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Community-based monitoring reveals spatiotemporal variation of sargasso inundation levels and morphotype dominance across the Caribbean and South Florida

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ABSTRACT

During the past decade, massive inundations of holopelagic *Sargassum* spp. (*S. natans* I, *S. natans* VIII, and *S. fluitans* III), commonly known as sargasso, have drastically affected beaches and coasts throughout the tropical Atlantic, leading to strong forecasting and monitoring efforts. This study aimed to characterize spatiotemporal variation in accumulation levels and morphotype composition of sargasso inundations. Community science initiatives can aid in monitoring sargasso regionally by locally collecting data on morphotype composition and accumulation level. A volunteer network compiled community-contributed photos from the "Sargassum Watch" Epicollect5 digital application. Florida and the Gulf coast showed less susceptibility to high accumulations than other subregions of the tropical Atlantic. *S. fluitans* III was the most frequently encountered morphotype, though the probability of encountering any of the three morphotypes depended on accumulation level. Despite differences in latitude, the 2021 season demonstrated similar ’peak’ sargasso months between South Florida and Mexican Caribbean (May–July), though the intensity and duration of high-accumulation months differed. Much of these composition patterns and accumulation levels were likely related to the proximity of both regions to the Great Atlantic Sargassum Belt and dispersal through wind and water currents. Using community-collected data to outline quantitative trends and patterns in sargasso accumulation levels and composition, this study can be useful for future collaborations and syntheses with other forecasting and monitoring programs.

1. Introduction

Regional influxes of holopelagic *Sargassum* spp. (*S. natans* I Parr, *S. natans* VIII Parr, and *S. fluitans* III Parr) during the past decade have led to drastic ecological and economic effects on coastal systems (Wang et al., 2019). To harmonize terms used in this paper relevant to other published research done on *Sargassum* spp., we’ll be referring to ‘sargasso’ as a common term to include only holopelagic *Sargassum* species to avoid confusion with other benthic species of the genus *Sargassum*. Excessive biomass of sargasso decomposes in the water column or on the beach, producing a ’Sargassum-brown tide’ that results in anoxic conditions that kill marine fauna and shift benthic communities (Cruz-Rivera et al., 2015; van Tussenbroek et al., 2017; Rodríguez-Martínez et al., 2019). These environmental impacts of sargasso inundations can have long-term effects, and recovery of these coastal systems requires effective and proactive management (van Tussenbroek et al., 2017).

Prior to initial inundation events of 2011, the most prominent source of sargasso was the Sargasso Sea in the North Atlantic region (Parr, 1939; Sissini et al., 2017). This sargasso assemblage was composed of two species, *S. natans* and *S. fluitans*, each with their representative morphotypes (Parr, 1939; Wrinn et al., 2016). This area was reputed as a "golden rainforest," harboring endemic biodiversity in a largely pelagic ecosystem and essential to fisheries in the Gulf of Mexico (Butler et al., 1983). However, recent observational studies and oceanographic models suggest that the bloom-forming sargasso most likely originated from the North Equatorial Recirculation Region (NERR), between the

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eastern coast of Brazil and West Africa, where the Great Atlantic Sargassum Belt (GASB) formed (Franks et al., 2016; Wang et al., 2019). Previous monitoring efforts showed the span of sargasso influxes to be vast, stretching from the western Gulf of Mexico (Tabone, 2011; Webster and Linton, 2013) to West Africa (Smetacek and Zingone, 2013; Oyesiku and Egunyomi, 2014), though the intensity of sargasso was strongest in the lower Caribbean (Franks et al., 2011; García-Sánchez et al., 2020; Trinanes et al., 2021). The factors that led to the development and dispersal of the GASB are multifactorial, and could be caused, among others, by wind patterns, North Atlantic Oscillations in water currents, changes in sea surface temperature (SST), and nutrient availability, though the contribution of these factors towards the bloom is unclear (Lapointe, 1995; Sanchez-Rubio et al., 2017; Broman, 2019; Johns et al., 2020; Andrade-Canto et al., 2022; Skliris et al., 2022). Analyzing the spatiotemporal distribution of sargasso inundations along the Caribbean can provide a baseline for understanding the origins, mechanisms, and fate of sargasso.

This phenomena’s ambiguous origin and sizable impacts have led to strong development of forecasting and monitoring efforts. Regional monitoring efforts focused on satellite imagery modeling using various tools such as Moderate Resolution Imaging Spectroradiometer (MODIS) and Sentinel-2 (Wang and Hu, 2016; Maréchal et al., 2017; Putman et al., 2018). Data collected from these tools are often calculated to indices such as the maximum chlorophyll index (MCI), the floating algal index (FAI), and the alternative floating algal index (AFAI) to name a few (Trinanes et al., 2021). Satellite imagery modeling effectively forecasts sargasso movements based on water and wind current dynamics (Brooks et al., 2018; Andrade-Canto et al., 2022). However, these models are often limited by the resolution of these predictions, which is inversely related to the large, regional-scale these models encompass (Arellano-Verdejo and Lazcano-Hernandez, 2020). Fine-scale satellite imagery resolution for local, nearshore areas are often lacking, and the frequency of model outputs is also slower than the real-time movement of large rafts (Trinanes et al., 2021). Finally, anomalies in wind and water currents, such as from eddies, can render the fine-scale movement of sargasso to be more unpredictable (Andrade-Canto et al., 2022). The large geographic scale and the unpredictability of landings results in high variability that cannot be detected in regular monitoring sites. Multiple and integrative approaches to estimate the inundations of sargasso are needed; shortcomings from satellite imagery methods can be overcome by integrating ground-truthing methods providing many observations. Those observation should also consider the morphological plasticity of sargasso that was outlined and documented before these periodic inundations (Parr, 1939). Many studies report sargasso as either one genus without mentioning species diversity (*Sargassum* spp.) or between the two species, *S. natans* and *S. fluitans*, without further classification of morphotypes (Fidai et al., 2020). Using morphological traits, this taxonomic resolution of sargasso morphotypes proved useful in previous studies examining assemblage composition (Schell et al., 2015; Govindarajan et al., 2019).

Community science initiatives, synonymous with ’participatory science,’ ’volunteer monitoring,’ ’crowdsourcing’, or ’citizen science’, can aid in monitoring ecological phenomena at a large spatial scale (Trainer and Hardy, 2015; Gillis et al., 2018). Many initiatives monitor sargasso using community-contributed photos and observations (Franks et al., 2011; Iporac et al., 2019; Arellano-Verdejo and Lazcano-Hernandez, 2020; Valentini and Balouin, 2020). *In situ* photo data is adequate for collecting less than a meter in resolution observations, and can produce large amounts of data over a long period (Forrester et al., 2015; Chandler et al., 2017), suitable for long-term biogeographic analyses. This collection of data can then be forwarded to be deposited onto a larger database for more accessibility, facilitating more collaborations and expanding spatial and temporal scope (OceanViewer, 2021; Sargassum Monitoring, 2021). In May 2019, during the 39th Association of Marine Laboratories in the Caribbean (AMLC) meeting, a workshop was held that developed the International Sargassum Network Listserv (SargNet) and the “Sargassum Watch’’ citizen science program, both established at Florida International University, and is ongoing.

