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The spatial distribution and paleoecology of Caribbean peatlands

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Tropical peatlands are being lost at a rate three times greater than forests, with large and rapid impacts on carbon and water cycling, biodiversity, and human health. Despite threats from land conversion and climate change, peatlands across the tropical biome remain poorly mapped, making it difficult to develop sustainable management solutions. Superimposed on this dearth of spatial data is poor knowledge of peatlands' net carbon balance. In this Review, we synthesize information on the paleoecology, carbon dynamics, and distribution of the peatlands of the Caribbean. Though data limitations are substantial, this work contributes to further confirm peatland occurrence and further our understanding of their functioning.

The number of studies on tropical peatlands has increased over the past decade because of a growing awareness of these ecosystems' existence and importance. The first synthesis on tropical peatland distribution suggested an extent of 441,000 km²¹, but more recent estimates that have been based on predictive mapping algorithms have roughly doubled (~ 600,000 to 1.07 M km²)²⁻⁵ the original extent. While many uncertainties have been associated with those recent maps, namely due to poor ground-referencing and differences in peatland definitions across countries, they highlight the potential for the uncovering of 'undescribed' peatland areas across the tropical biome. For example, work from the Congo basin⁶ has confirmed broad expanses of peat that were not accounted for previously¹. Such findings then allow for the development of improved predictive mapping algorithms⁷.

Better knowledge of the distribution of tropical peatlands is critically needed to help inform land management. Peatland degradation has been rampant over the past couple of decades across the tropical biome, with these ecosystems now being lost at a rate three times greater than forests⁵. Peatland conversion has sizable consequences on global carbon cycling due to massive and rapid losses of 'irrecoverable carbon' to the atmosphere⁸⁻¹⁰, but also on local water cycling, biodiversity, human health, and local livelihoods¹¹. Superimposed on this poor knowledge of peatland distribution is a lack of predictive understanding of the key mechanisms that control the carbon and water cycles in tropical peatlands. For instance, while it is generally known that tropical peatlands store large amounts of belowground carbon, we don't really know where this carbon is located, how much carbon is stored, how old and recalcitrant this carbon is, and the relative importance of carbon quality vs. quantity in controlling short- and long-term rates of carbon sequestration. These knowledge gaps hinder our ability to assess ecosystem sensitivity to environmental and land-use changes.

It is expected that increasing global temperatures will lead to greater amounts of methane (CH₄) emitted to the atmosphere from tropical

peatlands (and wetlands more broadly)¹². It is also expected that indirect peatland drying, which is caused by increased rainfall seasonality and/or lower annual rainfall, could result in a 20% loss of current carbon stocks from disturbed and intact tropical peat swamps by 2100 due to enhanced peat decay⁸. Knowledge of peatland resilience would help confirm or contrast these model predictions; paleoecological work could provide information on successional pathways, threshold dynamics, and past conditions that were conducive of peatland formation.

Furthering our knowledge of tropical peatlands would also benefit conservation efforts. Peatlands are being integrated into national greenhouse gas (GHG) inventories. Their wise management at the national level can also contribute to Nationally Determined Contributions (NDCs), which aim at improving terrestrial carbon sequestration and/or decreasing GHG emissions⁵. Peatlands have also become increasingly important in the context of the carbon market. This market may become especially beneficial for peat-rich tropical countries, as the funds obtained from these credits could be used to restore and further preserve existing (yet often undescribed) peatlands.

The peatlands of Latin America and the Caribbean are particularly understudied. It is important to note that many of the countries included in this region have yet to develop national peatland definitions. Oftentimes, there are no national peatland inventories, leading to a lack of information on the location, extent, and condition of peatlands⁵. We also lack the peat-soil data needed to quantify the region's peatland carbon pool. As for peatland carbon budgets, there has only been a handful of studies that have measured GHG emissions (CH₄, carbon dioxide (CO₂) and nitrous oxide (N₂O)). In terms of the regional history of peatland development, only a few paleoecological studies document peatland inception age or describe ecological succession.

This Review analyzes scientific articles that pertain to paleoecology, carbon dynamics, and mapping of tropical peatlands in the Caribbean. Our

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goals are to (1) identify patterns (if any) in the location and initiation of peat accumulation in the Caribbean tropics, (2) gain a better understanding of the paleoecological history of peatlands (and their ecological succession) across this region, (3) compile information regarding ecosystem-level carbon budgets, and (4) compare and contrast the current estimates for the peatland extent across the Caribbean. Through the harmonization and synthesis of the published research on Caribbean peatlands, we identify knowledge gaps and propose new research directions to help understand these complex ecosystems. Lastly, dissemination of the data collected in this review may help inform land management by providing spatially explicit peatland information and useful definitions.

Study region

The definition of the ‘Caribbean region’ varies between authors^{13,14}. We opted to include all countries that were included in these definitions. Our area of interest therefore ranges between 7–23°N and 60–91°W, includes 42 countries and territories, and spans ~240,000 km² (Fig. S1; refer to Fig. 1 for a complete list of countries). Note that in the cases of Mexico, Colombia, and Venezuela, only parts of these countries were included in our defined study area (Fig. S1).

Materials and methods

Data sources and search strategy

A scoping review was performed to gather information about Caribbean wetland and peatland paleoecology, carbon dynamics, and mapping products. We used an existing framework¹⁵ to complete this scoping review (Fig. 1). Searches were performed using Science Direct, Web of Science, and Google Scholar with search terms that included the name of the countries listed in Fig. 1, followed by “AND (mangrove* OR swamp* OR peat*) AND (pal* OR map* OR carbon OR methane).” Those clusters of terms were selected for the following reasons:

- (1) Mangrove*, swamp*, peat*: we strategically chose to cast a broad net around studies on common wetland types rather than limiting our search to peatlands only, since we know that the term ‘peatlands’ is seldom used to describe peat-accumulating deposits across our study region.
- (2) Pal*, map*, carbon, methane: we endeavored to include all wetland papers that might discuss paleoecology, mapping, as well as carbon dynamics across the Caribbean region. We added ‘methane’ to the list, again in an effort to include as many publications as possible.

Published studies that laid outside of our defined study region (Fig. S1) were excluded. Publications with multiple study sites were included in this

analysis, if at least one of the study sites was located within our study region. Only the first 200 results from Google Scholar were considered. Duplicate screening was performed in Zotero¹⁶; said duplicates were removed from the working list of publications. While we recognize that there may be some information published in local journals and reports (likely in Spanish), the latter were left out of the scope of this analysis, which focused on English, peer-reviewed publications. A total of 1588 publications, with data coming from 21 out of the 42 countries found within our study region, were collected across all platforms as of October 2023 (Fig. 1).

