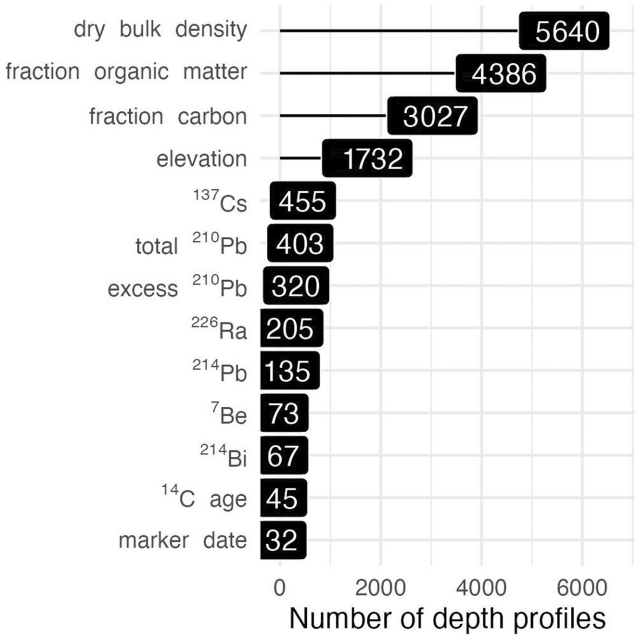

FIGURE 4 Summary of the count of cores with key measured attributes associated with them. Dry bulk density, fraction organic matter, and fraction carbon were most commonly measured. Data associated with core elevation and stratigraphic dating were less common.

5 | DISCUSSION

5.1 | Strengths of current effort

The Coastal Carbon Library and Atlas's strengths are in providing an example of how to build F.A.I.R. data in the earth and environmental sciences (Wilkinson et al., 2016). Providing support in issuing persistent digital object identifiers helps make data more findable. Accessibility was increased by preparing new data releases and distributing the Coastal Carbon Library all under creative commons open source licenses. Accessibility was further improved by creating the Coastal Carbon Atlas so that data could be queried by those without specialized data management and coding skills. The data were made interoperable by the creation and adoption of a controlled data structure and vocabulary. The data were made reusable by providing them in a highly disaggregated form. For example, for profiles available for calculating accretion rates and carbon burial rates, the majority of these data are fully reported, meaning that these metrics can be derived using existing publicly available age-depth modeling software (Aquino-López et al., 2018; Blaauw & Christen, 2011).

Beyond enacting F.A.I.R. data principles, the strengths of the Coastal Carbon Library and Atlas are in enhancing transparency.