The goal of this study is to characterize spatiotemporal accumulation levels and morphotype composition of sargasso inundations within the tropical Atlantic region that includes South Florida, the Caribbean, and the Gulf of Mexico. This is pursued by addressing the following objectives: 1. Detect spatial variability of sargasso across biogeographic zones by comparing sargasso accumulation levels across the Caribbean, 2. Compare morphotype dominance in inundation-associated areas, and 3. Detect seasonal variation of sargasso accumulations from select locations consistently monitored. This study is useful as a baseline to detect the potential origin of influx-causing sargasso and the severity of impacts associated with these inundations.

2. Methods

2.1. Study species and area

Five subregions were drawn out within the tropical Atlantic region based on surface current patterns in the Caribbean area (Roberts, 1997; Robertson and Cramer, 2014). The "Greater Caribbean" (GC) subregion spans from the eastern Caribbean islands to Nicaragua, "Western Caribbean" (WC) spanning from Honduras to the east coast of the Yucatán peninsula of Mexico, the "Gulf of Mexico" (GoM) subregion encompassing the rest of Mexico and US coasts aside from Southern Florida, "Floridian" (FL) subregion based mostly on Florida, and the "Bahamian" (BH) subregion encompassing the Bahamas and Turks and Caicos (Fig. 1).

We have identified five data-sufficient sites that were monitored anywhere from daily to bi-weekly strictly for seasonality analyses based on the cumulative amount of data collected ($n > 60$, Fig. 1). Two sites in South Florida were identified, including Dr. Von D. Mizell-Eula Johnson State Park (MJSP, N 26° 3’ 37", W 80° 06’ 41.126") and Key Colony, Key Biscayne (KCKB, N 25° 41’ 48.98", W 80° 09’ 21.236"). Two sites in Quintana Roo, Mexico were also identified, including Reef Systems Unit, Institute of Marine Sciences and Limnology, National Autonomous University of Mexico (UNAM, N 20° 52’ 07.82", W 86° 52’ 5.485") and Playa del Carmen (PdC, N 20° 38’ 40.016", W 87° 03’ 19.81"). Sufficient data was also available for the general Boddentown area in Grand Cayman, Cayman Islands, and was compiled together as the "Boddentown’’ site (Bdt, N 19° 16’ 50.52", W 81° 14’ 59.24"). MJSP and KCKB are separated by latitude and intensity of the shoreline cleanup, with MJSP having minimal cleanup of the beach and KCKB cleaned daily. Similar characteristics distinguish UNAM and PdC, with UNAM being rarely cleaned and PdC cleaned daily with an additional floating barrier utilized during the sargasso peak season.

2.2. Community science photo collection

Community-contributed photos were compiled by a volunteer network using the application (called "app" hereafter) Epicollect5 (Gupta et al., 2021). Epicollect5 is a free and easy-to-use app platform that allows form-based data collection to be distributed among volunteers to collect photo data. Using this app method, we made five publicly-available versions of the "Sargassum Watch’’ community science program that varied in length of the form and language used (Iporac et al., 2020). Volunteers were identified and recruited using SargNet and personal/professional networks and retained through email or personal communication if data collection had paused from the group or individual.

Volunteers were given protocols and training sessions in-person or online to use the app if the volunteer or group requested. Required information from volunteers included date and time, GPS coordinates, site and region name, three angled photos of the site, evidence of sargasso management (if applicable), and one photo containing all morphotypes present. Evidence of sargasso management can include, but not limited