All 1588 papers were input to Rayyan¹⁷ where a manual inclusion/exclusion analysis was performed using the title, abstract, and keyword subfields from each article¹⁵ to determine pertinence to paleoecology, carbon sequestration/fluxes, or mapping of Caribbean wetlands. Publications that did not fit these criteria were excluded. This screening resulted in 165 publications that directly addressed the themes of the research focus (Fig. 1; refer to Supplementary Data 1 for complete lists of publications). Out of those 165 publications, only 35 directly used the words ‘peat(s)’ or ‘peatland(s)’. With that said, we were able to identify 4 additional papers that presented peat data but that did not use the word ‘peat’. For the sake of this Review, thresholds of 30% organic matter content and 30 cm in thickness were used to identify peat¹⁸.

Peat-core information

Peat inception ages and paleoecological reconstructions were compiled from the published papers. To ensure fair comparison across our study sites, uncalibrated radiocarbon (¹⁴C) dates were re-calibrated by us, using the program CALIB 8.2¹⁹, with the IntCal20 calibration dataset²⁰. Once calibrated, the ages were reported in calibrated years before present (cal. yr BP). Each age estimate reported therein corresponds to the median of each calibrated 2 sigma-range probability distribution (see Supplementary Data 2 for the complete dataset). Peat basal dates were then compiled using a 2-sigma-range probability density function (in 10 yr bins), as described elsewhere^{21,22}, to establish the regional peat initiation frequency. We note that the stratigraphic information provided in the papers was used to confirm that the dated material corresponded to the ‘basal’ peat. In a few cases, however, the authors did not reach the base of the peat deposit, so the reported deepest age can only be interpreted as a minimal age rather than a basal one; those cores were marked with an asterisk in Supplementary Data 2. Lastly, long-term apparent rate of carbon accumulation (LORCA) was determined by dividing the peat depth (in cm) by the calibrated basal age (in cal. yr BP), and multiplying the result by DBD and carbon content. Given the broad range of peatland deposits, we used two combinations of

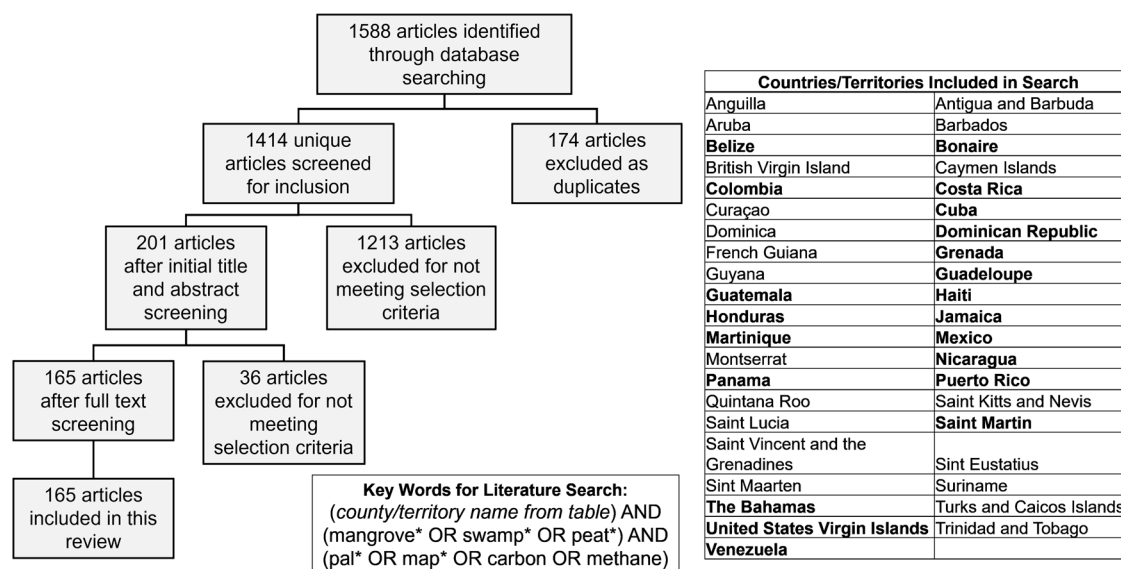


Fig. 1 | Flowchart of the literature selection process. Countries/territories with published articles included in this review are shown in bold in the table.

geochemical data: (1) a low DBD (0.1 g/cm^3) combined with a high carbon content (50%) to represent organic-rich sites (e.g., bogs), and (2) a high DBD (0.4 g/cm^3) combined with a low carbon content (10%) to represent less organic-rich sites (e.g., mangroves). The final LORCA values were then multiplied by 10,000 to convert from $\text{gC cm}^{-2} \text{ y}^{-1}$ to $\text{gC m}^{-2} \text{ y}^{-1}$.

The peat cores used for paleoecological reconstructions were required to contain peat-forming vegetation (or stratigraphic) information. Changes in the dominant vegetation type or environmental class along the peat profiles were used to classify peat types. If available, the dominant plant macrofossil component was used, though in almost all cases, such dataset was not available and lithological descriptions were used as a resource. The categories for vegetation/lithology were ‘palm swamp’, ‘forest swamp’, ‘herbaceous swamp’, ‘mangrove’, ‘marsh’, ‘bog’, ‘terrestrial’, and ‘aquatic’.

Results

Trends in publications on Caribbean wetlands and peatlands

Of the 165 articles on *wetlands*, 97 focused on paleoecology, 34 were centered on carbon dynamics, and 15 pertained to mapping wetlands (Fig. 2a). The remaining publications consisted of 8 reviews and 11 ‘other’ papers. Together, these 165 studies described 193 sites from 21 countries (Supplementary Data 1). Splitting the articles by ecosystem type revealed that most studies come from mangroves ($n = 70$), followed by lakes ($n = 63$), and swamps ($n = 15$). When only accounting for papers on *peatlands* (Fig. 2b), we report 25 studies on paleoecology, 13 studies on carbon dynamics, and 5 studies on mapping.

The *wetlands* articles gathered for this review were published between 1977 and 2023. The number of publications per year for this region has increased over this time span, from around 2 per year in the late 1990s up to 8 per year in the 2020s (Fig. 2c). Plotting those results by ‘focus categories’ (i.e., paleo, carbon, mapping) shows that publications related to carbon have been on the rise over the past decade (since 2012), while the other categories’ publication rates have remained unchanged (Fig. 2c). The paleo studies are the most prevalent, with publications every year since 1998. Lastly, publications of wetland maps have been infrequent, but there has been an uptick in the last decade (Fig. 2c). As for the articles on *peatlands*, the first study was

published in 1992, followed by 0 or 1 article per year through 2007 (Fig. 2d). Publications peaked in 2011 and 2019 ($n = 4$ each of those years). Paleoecology studies accounted for the majority of these articles, and they were also the most consistent over time. An increased frequency of peatland carbon publications was observed over the past decade (Fig. 2d). The first peatland mapping article covering this region was published in 2011, with other studies published in 2017, 2018, and 2022.