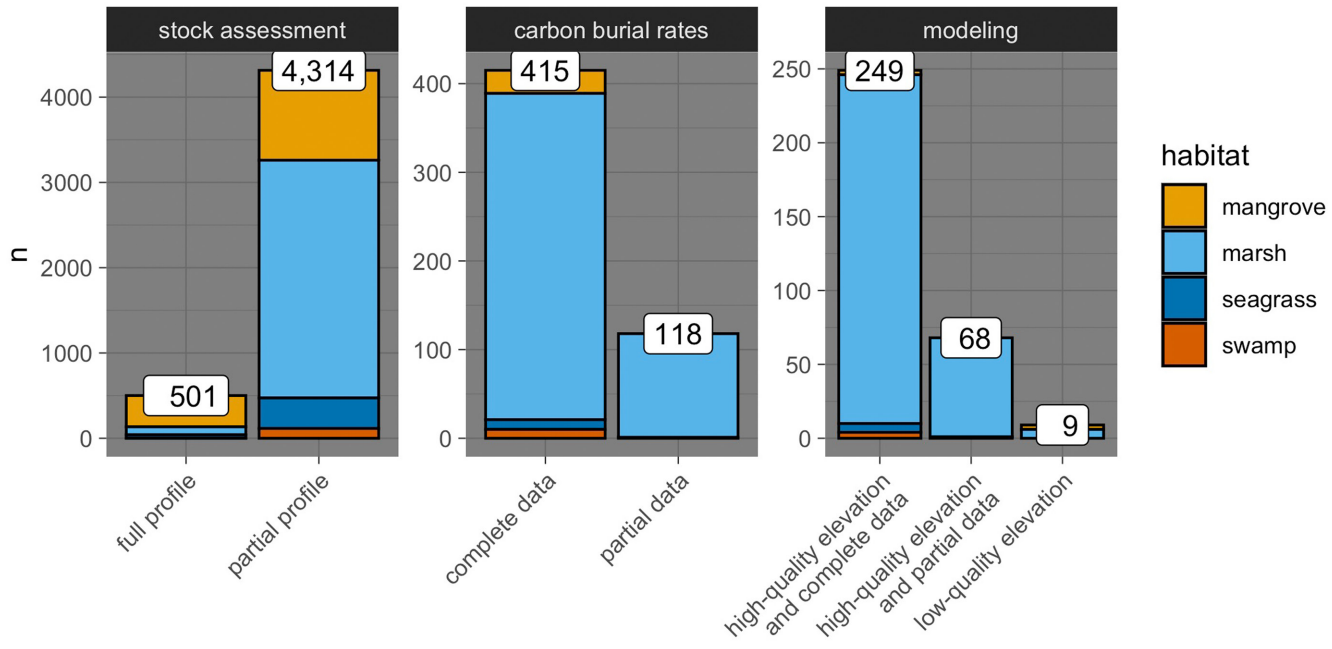

FIGURE 5 Summary of data quality and completeness for three different purposes: carbon stock assessments, estimating carbon burial rates, and parameterizing models of future carbon sequestration. We define sediment profiles as complete if reaching the contact point between wetland sediment and bedrock or lower non-wetland sediment.

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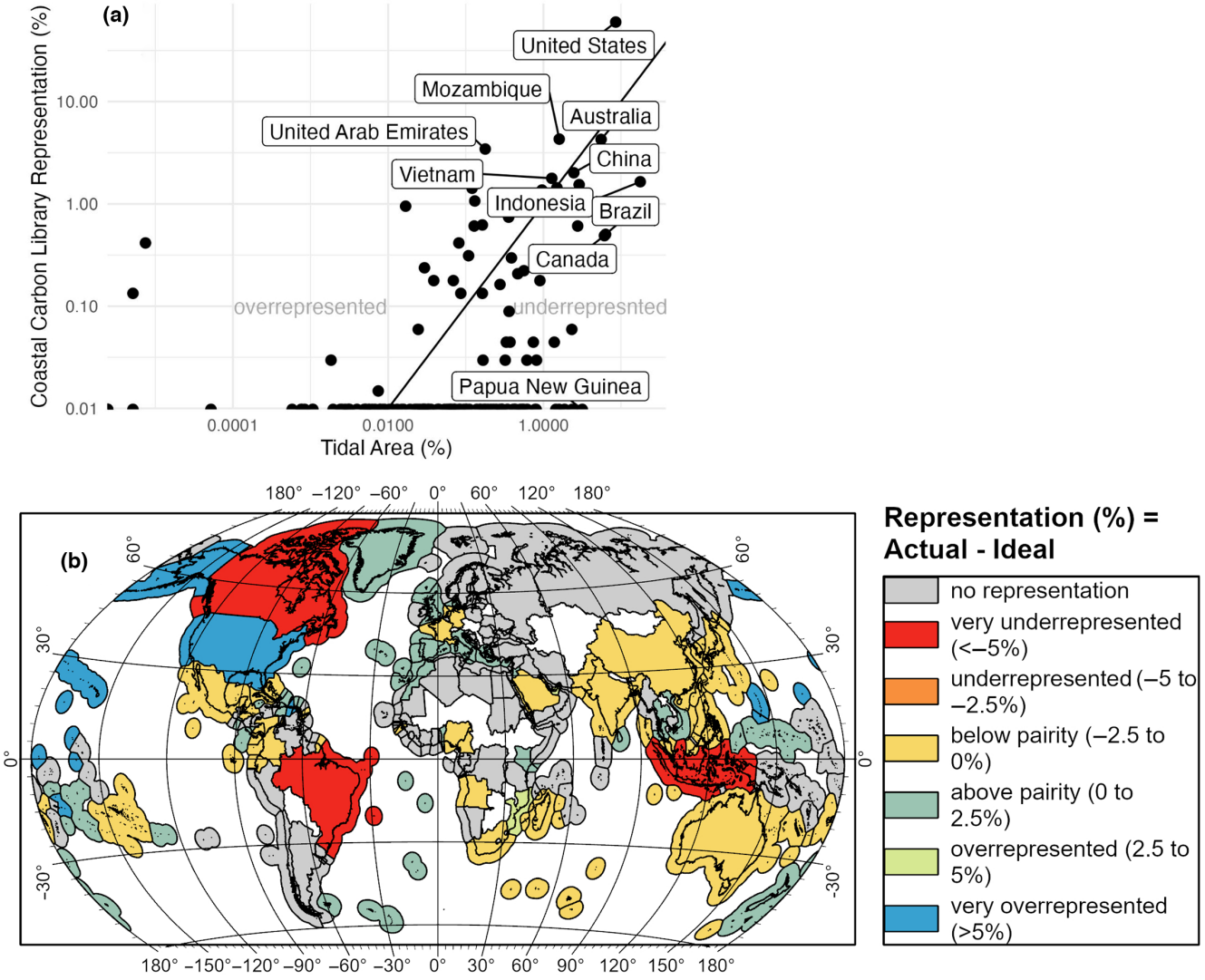