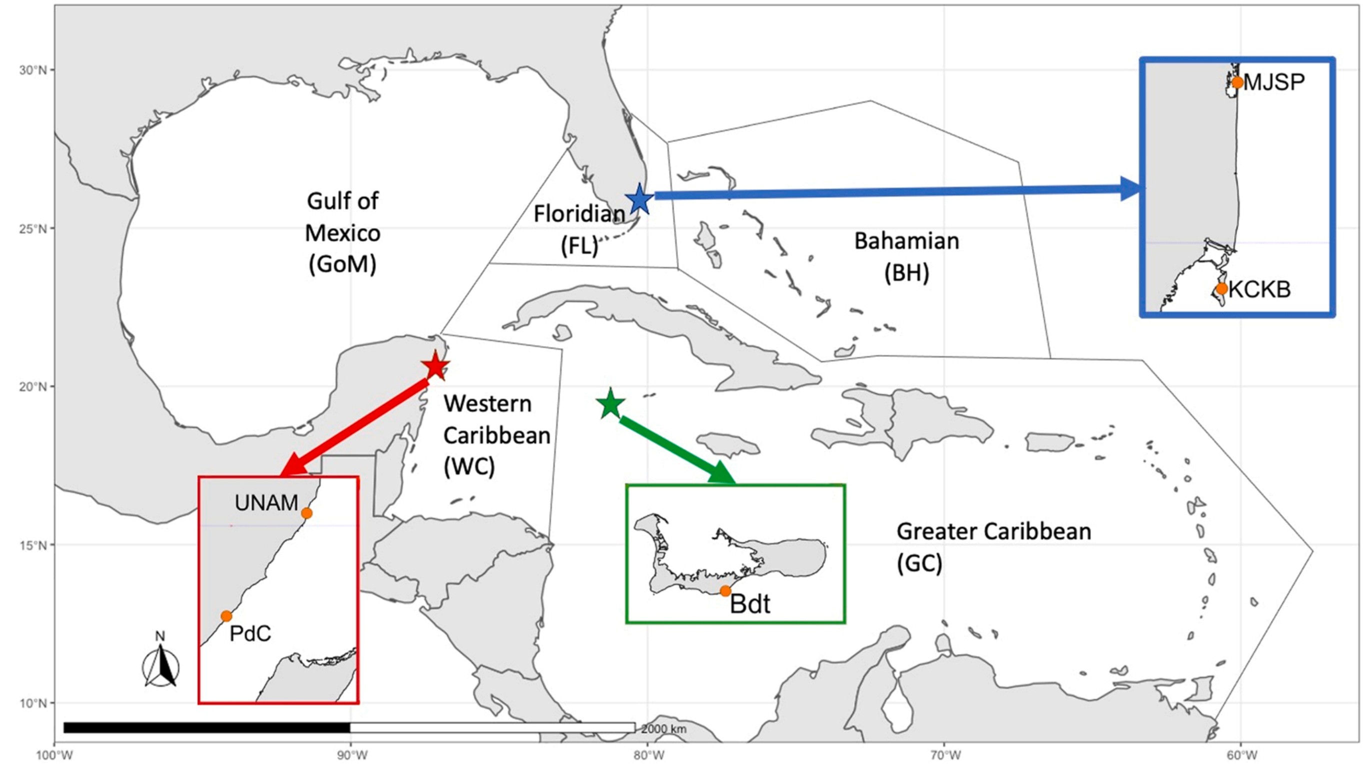

Fig. 1. Map showing the five subregions and locations of the five data-sufficient monitored sites. Two sites, Dr. Von D. Mizell-Eula Johnson State Park ((MJSP, N 26° 3’ 37", W 80° 06’ 41.126")) and Key Colony, Key Biscayne (KCKB, N 25° 41’ 48.98", W 80° 09’ 21.236") are shown in the blue inset in Florida. Two sites inside the red inset representing the Western Caribbean include the Reef Systems Unit, Institute of Marine Sciences and Limnology, National Autonomous University of Mexico (UNAM, N 20° 52’ 07.82", W 86° 52’ 5.485"), and Playa del Carmen (PdC, N 20° 38’ 40.016", W 87° 03’ 19.81"), both in Mexico. Boddentown (Bdt, N 19° 16’ 50.52", W 81° 14’ 59.24") site is also shown up-close in the green Grand Cayman inset.

Table 1
Accumulation table for photo classification slightly modified by Collado-Vides et al. (2018).

Accumulation level	Description of sargasso accumulation	Water color	Example photos
Level 1	• Very little sargasso on the sand on beaches. Wrack line may or may not be noticeable	Unchanged	
Level 2	• Low accumulation of sargasso on the sand on beaches	Unchanged	
Level 3	• Moderate backing of sargasso to the coast that causes a moderate accumulation on the sand on beaches	Slightly brown	
Level 4	• Excessive overflow of sargasso to the coast that causes a high or massive accumulation on the sand on beaches. • Forms mounds on seashore • Some floating in the sea	Brown	

to, large tire tracks, appearancy of cleanup machinery such as trucks or tractors, sargasso cleanup crews, and sargasso buried in sand after cleanup. Volunteers then uploaded their observations onto the open-source database for later analyses.

Accounting for this study's biogeographical scope being limited by the availability of volunteers per geographic area, additional data from the iNaturalist database was downloaded to supplement the biogeographical scope of this study. Unlike Epicollect5, which utilizes networks of committed volunteers to consistently monitor selected sites, iNaturalist data collection is more occasional and opportunistic in frequency of encountering sargasso but does so at a much larger geographical scale. Keywords used to retrieve iNaturalist data included "Sargassum," "Sargassum natans," and "Sargassum fluitans," and were restricted to the Gulf, Florida, and Caribbean areas. Morphotype names could not be used as keywords on the iNaturalist search engine.

2.3. Data processing and analyses

Multiple criteria were used to determine the usability of observations collected for analyses. At minimum, all observations needed to have photos of a site (beach, dock, etc.), regardless of whether there was sargasso present or not. If sargasso was present, the accumulation shown must be comparable to the rest of the site where it was present (beach, dock, cliff, etc., supplemental Table 1). Observations collected were either classified as "opportunistic" if collected less than once a month on average anywhere within the five subregions, or "monitored" if collected at the same-named site on a more frequent basis (bi-weekly to daily). Observations with low-quality photos or only close-up specimens were removed from further analyses.

Each observation was categorized into an accumulation level based on a modified table by Collado-Vides et al. (2018) (Table 1). To minimize the subjectivity of classifying an accumulation level depending on the analyzer's perception, at least two processors examined a photo to calibrate our perception of an accumulation level prior to finalizing an accumulation level. However, multiple processors often lead to disagreements on an assigned accumulation level of an observed landing. Any unresolved consensus of an observed accumulation level was determined by the discretion of the most experienced processor present or by majority vote (mode). Morphotype photos were also examined for the presence or absence of sargasso morphotypes per observation as outlined by Parr (1939) and Wrinn et al. (2016).

Given the more opportunistic modality of data collection by iNaturalist contrasting the more consistent monitoring of volunteers using Epicollect5, a linear regression analysis was conducted to determine the usability of iNaturalist data. This analysis accounts for observation bias by testing the hypothesis that the number of observations would increase as a function of the increased accumulation level encountered (Geldmann et al., 2016). The regression analysis involves using accumulation level as a predictor and the number of observations as the response variable.

Observations were grouped onto a contingency table by accumulation level and subregion. Relative proportions of observed accumulations were plotted onto the map of the subdivided Caribbean region to visualize the variability of sargasso inundation levels. Pearson's chi-square test was used on the frequency of observations associated with accumulation levels and subregions to detect the susceptibility and intensity of observed sargasso accumulations between subregions, regardless of time.

Presence-absence data of morphotypes were converted into normalized relative frequency per number of observations per subregion. Observations with no sargasso present were removed for this analysis. Relative frequency of each sargasso morphotype per subregion (R_{mr}) was calculated using this equation:

$$R_{mr} = F_{mr} / N_r$$

Where F_{mr} is the total frequency of a sargasso morphotype m per subregion r, and N_r is the total number of observations per subregion r. Relative frequency values for each morphotype and subregion combination were calculated separately because many observations display more than one morphotype present. Normalized relative frequency data of morphotypes per total observations per subregion was graphed to visualize the dominance of morphotypes in inundation-associated areas. Pearson's chi-square analysis was used on the total frequency of morphotypes per subregion to determine the variability of sargasso morphotype composition found per subregion in inundation-associated areas. Using all morphotype data, including those with an absence of morphotypes, logistic regression curves were compiled using the ggplot package of RStudio to determine the probability of encountering a morphotype per subregion based on accumulation level. For each curve, binomial logistic regression analysis was conducted to assess the likelihood of encountering a morphotype depending on the accumulation level.

Accumulation levels between the five monitored sites were summarized using a contingency table and bar plots showing the relative proportion of observations per month during the 2021 season. A similar plot was formed showing the relative proportion of accumulation levels in MJSP for 2019–2021 sargasso seasons to examine temporal variability in accumulation levels in one site. Pearson's chi-square test was used on the frequency of observations associated with accumulation levels and month to detect the susceptibility and intensity of observed sargasso accumulations between months per year in both analyses.

To compare the probability of encountering an observed accumulation level per month during the 2021 season, density plots were compiled using the ggplot2::geom_density function in RStudio using the total frequency of accumulation levels per month. Monitored site data was compiled to represent subregions; the FL density plot was constructed using the MJSP and KCKB datasets, and the WC density plot was constructed using the UNAM and PdC datasets. Bdt dataset was too restricted in sampling months for density plots, and no monitored sites were identified in the GoM or BH subregions.

3. Results

A total of 1756 observations were collected from the Epicollect5 program and used for this study. An additional 146 observations of *Sargassum* spp. (based on keywords used from the app search engine) were retrieved from the iNaturalist database after quality-checking that included the identification of pelagic species. Most of the data available were from 2019 onwards due to the implementation of Epicollect5 (Supplemental Fig. 1), although few observations from iNaturalist were available before 2019 (supplemental Fig. 2). No statistically significant relationship was found between accumulation level and number of observations on either iNaturalist data ($R^2 = 0.21$, $p = 0.54$) or Epicollect5 ($R^2 = 0.81$, $p = 0.09$) (Supplemental Fig. 1). With no evidence to suggest observational bias as a lurking factor, both iNaturalist and Epicollect5 data were combined for the following analyses.