For the *wetlands* studies, interrogating the data by country of origin (Fig. 3a) showed that the country of Mexico has the greatest number of studies ($n = 32$), followed by Costa Rica ($n = 28$). The islands of the Caribbean had the least number of published studies, with most of those countries having less than five publications each. Paleoecological studies were available from across most of the study region, and the same was true for articles on wetland carbon dynamics. In contrast, regional mapping publications were only found for 6 of the 21 countries for which we have data. As for the *peatlands* studies, the greatest number of publications came from Belize ($n = 9$) and were mainly focused on paleoecology, followed by peatland publications from Costa Rica ($n = 7$), which were dominated by carbon dynamics studies (Fig. 3b).

We also analyzed the geographical distribution of first author affiliations for all the publications²³ (Table 1). For the *wetlands* studies, affiliations of first authors were associated with 22 countries. Of those 22 countries, 8 were from the Caribbean region (e.g., Mexico), while the other 14 came from countries located in other parts of the world (e.g., United States). In total, 34 studies were published by in-country scientists vs. 121 studies that were authored by foreign scientists (Table 1a). Notably, in the case of Mexico and Colombia, the number of studies from in-country scientists was close to, or surpassed, those from foreigners (Colombia: $n = 7$ out of 15; Mexico: $n = 16$ out of 31). In all other cases, the number of studies published by foreigners surpassed the number of studies published by nationals. In total, 71 of the 164 papers were authored by scientists located in the United States. Of the 10 global and regional studies, no authors were affiliated with countries from the Caribbean region. The largest number of authors were affiliated with the United States ($n = 4$), and the remaining authors had affiliations in Europe and Asia. As for the *peatlands* sites, first authors were affiliated with 12

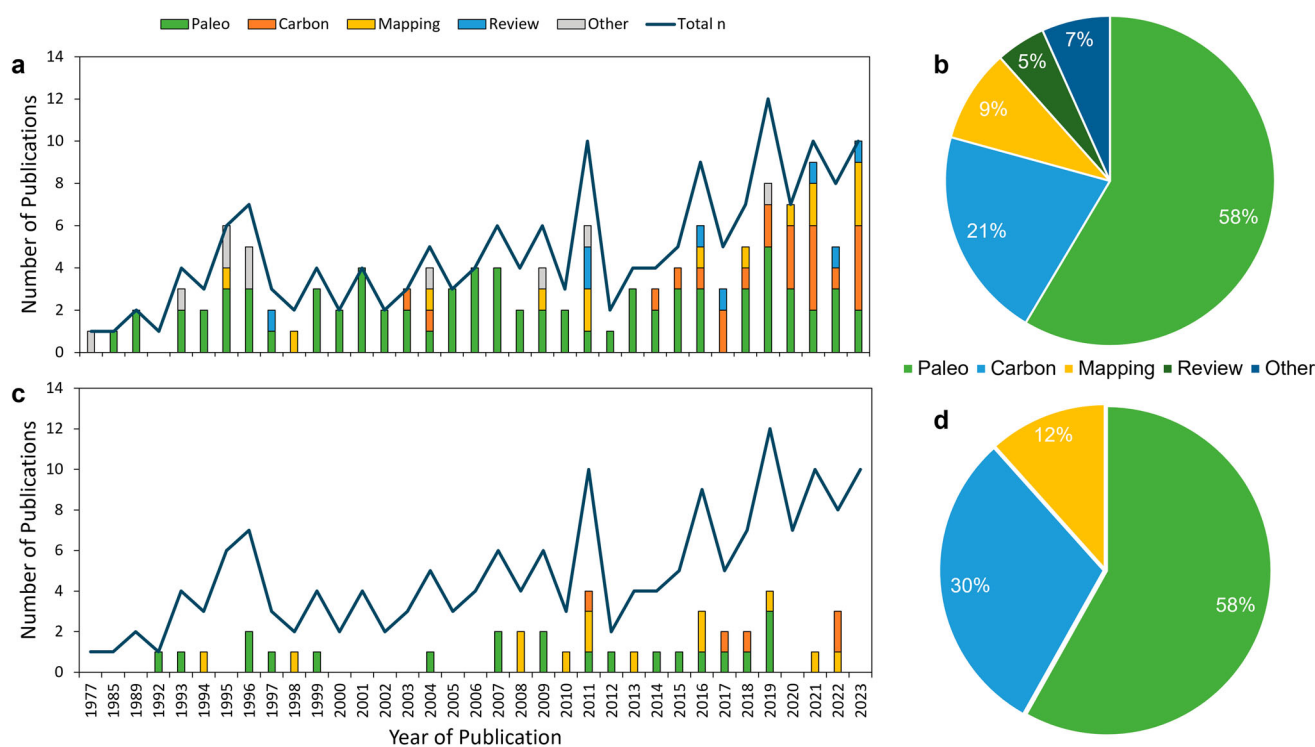
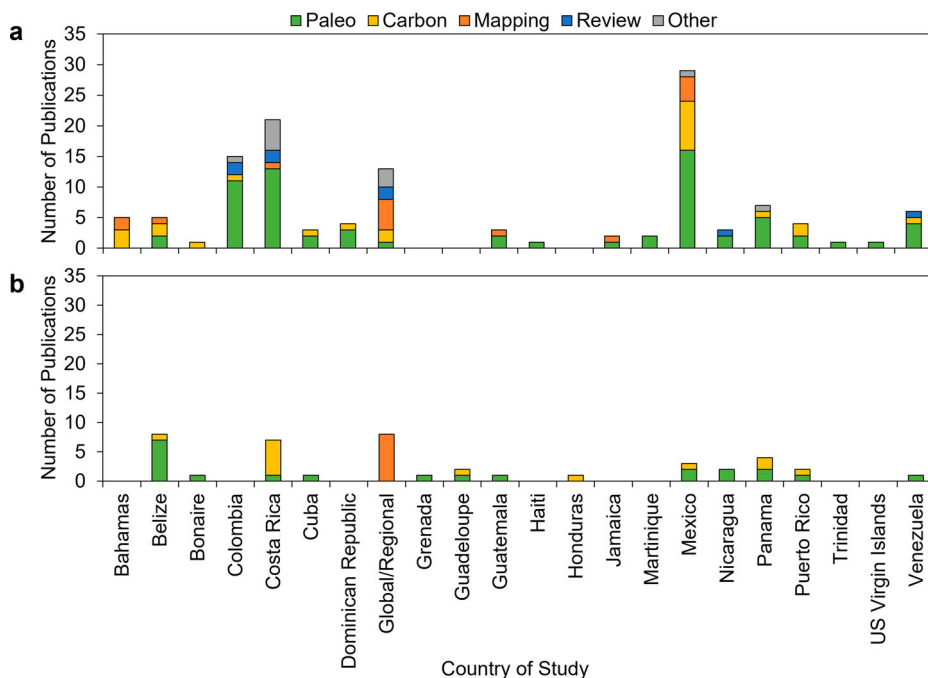


Fig. 2 | Temporal trends in the number of publications for each category. a Wetlands vs. b peatlands, and the proportion of publications that were included in each focus category. c Wetlands vs. d peatlands. The ‘Total n’ line in a and c shows the total number of publications across both wetland types.