FIGURE 6 (a) Points show country by country, the makeup of the Coastal Carbon Library as percentages, with respect to the global area of tidal ecosystems (Murray et al., 2022). Countries in the top 6 of database representation and/or tidal area are labeled. The black line represents an idealized one-to-one relationship with countries above the line being over-sampled and those below, under-sampled. Note the log-10 scale. Countries with no representation in the Coastal Carbon Library are plotted at the bottom of the *y*-axis. The United States is over-represented, while Indonesia, Brazil, Papua New Guinea, and Canada were underrepresented. (b) Maps show same information as (a), with colors visualizing the degree of over- or under-representativeness. Here we define over- or under-representation as actual minus ideal representation. Ideal representation is based on based on tidal habitat coverage (*x*-axis of a), actual on database representation (*y*-axis of a). Map lines do not necessarily depict accepted national boundaries.

The ability to independently replicate derivative calculations and link measurements to original studies are both important to the validity of greenhouse gas inventories (Crooks et al., 2018) and carbon market verification (Needelman et al., 2018).

When collating data for use by a broad swathe of researchers and managers, the importance of grassroots approaches cannot be understated. The fact that this was a domain-specific effort allowed us to grow the database by leveraging professional networks, generate enthusiasm with a community that understood the immediate utility of the synthesis, and build trust based on relationships. Building trust took an understanding of both academic incentives around sharing data and the personal nature of many datasets. In shifting the burden of curation from data producers to dedicated staff this effort has helped data creators comply with open data standards (Tedersoo et al., 2021), and rescued data that otherwise would have never been made public (Todd-Brown et al., 2022). Our ambition is to continue providing some data curatorial services depending on the availability of funding through new projects.

5.2 | Future improvements

While there are myriad strengths to the current effort, there are also limitations to estimating deep carbon stocks and assessing carbon burial rates outside of marsh ecosystems. Most of the dated or deep

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TABLE 10 Summary statistics of organic matter fraction, dry bulk density (g cm^{-3}), and organic matter density (g cm^{-3}). Summary statistics include mean, median, lower and upper 95% quantile, standard deviation (SD) and data point count (*n*).