The sample size of each subregion varied from $n = 31$ in GoM to $n = 1093$ in FL. The observed accumulation levels varied over different regions X^2 (15, $N = 1901$) $= 310.46$, $p < 0.0001$. FL showed less susceptibility for moderate to high sargasso inundations, noted by a higher-than-expected amount of level 1 observations and lower-than-expected amount of level 3–4 observations. WC showed a lower than expected amount of level 1 observations and a higher than expected amount of levels 2–4 observations. GC showed similar trends as WC, with a more than expected amount of level 4 observations and a lower than expected amount of level 1 observations, demonstrating that GC and WC showed higher susceptibility to sargasso inundations relative to other subregions in the Caribbean (Fig. 2).

The number of observations with sargasso morphotypes identifiable ranged from $n = 15$ in GoM to $n = 503$ in FL, and included both observations collected by monitoring groups ("monitored") and

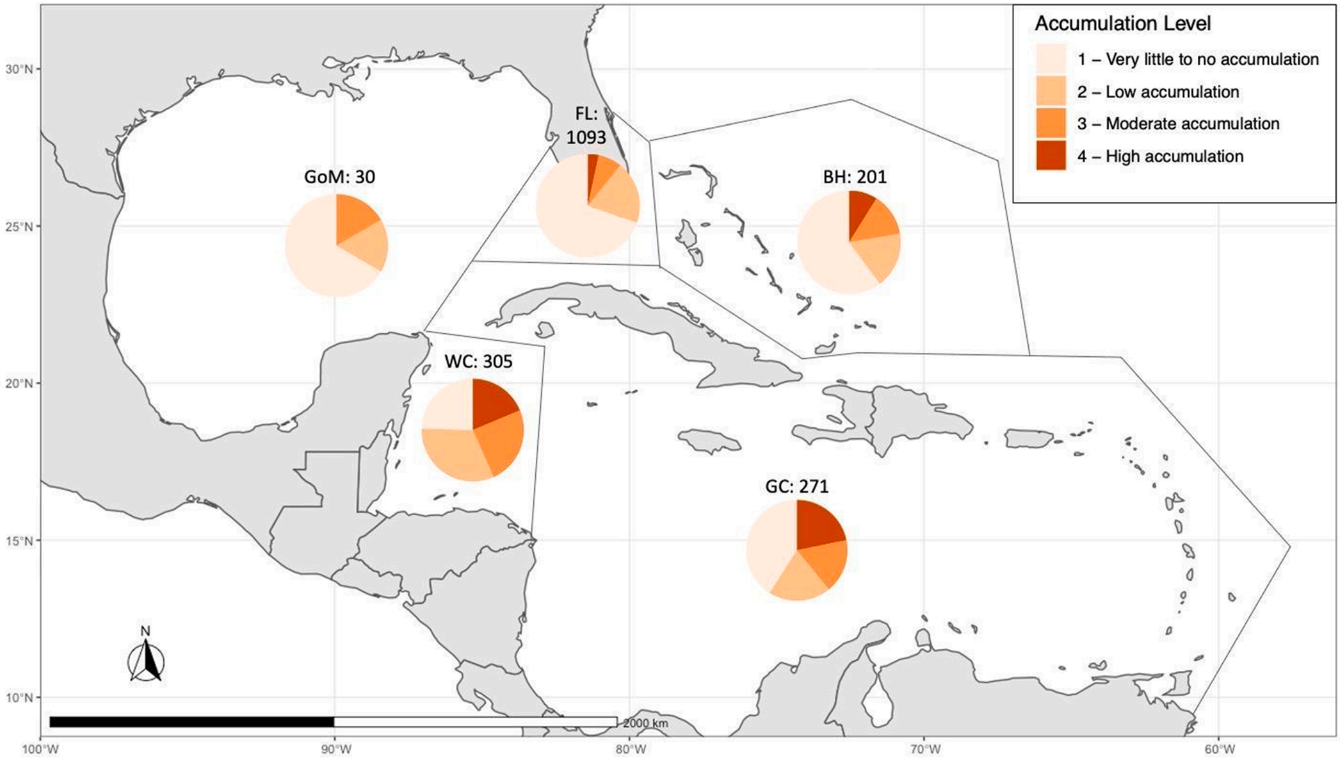

Fig. 2. Number of observations and proportion of observed accumulation levels of sargasso compiled from 2011 to 2021 for "Greater Caribbean" (GC), "Western Caribbean" (WC), "Gulf of Mexico" (GoM), "Floridian" (FL) and "Bahamian" (BH) subregions. Numbers represent sample size per subregion. The size of pie charts is not proportional to the sample size of the subregion.

"opportunistic" observations (Supplemental Fig. 4). Observations with no identifiable sargasso present were excluded from normalized relative frequency calculation. There was considerable variation in morphotypes found throughout the subregions associated with the inundations X^2 (8, N = 921) = 29.704, $p < 0.01$. Throughout the Caribbean, *S. fluitans* III was the most commonly encountered morphotype. Relative frequencies of *S. fluitans* III ranged from 0.73 in the GoM to 0.95 in GC and WC. In four out of five subregions, *S. natans* VIII was the second most commonly encountered morphotype, except in GC, where the relative frequencies of *S. natans* VIII and *S. natans* I were roughly equal. The lowest relative frequency of *S. natans* VIII was 0.41 in GC, while the highest relative frequency was 0.80 in WC. *S. natans* I was the least commonly encountered morphotype; the lowest relative frequency of *S. natans* I was 0.14 in BH, while the highest relative frequency was 0.38 in GC (Fig. 3).

Logistic regression analyses shows that the probability of finding any of the three morphoptypes is dependent on subregion and accumulation level (Fig. 4). All *S. fluitans* III subregional regression models showed that the probability of encountering that morphotype increases as accumulation levels increase ($p > 0.0001$). Similar trends were found