Fig. 3 | The number of publications per country. The stacked colored bars show the different focus categories. **a** Wetlands vs. **b** peatlands. Note that some papers may appear twice on this chart if they include study sites from more than one country.



countries (Table 1b). Of those 12 countries, 3 are part of the Caribbean region, and 9 are located in other parts of the world. Colombia, Mexico, and Puerto Rico have publications from in-country scientists ($n = 2$, $n = 3$, $n = 1$, respectively). Most publications were from scientists affiliated with the United States ($n = 21$).

Paleoecological studies from Caribbean peatlands

The *wetlands* scoping review returned 97 articles (138 coring sites) that were related to the region's paleoecology. Those paleoecological reconstructions primarily came from lake sediments ($n = 63$) and mangrove soils ($n = 35$); the other sediment archives were palm swamps ($n = 4$), forest swamps ($n = 3$), sawgrass swamp ($n = 1$), lagoon sediments ($n = 12$), bogs ($n = 4$), marsh sediments ($n = 5$), and unspecified wetland sites ($n = 9$). As for the *peatlands* studies, we found 25 of them (with 32 coring sites; Fig. 4). The sections below synthesize the main findings from those 25 paleoecological studies that came from peat-accumulating systems, which consist of the following modern-day ecosystems: 15 mangroves, 4 palm swamps, 3 marshes, 1 forest swamp, 1 sawgrass swamp, 4 bogs, and 4 aquatic environments (lagoons and beaches with peat sections). Of the 35 mangrove soils that were documented in the literature, only 15 were included in our 'peat-based' reconstructions because these studies either directly referenced 'peat' in relation to the core taken, or they provided core descriptions that fit the definition of peat¹⁸.

Peat inception ages, thickness, accumulation rates, and geochemical properties

A total of 31 peat basal dates were gathered from the literature and used to infer peatland inception timing across the region. Basal ages ranged between ~9000 and ~3000 cal. yr BP and there was no discernable pattern in their spatial or temporal distribution (Fig. 4a, b). The majority of the peat deposits were underlain by clay, though fine sands, marl, and carbonate layers were also noted under the peats at a few coastal sites. The controlling factor(s) for tropical peat initiation has seldom been studied across the Caribbean; the publications generally suggest that sea-level stabilization (around 6,000 cal. yr BP) could have led to conditions allowing for peat accumulation along the coast, which would explain why almost all our sites are younger than 6000 years^{24,25}. At the local scale, Mayan forest clearance and agricultural practices during the late Holocene could have modified the landscape in a way conducive for peat initiation^{26–29}. Overall, given the relatively small number

of data available, it is best to interpret our peat initiation dataset with caution.

Peat thickness varied substantially across the 31 sites, from 70 to 850 cm, with a median thickness of 360 cm. There is a strong correlation between basal age and total depth, with the oldest sites harboring the thickest peats (Pearson $R^2 = 0.65$; Fig. S2). We note that peat accumulation was not always continuous along the profiles. For example, several coastal site reconstructions harbor interspersed sand layers deposited by storms^{30,31}; temporary increases in sediment load from local rivers is also a process known to have deposited mineral layers onto some peatlands throughout their evolution^{13,32,33}. However, we were unable to systematically filter out all the non-peat layers from the stratigraphies. The 'peat depth' dataset may thus also include some mineral layers.

Peat geochemical data were seldom available from the published cores. We retrieved a total of 6 loss-on-ignition (LOI) records, 5 total organic carbon (TOC) records, and 3 dry bulk density records (DBD). The time series were unavailable for download; visual inspection of the published graphed data indicates high organic matter content (LOI data) for all peat sections, typically between 50 and 85%^{34–36}. Likewise, high TOC values were reported, and they varied from ~25 to 50%^{14,33}. As for DBD, it ranged from ~0.1 to 0.2 g cm⁻³³². Altogether, these results are in line with regional and global peat geochemical datasets^{1,37,38}.

The long-term apparent rate of carbon accumulation (LORCA) was also computed for each core for which a basal age and a basal depth were provided ($n = 27$ sites). We found vastly varying rates across the sites. Using the organic-rich parameters (DBD = 0.1 g cm⁻³, C = 50%), LORCAs varied from 12 to 130 gC m⁻² y⁻¹, with a mean of 51 gC m⁻² y⁻¹ (Fig. S3). When using the low-organic parameters (DBD = 0.4 g cm⁻³, C = 10%), LORCAs were found between 9 and 104 gC m⁻² y⁻¹, with a mean of 41 gC m⁻² y⁻¹. The aforementioned figures exclude 2 extreme LORCAs of 294 and 591 gC cm⁻² y⁻¹ (using the high-organic values) that were reported for very thick but young peat deposits^{14,39}. Interestingly, there is a positive relationship between peat depth and LORCA (Pearson $R^2 = 0.42$), with deeper peats associated with greater LORCAs (Fig. S3). Also noteworthy is that bogs were characterized by much higher LORCAs (mean = 98 gC m⁻² y⁻¹, $n = 4$) than mangroves (mean = 48 gC m⁻² y⁻¹, $n = 16$), marshes and coastal wetlands (mean = 44 gC m⁻² y⁻¹, $n = 5$), and swamps (mean = 20 gC m⁻² y⁻¹, $n = 4$) (Fig. S3). The aforementioned values were all calculated using the high-organic parameters because we lacked specific information at the site level

Table 1 | Number of publications across the Caribbean countries (rows) contrasted with the origin of the first author's country of affiliation (columns)

