phycology

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Comprehensive Analysis of Biomass, Nutrient, and Heavy Metal Contributions of Pelagic *Sargassum* Species (Phaeophyceae) Inundations in South Florida

Danielle C. Hatt [1,*], Natalie K. Bally [2], Lowell Andrew R. Iporac [1], Samantha Olszak [3], Justin E. Campbell [1] and Ligia Collado-Vides [1]

1 Department of Biological Sciences, Institute of Environment, Florida International University, Miami, FL 33199, USA; lowell.ecology@gmail.com (L.A.R.I.); jcampbel@fiu.edu (J.E.C.); colladol@fiu.edu (L.C.-V.)
2 College of Agricultural and Life Sciences, University of Florida, Gainesville, FL 32603, USA; nataliebally98@gmail.com
3 Halmos College of Arts and Sciences, Nova Southeastern University, Davie, FL 33328, USA
* Correspondence: dhatt002@fiu.edu

Abstract: Pelagic *Sargassum* landings (hereby referred to as sargasso) increased dramatically in 2011 throughout the equatorial tropical Atlantic due to the formation of the Great Atlantic Sargassum Belt (GASB). Despite increasing reports, understanding of local abundances and vegetative characteristics, especially in South Florida, remains limited. From 2018 to 2021, sargasso was collected at two South Florida beaches, with additional sampling at a third beach to assess nutrient and heavy metal concentrations. Biomass landings varied greatly, with *S. fluitans* III predominant during the "peak season" (May to July) and *S. natans* I predominant in the "off season", while *S. natans* VIII was consistently least abundant. This suggests that South Florida may receive sargasso from the Sargasso Sea during the low season and from the GASB during the peak sargasso season. Across all three morphotypes, mean nitrogen (N) and phosphorus (P) contents were 0.97% and 0.04% (dry weight), respectively. Out of the 16 heavy metals detected, our values were similar to those reported across the Caribbean. Arsenic was the most prevalent heavy metal, with sargasso containing epibionts having higher arsenic concentrations. These results provide comprehensive information to better understand the characteristics and potential origin of sargasso landings in South Florida.

Keywords: sargasso; pelagic *Sargassum*; morphotypes; biomass; nutrient content; heavy metals; inorganic mass fraction; arsenic

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Citation: Hatt, D.C.; Bally, N.K.; Iporac, L.A.R.; Olszak, S.; Campbell, J.E.; Collado-Vides, L. Comprehensive Analysis of Biomass, Nutrient, and Heavy Metal Contributions of Pelagic *Sargassum* Species (Phaeophyceae) Inundations in South Florida. *Phycology* **2024**, *4*, 235–255. https://doi.org/10.3390/phycology4020013

Academic Editor: John James Milledge

Received: 22 February 2024
Revised: 13 April 2024
Accepted: 16 April 2024
Published: 20 April 2024

1. Introduction

The genus *Sargassum* C. Agardh (Phaeophyceae, Fucales), considered the most species-rich genus in the class Phaeophyceae, contains approximately 359 species [1] and has caused many blooms and influx events in different regions around the world. For example, *S. horneri* (Turner) C. Agardh has been observed proliferating and detaching to form floating mats in the Yellow Sea [2]. In the Western Tropical Atlantic, the holopelagic species *Sargassum fluitans* (Borgesen) Borgesen and *Sargassum natans* (Linnaeus) Gaillon, with the three morphotypes described by Parr (1939) [3]: *S. fluitans* III, S. natans I, and *S. natans* VIII, comprise the massive equatorial Atlantic bloom [4]. Three morphotypes composing the holopelagic *Sargassum* spp. community will be referred to collectively as "sargasso" to distinguish from other benthic species within the genus.

Low-biomass landings of sargasso are a beneficial subsidy to coastal environments by providing habitat for terrestrial arthropods and increasing nutrient availability to terrestrial plants [5,6]. However, high accumulations and subsequent decomposition produce a "brown tide" by releasing colored dissolved organic matter, increasing light attenuation while decreasing pH and oxygen levels and degrading water quality via increased ammonium and leaching of heavy metal contaminants [7–9]. These sargasso brown tides promote anoxic conditions that can alter benthic macrophyte composition and reduce faunal diversity via mass mortality in coastal communities [7,10]. The increase in abundance and frequency of sargasso on shorelines and associated "brown tide" events can cause ecological, economical, sociopolitical, and human health problems [11–13]. Estimating the biomass, nutrients, and heavy metal content of these sargasso accumulations is important to understand their impact and design effective management strategies.

Given the dynamic nature of sargasso accumulations, efforts estimating their influxes and landings onto shorelines have varied in geographical scope and resolution [14–16]. Monitoring efforts of sargasso primarily utilize high-resolution satellite imagery to cover a large spatial area [17–19], yet they are limited in resolution at the nearshore, local scale where sargasso brown tide effects often occur. In contrast, local-scale monitoring methods can ground truth satellite imagery by providing a finer-scale estimate of biomass [15,16,20]. In situ monitoring can also capture variations in morphotype composition, which can have implications for estimating nearshore impacts via inputs of nutrient and metal contents and associated epibionts onto the coastal area [21,22].