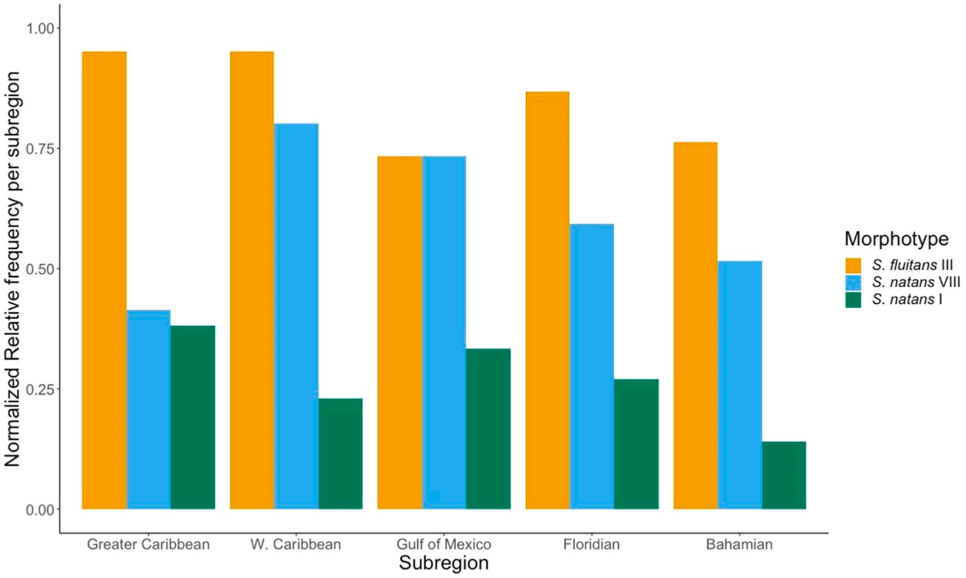

Fig. 3. Normalized relative frequency of sargasso morphotypes present in an observed inundation per subregion.

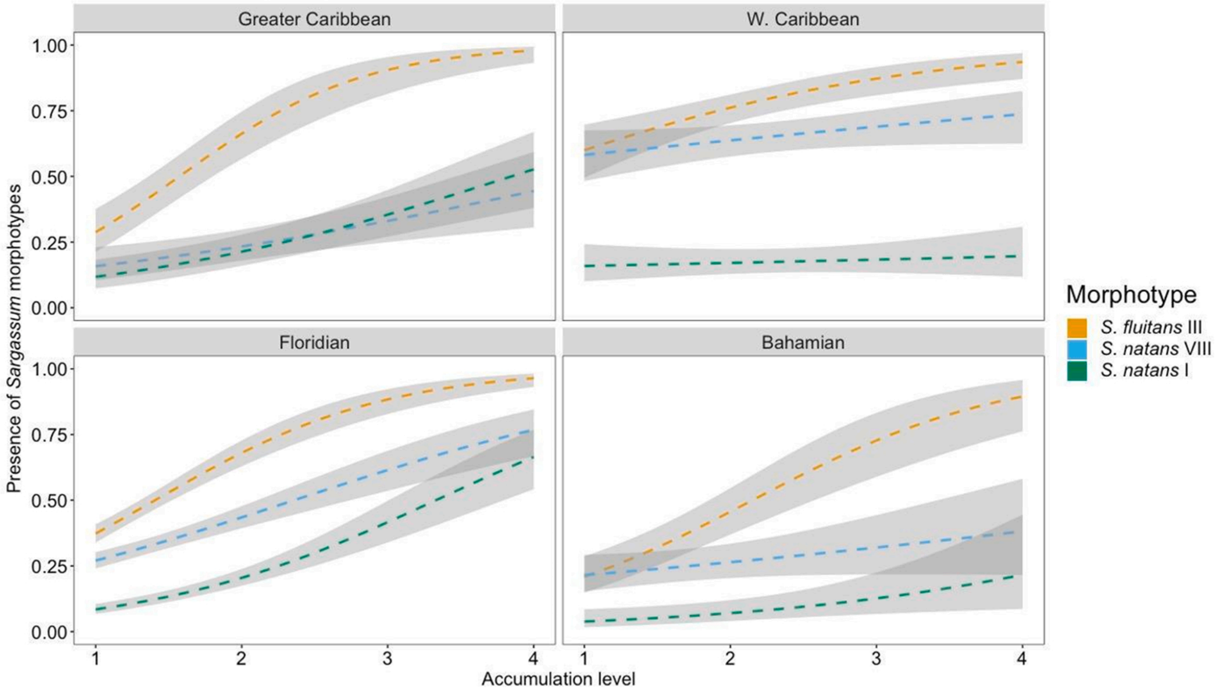

Fig. 4. Logistic probability models of *Sargassum* spp. morphotypes presence as a function of accumulation level per subregion. No probability models were made for GoM with lack of sufficient data.