Country of Study Focus	Country of first author affiliation																							
	Colombia	Costa Rica	Jamaica	Mexico	Panama	Puerto Rico	Trinidad	Venezuela	Australia	Belgium	Brazil	Canada	Denmark	France	Germany	Netherlands	Peru	Qatar	Singapore	Spain	UK	USA		
Bahamas	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	1/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	2/0	
Belize	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/1	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	4/8	
Bonaire	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	1/1	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0	
Colombia	5/2	0/0	0/0	0/0	1/0	0/0	0/0	0/0	0/0	0/0	0/0	1/1	0/0	0/0	0/0	3/0	0/0	0/0	0/0	0/0	0/0	0/0	2/0	
Costa Rica	0/0	4/0	0/0	0/0	0/0	1/0	0/0	0/0	0/0	0/0	1/0	1/0	0/0	0/0	0/0	4/2	0/0	0/0	0/0	0/0	0/0	0/0	19/6	
Cuba	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/1	0/0	0/0	0/0	0/0	0/0	1/0	0/0	0/0	0/0	0/0	0/0	
Dominican Republic	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	2/0	0/0	0/0	0/0	0/0	0/0	0/0	2/0	
Grenada	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/1	
Guadeloupe	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/1	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/1	
Guatemala	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	3/1	
Haiti	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	1/0	0/0	0/0	0/0	0/0	0/0	
Honduras	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/1	
Jamaica	0/0	0/0	1/0	0/0	0/0	0/0	1/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	
Martinique	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	1/0	0/0	0/0	0/0	0/0	0/0	0/0	1/0	
Mexico	0/0	0/0	0/0	13/3	0/0	1/0	0/0	0/0	1/0	0/0	0/0	2/0	0/0	0/0	0/0	1/0	1/0	0/0	0/0	0/0	0/0	0/0	1/1	7/0
Nicaragua	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	1/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	5/2	
Panama	1/0	0/0	0/0	1/0	1/0	0/0	0/0	0/0	0/0	0/0	0/0	1/1	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	1/2	3/0
Puerto Rico	0/0	0/0	0/0	0/0	0/0	1/1	0/0	0/0	0/0	0/0	1/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	3/0	
Trinidad	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	
US Virgin Islands	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	1/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	
Venezuela	0/0	0/0	0/0	0/0	0/0	0/0	0/0	3/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	1/0	0/0	0/0	0/0	0/0	0/0	0/0	2/0	

Shown here as wetlands / peatlands. Publications discussing more than one country appear more than once in this count. Global studies are not included in this matrix.

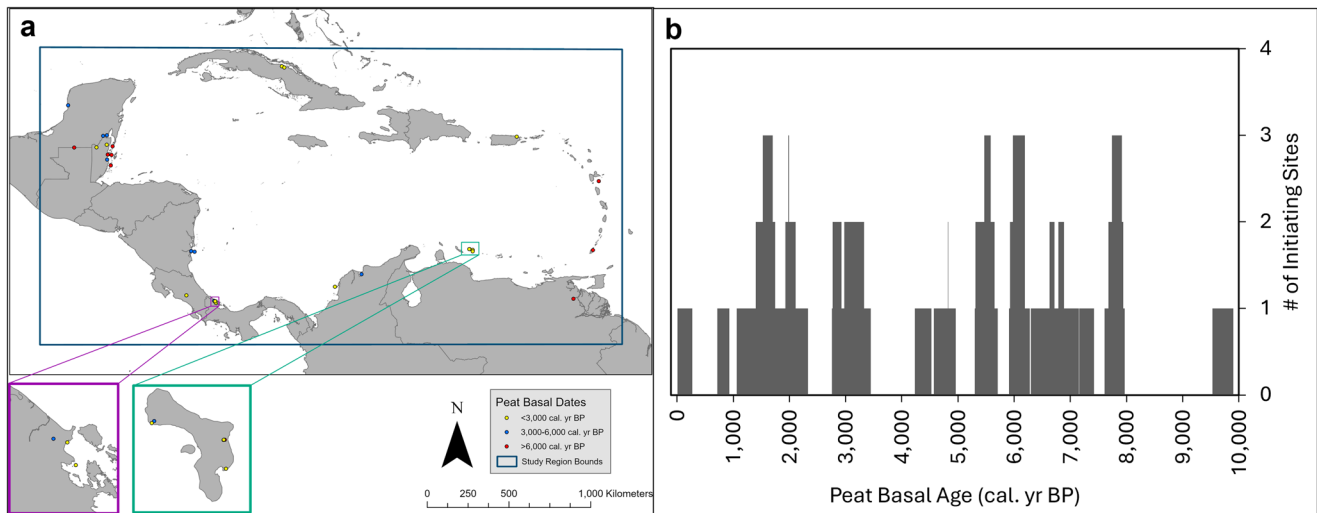


Fig. 4 | Caribbean peatland paleoecology data synthesis. a Peat basal age distribution. b Peat initiation frequency.

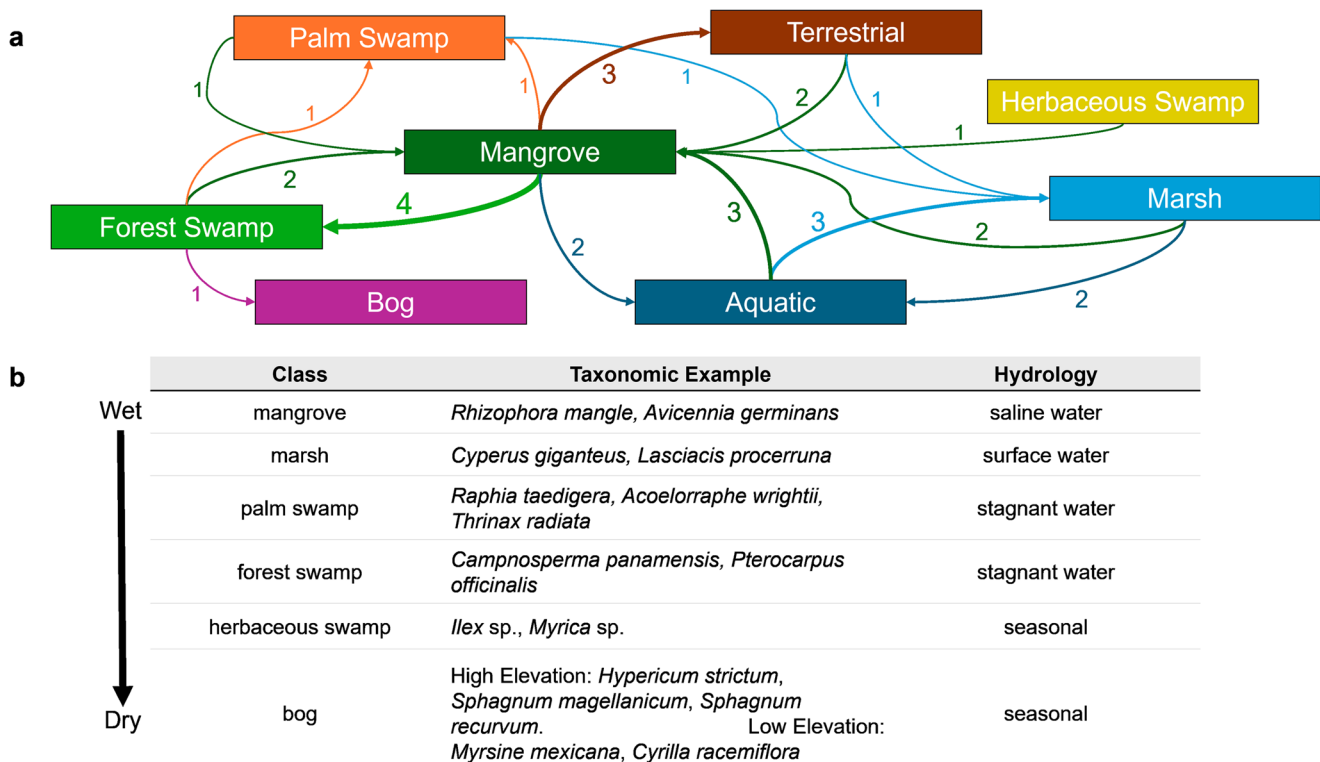


Fig. 5 | Ecosystem succession pathways in Caribbean peatlands. a The frequency of transitions among environmental classes based on peat stratigraphy. The thickness of the arrows is proportional to the frequency of transitions between environmental classes. Note that the number of transitions among environmental classes is greater than the number of cores, as each core might have undergone multiple transitions. b Caribbean wetland classes, taxonomic examples, and hydrology arranged from wettest to driest.

and were unable to make assumptions about soil density and carbon content on the basis of peat type. No clear spatial distribution of LORCA was found (Fig. S3).