Variable	Habitat	Lower 95%	Median	Mean	Upper 95%	SD	*n*
Fraction organic matter	Marsh	0.02	0.15	0.2	0.66	0.17	12,746
	Mangrove	0	0.06	0.18	0.67	0.22	1433
	Swamp	0.03	0.27	0.36	0.91	0.27	594
	Seagrass	0	0.02	0.02	0.12	0.04	2805
Dry bulk density	Marsh	0.09	0.48	0.56	1.47	0.37	12,746
	Mangrove	0.13	0.75	0.75	1.61	0.46	1433
	Swamp	0.06	0.31	0.45	1.4	0.39	594
	Seagrass	0.31	0.99	1.06	1.93	0.45	2805
Organic matter density	Marsh	0.01	0.06	0.07	0.19	0.04	12,746
	Mangrove	0	0.05	0.06	0.13	0.04	1433
	Swamp	0.03	0.08	0.08	0.19	0.04	594
	Seagrass	0	0.02	0.02	0.07	0.02	2805

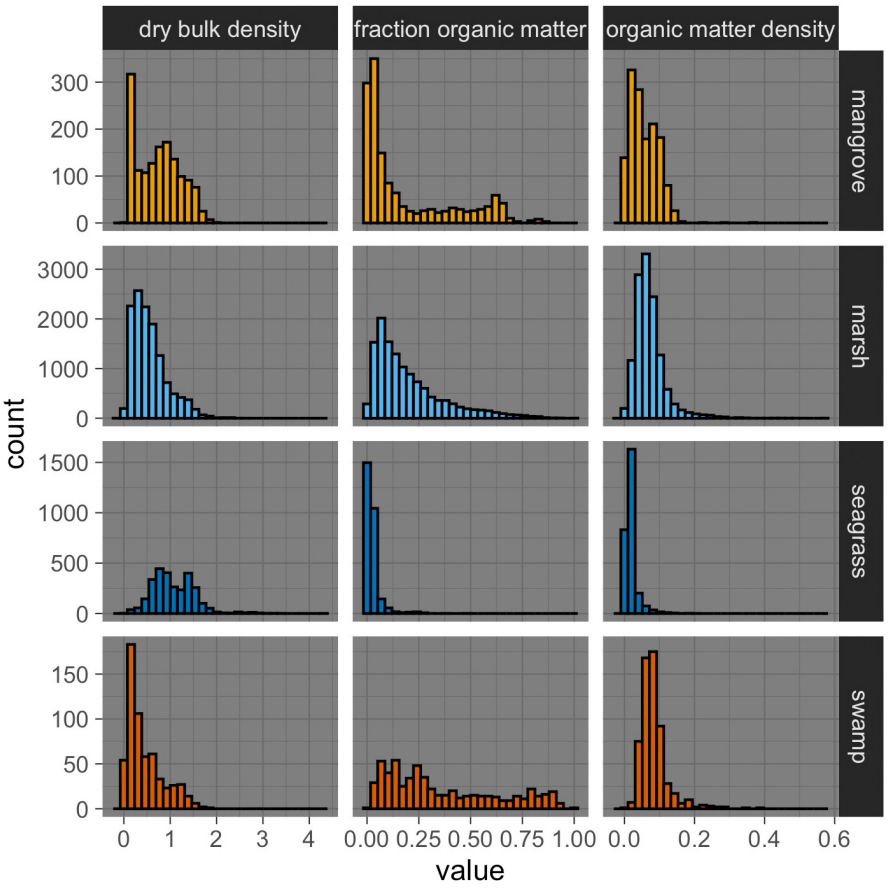

FIGURE 7 Summary of global blue carbon data shown as the frequency distribution of dry bulk density (g cm^{-3}), fraction organic matter, and organic matter density (g cm^{-3}). Note, the *y*-axes are different for each type of ecosystem in the rows.

cores in the Coastal Carbon Library were from tidal marshes. For carbon stocks, we showed that the majority of datasets did not represent full profiles, reaching a contact point between wetland and deeper non-wetland layer, and in most cases, soils datasets were limited by the depth of the coring device. So, while the characterization of shallow carbon stock is the most widely available application of the data, future work could quantify the effect that profile depth has on total carbon stock assessments, how spatially predictable that contact point is from existing data, and how predictable deeper carbon stocks are from shallower ones.