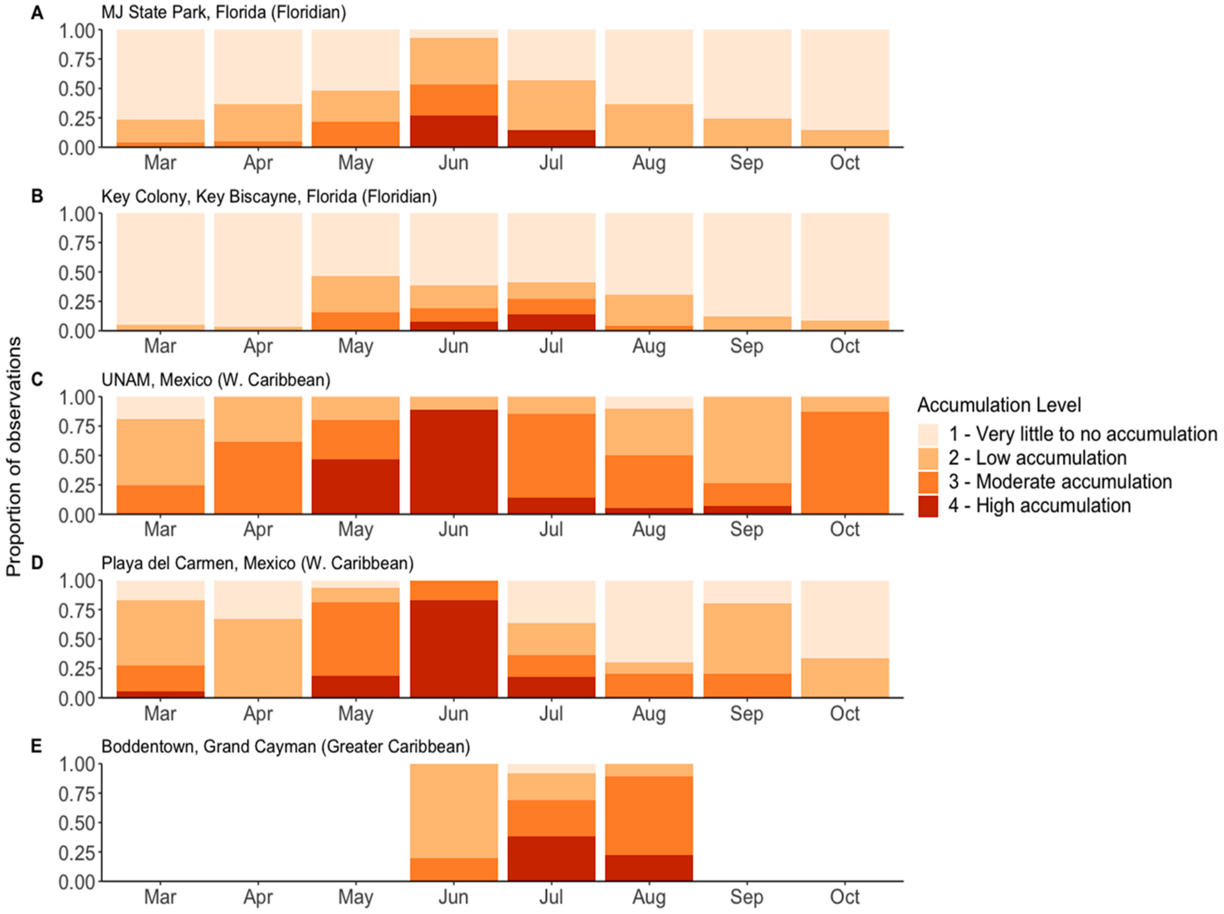

Fig. 5. Proportion of observed accumulation levels per month from March to October 2021 across the five study areas (A) MJSP, Florida, (B) Key Colony, Key Biscayne, Florida, (C) UNAM, Mexico, (D) Playa del Carmen, Mexico, and (E) Boddentown, Grand Cayman. No data was available from March-May and September-October in Boddentown, Grand Cayman, Cayman Islands.

for most subregional models of *S. natans* I ($p > 0.001$) except for the WC subregion ($R^2 = 0.033$, $p = 0.59$), and *S. natans* VIII ($p > 0.0001$) except for WC ($R^2 = 0.11$, $p = 0.071$ NS) and BH subregions ($R^2 = 0.12$, $p = 0.11$ NS). Supplemental table 2 summarizes the results of logistic regression models associated with the probability curves.

Seasonal variation of accumulation levels was examined between the five data-sufficient sites during 2021 (Fig. 5). No data was collected outside of June–August in Bdt. MJSP and KCKB in Florida have similar proportional accumulation levels observed between UNAM and PdC in Mexico. Both Florida and Mexico sites showed a gradual increase in accumulation levels in May (though PdC observed high accumulation levels in March). Sargasso accumulation levels peaked in June at MJSP, UNAM, and PdC. Accumulation levels in KCKB during June and July are roughly similar, though there were slightly higher proportions of observations during July. Bdt showed increased accumulation between June and July before slightly decreasing in August. July showed the highest proportion of accumulation levels observed between these three data-available months.

MJSP has the largest sample size of all other sites ($N = 452$) spanning three years (2019–2021); this site was used for interannual comparisons of accumulation levels between months and years (Fig. 6). No observations were collected from November to February each year. Considerable variation occurred between 2019 and 2021 X^2 (105, $N = 372$) $= 336.05$, $p < 0.0001$. In 2019, the sargasso season started in April and continued until July, when accumulation levels decreased from August to October. In 2020 the sargasso season started in May and peaked between June and July before decreasing in August. The 2021 sargasso season showed a similar trend to the 2020 season, though the intensity of accumulation levels was higher that year.

Density curve models between FL and WC subregions showed similar trends in dominant accumulation levels observed between months during the 2021 season (Fig. 7). Higher accumulation levels coincided with a more restricted time frame when those observations were present. Level 1 and 2 observations were present in most months of the season but had the highest density before and after the peak season, depending on the subregion. FL level 3 observations were concentrated from May to June and WC in May and August, months adjacent to the peak season. Level 4 observations were mostly present in June–July in FL and May–July in WC, representing the peak season.

4. Discussion

This study utilizing collaborations between individual and groups of volunteers was fundamental to garner a region-wide perspective on sargasso inundations between large-scale satellite imagery and small-scale in situ monitoring approaches such as quadrats. Using community-contributed data, our results showed spatial variability in sargasso inundations levels, demonstrating that Florida and the Gulf were less susceptible to high accumulation levels than the rest of the tropical Atlantic region during the studied period. Morphotype composition and accumulation levels varied within the tropical Atlantic independent of wherever sargasso landed. Finally, seasonal variation was detected between years of one site and between sites during one season. Though the 2021 season showed similar peak seasons between the Florida and Western Caribbean subregions, the duration and intensity of these peak months differed.

Overall biogeographic trends were consistent with the satellite imagery models at a regional level. The intensity and frequency of sargasso depend on an area's proximity to the GASB and dispersal of sargasso biomass through wind and water currents (Brooks et al., 2018; Johns et al., 2020). Putman et al. (2018) simulated sargasso transport and found that the Equatorial Atlantic (east of EC) would eventually export sargasso through the Caribbean Sea within a year. Johns et al. (2020) noted that windage patterns could form long mats of sargasso and transport them from the Inter-Tropical Convergence Zone (ITCZ), where the GASB is sourced, to the Central Atlantic across the Caribbean. Remnant populations of sargasso can still exist during the off-season before recovering the following year (Johns et al., 2020). Recent oceanographic models also suggested mesoscale eddies can collect and disperse sargasso to trajectories that would differ from initial, main current patterns (Andrade-Canto et al., 2022). While this study did not examine the transport of sargasso, emphasis was placed on the fate of sargasso from the GASB to landed areas across the Caribbean. Subregions that did not report as high a frequency of high-accumulation levels as others can still be susceptible to lasting impacts from sargasso, as was the case in seagrass beds in Turks and Caicos in the BH subregion. In that area, stakeholders noted that sargasso accumulations have always been observed but were noted to be a problem in 2018 (Bartlett and Elmer, 2021). Though our Sargassum Watch Epicollect5 Program could not get observations from before 2019, consistent monitoring and opportunistic, single observations can be valuable to show the extent of these massive inundations.

Our results examining morphotype composition associated with landed sargasso can be a useful baseline to compare future monitoring programs and previous baselines associated with morphotype composition onshore or offshore. Other studies that monitor sargasso morphotype composition across the Eastern Atlantic region have found considerable temporal and spatial variation. Offshore surveys from 2015 revealed a dominance of *S. natans* VIII across the Caribbean, contrasting with *S. natans* I dominance in the Sargasso Sea (Schell et al., 2015).

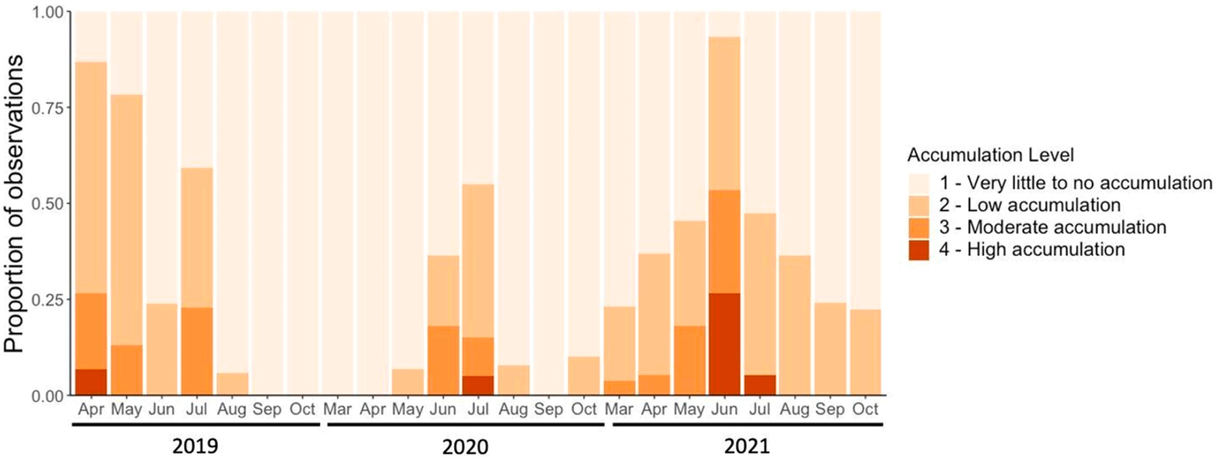

Fig. 6. Proportion of observed accumulation levels per month from 2019 to 2021 in MJ State Park, Fort Lauderdale, Florida, USA. No data was available from November-February in all three years and March 2019.