Ecological succession in peatland environments

The peatland stratigraphic information showed that a majority of cores experienced transitions among the different environmental classes (Fig. 5). The reconstructed paleoecological successions were typically from wetter to drier environments, with ‘aquatic’, ‘marsh’, and ‘mangrove’ environments majoritarily found at the base of the cores. Most sites then transitioned from aquatic to mangrove or marsh, from marsh to mangrove, and/or from

mangrove to swamp palm or swamp forest (Fig. 5a). The most complete ecological succession was found for the Changuinola site in Panama⁴⁰, which evolved from a palm swamp into a mangrove, followed by a forest swamp and a bog plain. In general, swamp deposits were almost always found atop mangrove deposits, though the opposite (mangrove atop swamp) was also described in the literature. A few sites also transitioned from drier to wetter classes; in many cases, those transitions were linked to local changes in hydrology, including flooding due to local land subsidence that was caused by earthquakes^{39,40} or large storms (hurricanes)^{36,41}. In terms of the geographic locations of these sites, most were coastal and have now transitioned to mangroves, with the exception of one coastal palm swamp⁴²,

and two marshes^{36,43}. Of the inland sites, two are reported to be palm swamps^{44,45}, and one is reported to have transitioned to a marsh within the last 200 years⁴⁶.

Peat-based proxies for paleoecological reconstructions

A total of 29 peat-based paleoenvironmental records were identified. The proxies that were used include pollen and spores ($n = 21$ sites), non-pollen palynomorphs ($n = 2$ sites), charcoal ($n = 1$ sites), stable isotopes ($n = 2$ sites), and organic geochemistry ($n = 5$ sites). These proxies were often used in conjunction with each other as they elucidate different aspects of the paleoenvironment. Across the Caribbean sites, fossil pollen was used to determine regional vegetation cover and related environmental conditions. Non-pollen palynomorphs described in the publications included phytoliths, microalgae and microscopic invertebrates⁴⁷; those were primarily used to reflect changes in vegetation¹³, water salinity⁴⁸, or changes in water level⁴⁹. Charcoal analysis was performed at a site near Akab Muclil to reconstruct the duration of the Mayan occupation in Belize; the authors were able to link higher amounts of charcoal within the core with managed burning for agriculture⁴⁹. Stable isotopes of C, N, O, and Sr were measured along 5 peat cores and used to infer changes in salinity⁵⁰, sources of sediment organic material⁴⁸, local history of maize agriculture⁴⁹, and vegetation stand structure^{51,52}. A few peat cores were also subjected to magnetic susceptibility measurements⁴⁶. Altogether, we note that the vast majority of peat-based paleo studies in the Caribbean have been based on pollen analysis with the objective of reconstructing regional vegetation changes.

Carbon dynamics in the Caribbean wetlands and peatlands

A total of 21 papers (30 study sites) presenting data on carbon dynamics of Caribbean wetlands were found. Of these, 8 discuss carbon stocks, 7 address CH₄ and/or CO₂ fluxes, 4 broadly cover the topic of carbon sequestration, and 6 are various literature reviews of these topics. Mexico has the highest number of papers discussing carbon dynamics ($n = 6$), followed by Costa Rica ($n = 5$). The majority of carbon-related measurements were performed in mangrove ecosystems ($n = 25$ sites), with a small number coming from palm swamps ($n = 9$ sites), swamp forests ($n = 6$ sites), marshes ($n = 3$ sites), and high-elevation wetlands ($n = 6$ sites). Of these, 13 papers (19 study sites) focused on peatland carbon dynamics. Those sites included mangroves ($n = 6$ sites), palm swamps ($n = 4$ sites), forest swamps ($n = 4$ sites), and bogs ($n = 5$ sites); the measurements include carbon stocks ($n = 3$), CH₄ and/or CO₂ fluxes ($n = 3$), carbon sequestration ($n = 2$), organic carbon content ($n = 1$), and dissolved organic carbon in high-elevation peat bogs ($n = 1$).

Among the peatland sites, only one study reported CO₂ fluxes. This record was for a degraded/cleared mangrove ecosystem. Using a soil respiration chamber to make measurements in 02/2004 and 01/2007, the authors estimated annual emissions of 2900 tonnes CO₂ km⁻² y⁻¹⁵³. The authors also found that the highest levels of CO₂ emissions occurred directly after disturbance and decreased significantly two days after the disturbance⁵³. Peatland CH₄ fluxes were measured at 2 sites and were found to range from 67.1⁵⁴ to 120 mg CH₄ m⁻² d⁻¹⁵⁵. The lower value was associated with an undisturbed *Rhizophora mangle* mangrove in Puerto Rico⁵⁴; lower values were reported under high-tide conditions, and vice versa. The higher flux measurement came from a tropical humid Costa Rican palm swamp (La Reserva Wetland) with measurements from summer 2006, winter 2007, and spring 2007 using non-steady-state gas chambers⁵⁵. No significant differences were found in measurements taken for this site in intermittently flooded vs. seasonally flooded conditions or across those different months⁵⁵. Lastly, we found only 3 publications that reported carbon sequestration rates; they came from the same site in the La Reserva Wetland. Reported values suggest carbon accumulation rates between 255 and 465 gC m⁻² y⁻¹^{56,57}.

Peatland mapping in the Caribbean

The scoping review returned 15 articles that related to Caribbean peatland and wetland mapping. Of these publications, 8 provided mangrove maps, 4 provided global peatland maps, 4 provided regional peatland maps, 1

provided an estimated global peatland extent with no map, and 3 provided general global wetland maps (Fig. 6a). Overall, 11 of these estimates were of global extent, 1 covered the Caribbean region, and the other 6 covered mangrove areas in Mexico ($n = 3$), Belize ($n = 1$), Costa Rica ($n = 3$), and Jamaica ($n = 1$). The spatial resolution (i.e., grid cell size) of these studies ranged from 1.84 m to 111 km; spatial resolution decreased as the study region extent increased, with maps on a local scale presenting the highest resolution data, and vice versa. The majority of those published maps were based on the presence/absence of vegetation communities known to be associated with wetlands ($n = 5$), followed by maps based on climatic, hydrological, topographic, and/or soil data from regional datasets of peatlands, histosols, and/or flooding zones (if these are available) ($n = 4$). Some local maps focused on confirmed and ground-referenced mangrove areas, while others used probabilistic mapping to generate areas of high vs. low probability of peatland/wetland presence. The following sections describe the key methodologies and findings. It is noteworthy that regional and national peatland extent maps in the Caribbean are scarce.