One factor that might contribute to seasonal sargasso influxes is the global increase in nutrient input to oceanic areas, especially nitrogen, as deforestation and increased fertilizer use with upwelling along coastlines may be stimulating sargasso growth [10,21,23]. Large sargasso mats found in the open ocean, especially in oligotrophic waters like the Sargasso Sea, may be sustained by fish excretion, upwelling, and nitrogen fixation [24]. Areas with a high input of agricultural runoff, such as the Amazon River and Mississippi River, compounded by upwelling and input from terrestrial flood and hurricane damage, may be sustaining the GASB across the Tropical Atlantic region and the Gulf of Mexico, respectively [10]. An increase in nitrogen availability within marine systems has been linked to a 35% nitrogen tissue content increase observed in sargasso across the Atlantic region. However, individuals in the GASB have a higher nitrogen and phosphorus content, which is easily distinguishable from individuals in the Sargasso Sea [21,24–26].

Sargasso contains high concentrations of leachates, like heavy metals or other compounds with allelopathic properties, which have been reported to have negative impacts on coastal ecosystems such as coral reefs, particularly via decomposition [27,28]. Studies across the Caribbean and West Africa suggest that both sargasso collected in the open ocean and beaches have high levels of toxic pollutants, particularly arsenic [13,29,30]. Both acute and chronic exposure of high levels of arsenic can cause health issues in humans, such as skin lesions, cardiovascular disease, neurological and reproductive issues, developmental abnormalities, and a variety of cancers [31,32]. Inorganic forms of arsenic, AsIII and AsV, are more toxic than organic forms and account for an average of 62% of total arsenic found in sargasso tissue in Barbados [33]. These high concentrations of arsenic in sargasso tissue can pose a risk for the use of sargasso biomass for valorization after harvest from shorelines.

The proximity and connectivity of South Florida to the North Atlantic Gyre via both the Florida Current and the Gulf Stream and wind patterns sustain sargasso landings in South Florida [26,34]. In 2011, when sargasso biomass dramatically increased in the Atlantic, while the tropical Atlantic and West Africa was being inundated with a high biomass of sargasso, the Gulf Stream and consequently the North Atlantic and Gulf of Mexico regions received minimal sargasso biomass [17,34]. In Florida, the peak season for sargasso landings is usually between May and July with generally lower accumulations as compared to the tropical Atlantic region [16]. Studies quantifying the landings of sargasso in South Florida are scarce. This study aims to analyze potential impacts of sargasso landing on South Florida by 1. monitoring biomass and morphotype composition at sargasso-affected sites, 2. comparing organic to inorganic mass fraction ratios contributed by sargasso and associated epibionts, 3. determining spatiotemporal patterns in nutrient tissue content, 4. quantifying heavy metals concentrations from the tissue of sargasso, and 5. comparing total arsenic concentrations of sargasso in clean versus unclean samples.

2. Materials and Methods

2.1. Study Area

Sargasso was collected from three sites within South Florida located at the northern limits of the distribution of sargasso influenced by the GASB: Dr. Von D. Mizell-Eula Johnson State Park at Dania Beach (referred to as "Dania Beach" hereafter), North Crandon Park (referred to as "Crandon Park" hereafter) and Bill Baggs Cape State Park (referred to as "Bill Baggs" hereafter; Figure 1). These sites were selected based on the limited removal of landed sargasso by local management. Dania Beach (26.0523° N, 80.1439° W), the northernmost site, is located in Broward and influenced by the Gulf Stream running parallel to the open beach [35]. Crandon Park (25.7094° N, 80.1562° W) and Bill Baggs (25.6755° N, 80.1603° W) are located south of Dania Beach on a barrier island along Key Biscayne in Miami. Both sites are along the northern areas of Biscayne Bay, a coastal lagoon characterized by shallow seagrass systems. Crandon Park, located on the northern part of the barrier island, has limited wave action in its shallow waters given the shallow nearshore floor and wind currents perpendicular to the shore [36]. Bill Baggs, our most southern site, contains high current velocity given the proximal transition between the Atlantic Ocean and Biscayne Bay [37].

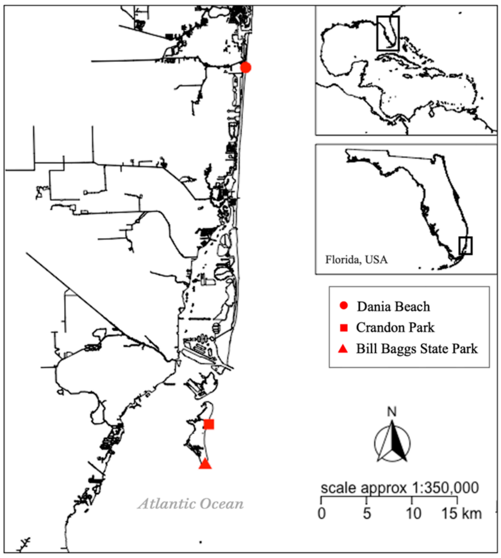

Figure 1. Map of Florida, USA, and three sites surveyed in South Florida: Dania Beach, Crandon Park, and Bill Baggs.