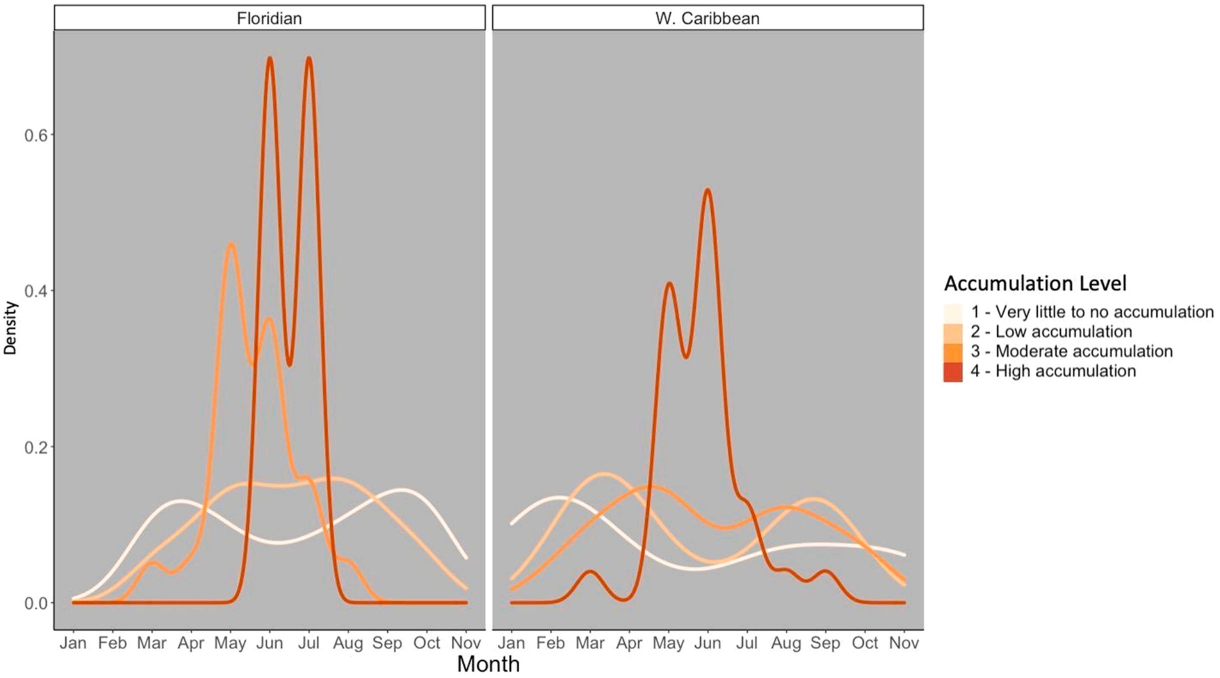

Fig. 7. Kernel density plots of observed accumulation levels between FL and WC subregions during the 2021 sargasso season.

Another shipboard survey from 2015 to 2016 showed *S. fluitans* III and *S. natans* VIII dominant in the Tropical Atlantic, Greater Caribbean, and Gulf of Mexico regions, while the Gulf Stream region is dominated by *S. natans* I and *S. natans* VIII. Only in the Sargasso Sea was there a sizeable representation of all three morphotypes, with *S. fluitans* III occurring in 33 % of dip net collections, *S. natans* VIII occurring in 23 % of collections, and *S. natans* I occurring in 43 % of collections (Martin et al., 2021). Interestingly, these post-2011 surveys differed from earlier surveys where *S. fluitans* III and *S. natans* I were previously the most dominant species, with little detection of *S. natans* VIII (Parr, 1939). It seems that *S. natans* VIII became an increasingly integral morphotype composing these inundations after 2011, along with the other morphotypes. From a regional perspective, our results are consistent with previous post-2011 surveys as *S. fluitans* III was the most commonly encountered morphotype. At the same time, *S. natans* VIII and *S. natans* I can also be present depending on subregion and accumulation level.

Our seasonal approach comparing morphotype composition using frequency contrasted with results that monitored biomass. Concurrent monthly monitoring of MJSP showed that *S. natans* I dominated in biomass during months without an inundation, while *S. fluitans* III dominated in biomass during influx seasons. *S. natans* VIII showed the least biomass throughout that study (Hatt et al., unpublished data). Previous monitoring programs of sargasso in the Mexican Caribbean from 2016 to 2020 found largely *S. fluitans* III dominance throughout, though dominance of *S. natans* I and VIII varied by sampling month (García-Sánchez et al., 2020). Other single-day sampling efforts in Jamaica and Mexican Caribbean also outlined *S. fluitans* III dominance, with a limited abundance of *S. natans* I and VIII (Machado et al., 2022; Vázquez-Delfín et al., 2021). Though *S. natans* I occurred in much less frequency than the other morphotypes, the absence of *S. natans* I on observed landings could not imply absence (Altman and Bland, 1995). Given morphological differences, *S. natans* VIII is often a readily identifiable morphotype than the more inconspicuous *S. natans* I. However, discerning differences in morphotypes requires identifying minute traits within the algal thallus (Parr, 1939), which could not be readily identifiable with photos often low in resolution. Marking the presence of a morphotype requires examining and identifying the overall thalli based on the rough level of structural complexity.

Seasonal comparisons of accumulation levels were mostly consistent with the satellite imagery models that would regionally predict an increase or decrease of sargasso, although the Floridian subregion would receive less accumulation than the Greater Caribbean. Peak seasons of sargasso also tend to vary yearly, but usually fall between April to September (García-Sánchez et al., 2020; Bartlett and Elmer, 2021; Vázquez-Delfín et al., 2021; Machado et al., 2022). Sargassum Inundation reports (SIR) during the 2019–2020 year noted Florida's southeast coast as having primarily low to medium susceptibility of sargasso inundations (Trinanes et al., 2021), which was largely similar to on-ground monitoring results of MJSP during those same years. Our analyses further support this before and during the 2021 season that showed a gradual transition of observations primarily of low accumulation to high accumulation that were characteristic of peak months from May to July. This transition and intensity of peak months also varied with subregion, with WC having more high accumulation events than FL, consistent with previous years' monitoring (Trinanes et al., 2021).