Mapping methodologies, main caveats, and common sources of error

Regional mangrove extent maps were largely based on vegetation types obtained from satellite imagery⁵⁸, sometimes in combination with random forest classifications^{59,60}. Another application of satellite-based data included the use of an NDVI-based classification to evaluate the health of a mangrove community in Mexico⁶¹. Spectral complexity metrics were also used in mangrove mapping, including Mean Information Gain and Marginal Entropy in Costa Rica⁶². Lastly, climate, vegetation, soil, and topography data were utilized to generate a species distribution model for predicting the geographic extent of mangroves in Mexico⁶³. The only regional peatland extent map of the Caribbean⁶⁴ used a combination of national-, regional-, and global-scale raster and vector data, as well as decades-old digitized printed maps. These datasets were considered to be indicative of peat presence and included information on histosols, vegetation, wetlands, and flooded vegetation⁶⁴. Their map showed areas of high and low probability based on the number of these peat indicator layers that overlap (i.e., areas with more overlapping data were given a higher probability of peat presence)⁶⁴. Lastly, we found a few local peatland extent estimates for Costa Rica⁶⁵⁻⁶⁷, which were produced with the goal of identifying peat deposits that could be used as energy resources in the 1980's and 1990's. These peatland extent estimates were based on national soil subgroup maps and ground-referencing field expeditions⁶⁵⁻⁶⁷.

Global wetland extent maps were based on two main types of analysis. The first group used wetland inventories, which are ground-referenced datasets^{68,69}. Similarly, many global peatland extent estimates use a collation of regional data inventories^{1,3,70}. This is in contrast with probabilistic maps such as the SWAMP wetland and peatland map², which was created using an expert system model based on climate, soil, and terrain data to identify areas that may be suitable for wetlands and peatlands. The Peat-ML map was similarly borne out of proxy data, including climate, soil, vegetation, and terrain datasets, using a machine learning model and a total of 30 predictor datasets⁴. The peatland map produced by UNEP⁵ used a combination of regional peatland inventories where available, and peatland proxy data for regions with no inventories. Their proxy data include datasets on soil, vegetation, and land systems⁵.

Wetland and peatland extent estimates are prone to an array of caveats and errors. Below we present the key limitations that have been highlighted in the literature we reviewed. First, finding cloud-free imagery for tropical regions can prove difficult, leading to over- or under-estimations of ecosystem extent^{2,71}. The effects of cloud cover were able to be mitigated by assembling a composite of cloud-free Sentinel-2 Multispectral Instrument surface reflectance images to map the extent of mangroves in Belize⁵⁹. However, special consideration should be taken in using this method when selecting the timespan of satellite imagery over which the cloud-free composite will be assembled. Another issue, this time with global datasets, is poor ground-referencing to verify peat-vegetation associations^{1,2}. Indeed,

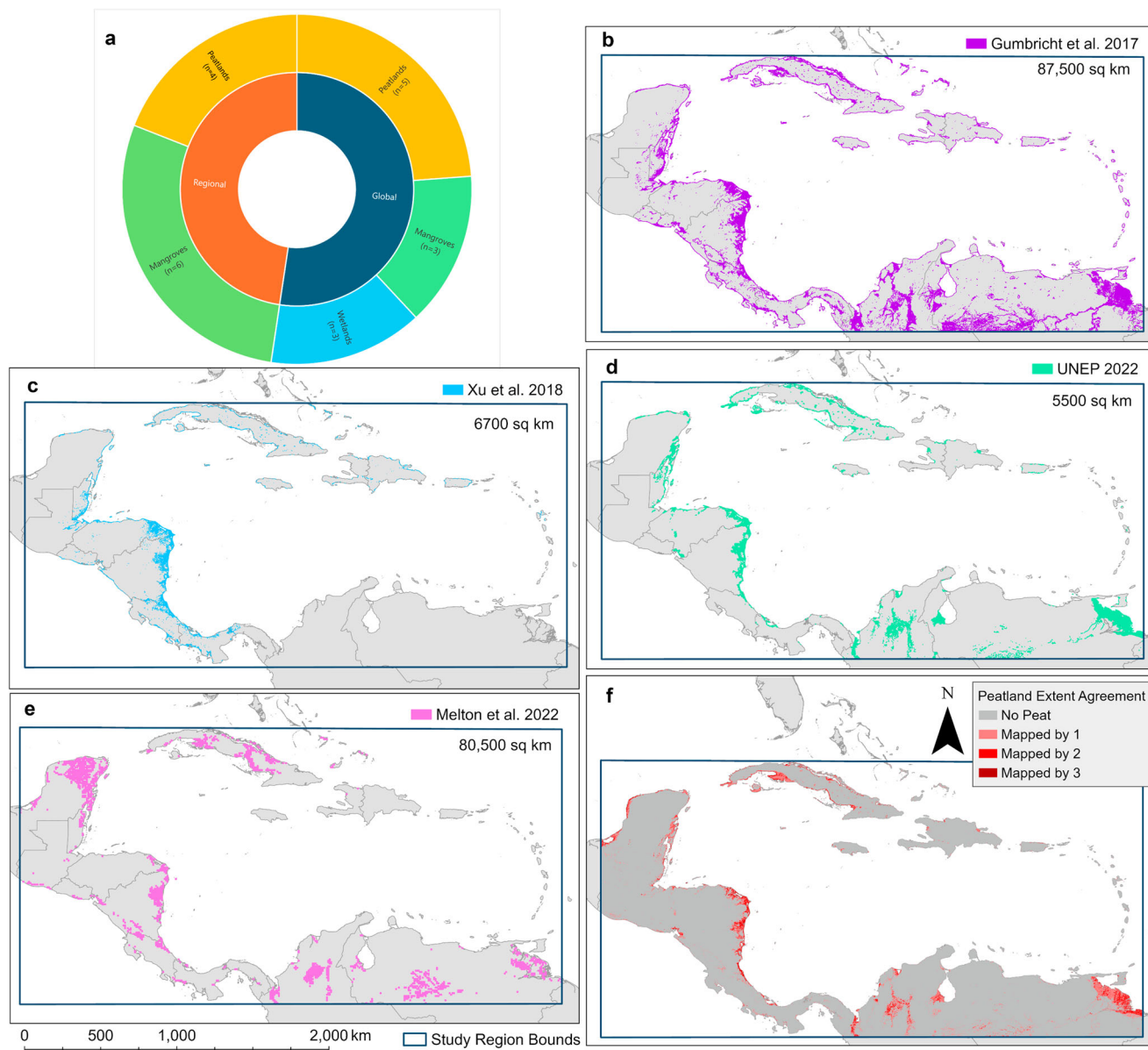


Fig. 6 | Mapping data collected on the Caribbean region. **a** The number of wetland and peatland mapping publications for the Caribbean region. The number of studies for each ecosystem type (outer ring) and the study area extent of these publications (inner ring) are displayed. **b** SWAMP map (Gumbrecht et al. 2017). **c** PEATMAP