Future efforts could also focus on improving the representativeness of data in the repository. The majority of the data were from the U.S. and future efforts could improve the representation of tropical and developing countries (Wylie et al., 2016). Poor representation in some cases is due to lack of data, and other times due to the fact that data has not yet been integrated. Efforts like this allow

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the community to take stock of what data are already available and focus on new data collection and synthesis where it would be most impactful.

Further, future efforts could include increasing the representation of mangroves, and seagrasses, especially for carbon burial data. Finally, future efforts could analyze whether the Coastal Carbon Library is biased towards pristine wetlands and underrepresents degraded or restored wetlands.

5.3 | Proposed best practices for blue carbon data dissemination and reuse

This data synthesis effort has resulted in proposed guidelines for both individual research groups as well as journal editors, reviewers, and funders. We suggest that best practices for reporting blue carbon soils data should include distributing disaggregated data associated with the summary statistics presented in journal articles and reports. We propose reporting at the level of original measurements, for example, loss-on-ignition and dry bulk density measurements reported for individual depth increments, and individual radioisotope measurements determining supported and unsupported ^{210}Pb activity profiles in addition to derived age-depth models. We propose that positional information, elevation, wetland management history, salinity, and vegetation composition are all vital to data reinterpretation; we provide multiple ways for coding data resolution and methodology (Tables 1 and 2) in order to represent the original studies with fidelity. We propose that data producers should provide separate files for original measurements and derivative calculations, ideally with an open-source scripting workflow documenting how derivations are made. We propose utilizing dataset templates and consistent vocabulary whenever possible, such as those provided as Data S1 (Holmquist et al., 2023). The templates we provide can be modified and added to. We propose metadata accompanying data releases should define attributes, specify units, and detail study methods.

We also propose best practices for data producers include making data freely available in public data repositories with open-source Creative Commons licenses. We encourage journal editors and funders to require data publication as part of publication and end-of-project reporting, and for reviewers to ensure data releases are analysis-ready and well-documented. Funders have a role in supporting both project-specific data curation, as well as community-wide aggregation efforts. This effort shows the value of dedicated staff in helping data producers meet their open data ambitions.

Having a synthetic dataset can allow researchers to develop additional best practices, and disentangle the effect different methodological choices have on carbon burial and accretion estimates (Holmquist et al., 2021). Fusing data with soil formation models (Morris et al., 2002; Schile et al., 2014) could allow for more standardization surrounding concepts such as accretion, burial, accumulation, and sequestration.

The adoption of open data policies has the potential to improve equity for researchers and communities in the global south (Serwadda et al., 2018). Although adopting open data is not free from ethical risks on its own, the protocol we propose does provide a way to avoid 'parachute science', in which data are collected from a middle-income or developing country, but not made available to the communities from which it came. Data and journal publications offer an avenue for credit towards researchers from the global south by recognizing a taxonomy of roles, including for local people who consulted and physically collected the data (Allen et al., 2014; Serwadda et al., 2018).

We finally propose some best practices for those reusing data for new purposes. Although the CC-BY 4.0 open data allows unrestricted use with attribution, we encourage data users to interact with the Coastal Carbon Library and Atlas products not only as a database but also as the community that built it. This could also include reaching out to original data producers when local knowledge is warranted for data interpretation. Data users can offer co-authorship when consultations result in more substantial contributions (Allen et al., 2014), or recommend data providers as reviewers, notify them of open-peer review periods, notify them of preprints, and provide copies of journal articles when a dataset they provided is vital to a new study.

Our hope is that by providing a centralized open database, building the practice of data publication, and implementing a data reuse policy that centers original data producers, we will contribute towards democratizing the development of coastal ecosystem service science.