When comparing our results to previous biomass monitoring programs, Florida monitoring previously reported upwards of 4.0 wet kg m^{-2} during April 2019 (Hatt et al., unpublished data), contrasting 17.3 wet kg m^{-2} in the Mexican Caribbean during the summer of 2018 (García-Sánchez et al., 2020). Based on these previous biomass monitoring efforts, the severity of sargasso accumulations can greatly differ between these two subregions. The Mexican Caribbean can receive at least four times the biomass landed in Florida. Given the proximity of these two subregions to the GASB and the trajectory of the water currents from the Caribbean Current, to Loop Current, to Gulf Stream, it could be that the Floridian subregion is receiving the residual biomass that did not land in the Mexican Caribbean, where much more of that biomass has landed (Putman et al., 2018; Johns et al., 2020). Alternatively, sargasso from the GASB can be transported to Florida via the Antilles Current (Putman et al., 2020). However, given the comparatively lower accumulation levels observed in the Bahamian subregion, it is difficult to tell how often that occurs.

The frequency and intensity of sargasso landings can also be influenced by small-scale coastal factors that occur daily and locally; and local managerial strategies. In areas with adjacent fringing reefs, lower wave and wind activity gradually increased sargasso accumulation. In contrast, high wave and wind activity would inundate the landed sargasso and flush it back into the water column. Depending on subsequent wind and wave activity, re-suspended sargasso can re-land on beaches or get flushed entirely (Rutten et al., 2021). Observations at the Reef Systems unit of UNAM in Quintana Roo, Mexico have somewhat detected this phenomenon; observations with high accumulation often coincided with high tide that inundates landed and floating sargasso (Rutten et al., 2021). Sargasso accumulations at UNAM would mostly have between level 2–4 accumulation levels, depending on the month of the sargasso season. Conversely, consistent management of local beaches through removal or displacement can also mediate otherwise high accumulations of sargasso. In our study, KCKB in Florida was cleaned daily through machinery. In contrast, PdC in Mexico was cleaned daily with machinery with an additional nearshore barrier set up during the peak season. Proportions of observed accumulation levels in cleaned sites were largely similar to sites that lack consistent cleaning, albeit fewer observations showing moderate and high accumulations were noted in cleaned sites.

This study also led to results related to conducting community science programs. Community science programs require rigorous data quality control, which can be maintained through protocols, active training, and feedback (Fore et al., 2001; Nerbonne and Vondracek, 2003). The uneven distribution of available volunteers in the Greater Caribbean region also leaves many impacted areas unmonitored, which can be a source of sampling bias that would prevent holistic assessment of sargasso landings (Nerbonne et al., 2008; Iporac et al., 2020). Our study attempted to mitigate sampling bias by utilizing supplemental iNaturalist data and testing for observational bias, which our regression results suggested was minimal.

The sheer potential of using photo observations for quantitative analyses is developing rapidly. Previous tools have been proposed for use, such as an accumulation table for manual classification (this study, Collado-Vides et al., 2018), to computerized neural networks for automated detection of sargasso landings in photos (Valentini and Balouin, 2020; Arellano-Verdejo and Lazcano-Hernández, 2021). The manual classification method was limited by the number of images to categorize and subjectivity of classifying an accumulation level per photo(s). The automated method can process large amounts of photos, quickly detecting the presence or absence of sargasso with over 90 % accuracy but currently does not translate to more comparative data beyond that (Arellano-Verdejo and Lazcano-Hernández, 2021). Both quantification methods were also limited by the quality of photos sent by volunteers for later processing. For monitored data to be useful, volunteers' frequency of photo collection must be maintained by constant communication and developed trust and commitment between volunteers and program managers. Opportunistic data from other sources, such as iNaturalist, can also be bolstered through outreach efforts, although data quality varies by available protocols associated with data collection.

This study is among the first known that attempts to use the collected citizen science data to outline quantitative trends and patterns in sargasso accumulation levels and morphotype dominance. Recent publications have used the Epicollect5 database for qualitative presence of sargasso landings with satellite imagery models, and these comparisons were effective in ground-truthing and detecting concordance (Trinanes et al., 2021). Other previous works acknowledged the effectiveness of the Epicollect5 program in data collection yet criticized the accessibility of app usage and limited usage of presence/absence data rather than the abundance of sargasso (Arellano-Verdejo and Lazcano-Hernandez, 2020). The United Nations Environmental Programme (UNEP) noted the quantity per volume of sargasso that landed as a major gap in monitoring sargasso (United Nations Environment Programme - Caribbean Environment Programme, 2021), especially given the heterogeneity of biomass landing within the tropical Atlantic region. Synthesizing photographic data with other methods such as in situ monitoring of biomass can be used to re-examine photographs to estimate biomass on a higher frequency. Estimating biomass through photos can then be recalculated to estimate inputs associated with sargasso, such as nutrient availability, metal concentrations, and foraging grounds for shorebirds feeding on terrestrial invertebrates. There is also potential for automated approaches to quantify the sheer amount of photos to quantitative data, as was done with presence-absence conversion (Arellano-Verdejo and Lazcano-Hernández, 2021). However, there is the challenge of calculating meaningful data from low-resolution images. Finally, these photos and associated biomass estimates can further be synthesized by satellite or aircraft images to validate the amount of biomass arriving, of which similar efforts are already developing recently (Baldwin et al., 2019; Degia et al., 2022; Hernández et al., 2022; Trinanes et al., 2021; OceanViewer: Ocean Observing System, 2021; Optical Oceanography Laboratory, 2022). This synthesis of data from different scales can be combined with other hazard, exposure, and vulnerability data to estimate the impact forecasting of sargasso on coastal environments and affected local communities (Degia et al., 2022).

Detection of accumulation levels largely relies on sampling efforts by volunteers, which may not always be available. Much of our currently collected data concentrated on a few areas with sufficient resources and collaborative research capacity to include citizen science as a monitoring strategy. Many of these under- or non-monitored areas may not have adequate support and simultaneously could be areas that experience highly impactful sargasso inundations. Many of these countries associated with sargasso inundations also have histories of colonial and neocolonial exploitation and imperialism that still manifest today through contemporary geopolitical situations. When collaborating via community science, we advocate for open use of our data and collaborations between community groups and nations to study and manage a regional issue, especially in data-insufficient areas of this study. However, we also highlight the need to ensure that practices of science and policy in this field lead to equitable and just science and policy for peoples in the global south, including Central America, West Africa, and the Caribbean that often gets impacted by sargasso (Edwards et al., 2021; Stefanoudis et al., 2021).

Declaration of Competing Interest

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

Data availability

Photo data are available for download through open repository links in the 'responses to reviewers' document. Data curated for statistical analyses are available upon request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.aquabot.2022.103546.

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