(Xu et al. 2018). **d** Global Peatland Map v.2.0 (UNEP 2022). **e** PEAT-ML map (Melton et al. 2022); for the latter, we present grid cells with >20% peatland coverage. **f** Agreement analysis of peatland extent between the SWAMP map, PEATMAP, and the GPM.

ground-referencing proves to be of high importance to create training datasets and confirm mapping products^{59,61,72,73}. As for the probability maps, the different proxies (e.g., climate, hydrology, flooded area, topography, etc.) each come with uncertainties, which can compound and produce large errors in terms of wetland and peatland extent predictions.

Caribbean peatland extent estimates

Peatland extent estimates that include the Caribbean region consist of global estimates that generalize the conditions of peat formation and accumulation⁵. While this generalization may be acceptable at the global scale, it leads to large over- and under-estimates of the true peatland extent at local to regional scales. The low spatial resolution of these datasets also makes regional or country-level analysis difficult as those probabilistic peatland extent estimates are not particularly useful to localize peatlands in the field. For example, the most widely cited peatland extent for Central America is 23,374 km²¹, but this figure should be used with reservation due to large uncertainties and due to the fact that it is not spatially explicit. As for

the most well-cited predictive maps that are currently published, they cannot rely on proxies that would represent the full scope of conditions that lead to peat formation and accumulation in the Caribbean, as those are not yet fully elucidated, making it difficult to select adequate proxy datasets. Those global predictive mapping products tend to yield larger peatland extent estimates than data-based maps^{3,70} (Fig. 6b–e). But those inventory-based maps have their own limitations, namely that national and regional datasets used in these maps are scarcely available in the Caribbean.

Peatland extent estimates varied widely for the Caribbean, from 5500⁵ to 87,500 km^{2,2}. As previously stated, larger estimates came from studies that utilized a predictive approach to estimating peatland extent^{2,4} (Fig. 6). When viewing the extent estimates visually, there was much agreement on the location of peatlands along the Caribbean coast of Central America. The SWAMP map² proposed peatlands along much of the coastlines in this region, as well as large areas inland. Large inland areas in Colombia and Venezuela were also proposed by the Global Peatland Map v.2.0⁵ and the Peat-ML map⁴, but to a lesser extent. These distributions contrast sharply

with the PEATMAP³ estimation that reported an absence of peatlands in these countries (Fig. 6f). The most notable difference of the Peat-ML map was the large area in the Yucatan Peninsula⁴. It is important to note that the Peat-ML map⁴ is presented in “percent of grid cell covered by peatlands,” therefore not all of the area is covered by peat (maximum coverage: ~33% in one cell). The general observations above were confirmed by a similarity analysis (Fig. 6f), which shows the largest agreement between these map products along the Caribbean coasts of Costa Rica, Nicaragua, Honduras, and Panama. The largest areas of disagreement are found along the Caribbean coast of Cuba and the Yucatán Peninsula, the eastern coast of Venezuela, and inland Venezuela and Colombia. The Peat-ML map was not included in this analysis as it does not give an explicit peatland distribution estimate (but we did compare the Peat-ML output to the other ones in Fig. S4).

Discussion and conclusions

While this literature synthesis highlighted a recent uptick in the number of wetland and peatland studies from across the Caribbean, it also made clear that the total number of study sites is wholly inadequate to address ecosystem understanding. For instance, it is still unknown where peatlands are, what controls peat initiation, how much carbon these systems contain, which conditions constrain their carbon dioxide and methane emissions, and whether these ecosystems are resilient to climate change. These data and knowledge gaps lead to large uncertainties in the global carbon budget, as they greatly hinder modeling efforts. In terms of ecosystem dynamics, peatland ecological succession is poorly known, as is a mechanistic understanding of peat formation processes. All this information is needed to develop process-based ecosystem model algorithms and optimize existing parameters.

The systematic collection of peatland samples (water, soil, gas) combined with long-term monitoring of carbon and water dynamics is essential to help identify the hydrological thresholds needed for peatland formation, to quantify the key constraints on the rate of peat formation over space and time, to determine the sensitivity of carbon inputs and outputs to environmental change, and more. For instance, the control(s) on peat decomposition rates in the tropics have not received much attention. It is paramount to better appraise the relative roles of water inundation from seasonal flooding vs. precipitation. While it is known that soil saturation is particularly important in slowing down peat decomposition processes⁷⁴, it is unknown whether those conditions are linked to the duration of flooded conditions, the height and variability of the water table, or both. Mechanistic understanding is needed in the face of a changing hydroclimate and land management, now and in the future.

Improved mapping techniques combined with extensive ground-referencing are also needed to reduce uncertainty on peatland extent estimates. The large differences (> 200%) in peatland extent between the published studies highlight a great need for improvement. Producing and ground-referencing maps at national scales for the Caribbean needs to occur, to obtain more accurate extent estimates for peatlands in this region.

Overall, greater knowledge of peatland ecosystems would help inform land management decisions. Peatlands provide regulatory environmental services, as well as ecosystem services to humans. They regulate groundwater recharge and discharge and protect underlying soil layers from erosion⁷⁵. Caribbean peatlands support biodiversity and provide habitats to many unique species⁷⁶. Peatlands are also key environments for nutrient cycling, particularly carbon, nitrogen, and phosphorus. These nutrient cycles are key to keeping an ecosystem viable for flora and fauna, allowing them to continue to support the local biodiversity. Peatlands also contribute to soil formation and natural long-term carbon storage^{76,77}.

There is a growing interest in nature-based climate solutions^{78,79}, and many countries have begun using peatland carbon stocks in the global carbon market, as a way to offset carbon emissions⁸⁰. It is likely that Central American countries have valuable carbon stores that need to be protected^{1,2}; accurate mapping of tropical peatland extent is of paramount importance

for the conservation, restoration, and monitoring of these valuable carbon-storing ecosystems^{59,81}.

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Author contributions

E.R. performed the literature review and prepared the figures and tables. E.R. and J.L. both contributed to this study's conceptualization, data analysis, and manuscript writing.

Competing interests

The authors declare no competing interests.

Additional information

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