6 | CONCLUSIONS

We present the Coastal Carbon Library, an open-source database for disaggregated global tidal wetland soil carbon stock, and accumulation rate data. It is made up of 6723 soil profiles, from 64 countries. In addition to the data itself, the vocabulary, structures, and metadata are all discussed in depth. The strength of these data products lies in their commitment to F.A.I.R. data principles and their transparency. The addition of the Coastal Carbon Atlas, which allows for data visualization, subsetting, and limited post-processing, increases the accessibility of the data for non-specialists. Future work is needed especially to increase the amount of deep carbon stock data across wetlands and calculate carbon burial rates consistently. While the database is global, new efforts are needed to increase the representation of countries outside the U.S. To conclude, we think that any scientific synthesis effort can learn important lessons from the grassroots nature of the Coastal Carbon Library. Data producers were incentivized to be involved by providing data templates, shifting the burden of curation from data producers to dedicated staff, and generating trust through a data use policy that rewards data producers through citation of primary material.

AUTHOR CONTRIBUTIONS

James R. Holmquist: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; software; supervision; visualization;

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writing – original draft; writing – review and editing. **David Klinges:** Conceptualization; data curation; methodology; software; visualization; writing – review and editing. **Michael Lonneman:** Data curation; methodology; software; visualization; writing – review and editing. **Jaxine Wolfe:** Conceptualization; data curation; methodology; software; visualization; writing – original draft; writing – review and editing. **Brandon Boyd:** Conceptualization; data curation; methodology; writing – review and editing. **Lauren N. Brown:** Conceptualization; methodology; writing – review and editing. **Meagan Eagle:** Conceptualization; data curation; methodology; writing – review and editing. **Jonathan Sanderman:** Conceptualization; data curation; methodology; writing – review and editing. **Kathe Todd-Brown:** Conceptualization; methodology; software; writing – review and editing. **E. Fay Belshe:** Conceptualization; data curation; writing – review and editing. **Samantha Chapman:** Conceptualization; data curation; writing – review and editing. **Ron Corstanje:** Conceptualization; writing – review and editing. **Christopher Janousek:** Conceptualization; data curation; methodology; writing – review and editing. **James T. Morris:** Conceptualization; writing – review and editing. **Gregory Noe:** Conceptualization; data curation; writing – review and editing. **André Rovai:** Conceptualization; writing – review and editing. **Amanda Spivak:** Conceptualization; writing – review and editing. **Megan Vahsen:** Conceptualization; writing – review and editing. **Lisamarie Windham-Myers:** Conceptualization; funding acquisition; supervision; writing – review and editing. **Kevin Kroeger:** Conceptualization; methodology; supervision; writing – review and editing. **J. Patrick Megonigal:** Conceptualization; funding acquisition; methodology; project administration; supervision; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors claim no conflicts of interest.

DATA AVAILABILITY STATEMENT

A more detailed version of the Coastal Carbon Library's data structures, as well as data entry templates, are openly available on Smithsonian Libraries Figshare at https://doi.org/10.25573/serc.23580474.v1, reference number (Holmquist et al. 2023). The Coastal Carbon Library version used in this analysis is also openly available on Smithsonian Libraries' Figshare at https://doi.org/10.25573/serc.21565671.v1, reference number (Coastal Carbon Network, 2023) 2023). Ingestion scripts and workflow for generating the Coastal Carbon Library are publicly available on GitHub (https://github.com/Smithsonian/CCN-Data-Library). Code used for analyses and figure generation is also available on GitHub (https://github.com/Smithsonian/CCN_database_paper).

ORCID

James R. Holmquist https://orcid.org/0000-0003-2546-6766
Kathe Todd-Brown https://orcid.org/0000-0002-3109-8130
André Rovai https://orcid.org/0000-0003-4117-2055
Amanda Spivak https://orcid.org/0000-0001-6743-0783
J. Patrick Megonigal https://orcid.org/0000-0002-2018-7883

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