2.2. Biomass

Biomass surveys were conducted at Dania Beach from September 2018 to December 2022 and at Crandon Park from January to December 2022 (Table S1). Surveys of landed biomass at Dania beach began as a pilot program to engage undergraduate volunteers to attempt to track the seasonality of sargasso landings in South Florida in September 2018 with morphotype distinctions added to surveys starting a month later in October 2018. Due to logistical constraints regarding beach access, volunteers were dispatched once a month when sargasso landings were reported by management. In some instances, limited availability of personnel resulted in missed surveys. Thus, while sporadic in its landings along South Florida coastlines, the absence of sargasso at Dania Beach cannot be distinguished and quantified for the months not documented. Further logistical issues arose from 2020 to 2021 due to COVID-19 restrictions and beach closures. To standardize reporting, despite conducting surveys at Dania Beach until December 2022, surveys were only reported for the months in which sargasso landings were present on the day of survey, and the remaining months were excluded. In response to the limitations to beach access and volunteers at Dania beach, we adjusted our survey protocols based on these experiences. Subsequently, in 2022, following the lifting of COVID-19 restrictions, we aimed to systematically survey Crandon Park. Its closer proximity and similar management approach towards sargasso landings allowed for monthly surveys to quantify the presence and absence of sargasso landings with the specific intent of depicting the seasonality of fresh sargasso landings. At this site, the absence of fresh sargasso landings (golden color) was reported as a zero. Surveys at both sites were restricted to once a month throughout 2022 due to limited resources; therefore, intra-monthly variations in sargasso landings during the surveyed period could not be determined in this study.

For each survey, four 1.0 m^2 quadrats were sampled (with a minimum separation of 250 m) along a 1.0 km transect at low tide, ensuring only fresh sargasso was collected. Following the fresh sargasso wrack line that washed in with the previous high tide, the quadrat was placed at the top of the wrack, and all sargasso present within the quadrat were obtained and weighted in situ to estimate a total wet weight (g). If this wet weight was too large to transport, a subsample was collected using two gallon-sized Ziploc bags (26.8 cm $\times$ 27.3 cm). Each collection was labeled and stored in a cooler with ice to transport back to the laboratory for later processing. These methods were adapted from similar sampling techniques conducted by García-Sánchez et al. (2020) [15] and Torres-Conde et al. (2023) [38] and adapted for the length of the beaches observed. This allowed our estimates to be comparable to other areas of the Caribbean. Each collection of sargasso was separated at the morphotype level based on Parr (1939) [3] and Wrinn et al. (2016) [39] to determine the morphotype composition of landings during that survey. Separated morphotypes were washed to remove debris and sand, placed into a salad spinner for 60 s to remove excess water, and weighed to obtain a laboratory wet weight (g). Samples were dried for a minimum of 48 h at 60 °C for subsequent dry weight measurements to 0.001 g accuracy.

2.3. Volunteer-Contributed Monitoring of Morphotypes

Determination of the composition of morphotype landings at Dania Beach associated with the biomass surveys described previously were limited to once a month. Data collected daily from the "Sargassum Watch" Citizen Science Program were utilized as a complement to our biomass surveys [16]. Previous use of volunteer-contributed data examined accumulation levels of sargasso at Dania Beach; however, monitoring of sargasso morphotype composition at Dania Beach remained underutilized. Data from this program contained daily photographs taken by citizen science volunteers to depict sargasso landings and associated morphotypes found at Dania Beach using the Epicollect5 app [40]. Once uploaded to the database, photos of morphotypes were examined to quantify the presence of any of the three morphotypes. To standardize comparison of morphotype composition obtained from photos with in situ collections described previously, only observations with sargasso present were used for subsequent analyses.

2.4. Nutrient Content

Three fresh individual thalli for each morphotype of sargasso were collected by hand from newly arrived patches floating on the surface of the water in the intertidal region at each of the three sites from 2018 to 2021 (Table S1). These collections were made once a month and independently of biomass surveys described previously. Morphotypes were separated and placed into individually labeled quart size Ziploc bags (17.7 cm $\times$ 18.8 cm) and stored in an ice cooler for transport to the laboratory. Each sample was thoroughly cleaned to remove epibionts and debris. Cleaned samples were dried for 48 h at 60 °C, then ground in a stainless steel mortar. Samples were analyzed by the Blue Carbon Analysis Lab at Florida International University. Carbon and nitrogen tissue contents were estimated using a CHN analyzer (Thermo Scientific CE FlashEA 1112 Elemental Analyzer, Waltham, MA, USA). Phosphorous tissue content was estimated using a dry-oxidation-acid hydrolysis extraction followed by a modified colorimetric analysis using a UV-2101 Shimadzu Spectrophotometer (Kyoto, Japan) [41].

2.5. Organic versus Inorganic Mass Fraction

A portion of thalli from each quadrat previously dried to estimate biomass landings at Dania Beach and Crandon Park were used to assess the organic and inorganic mass fractions of sargasso with their associated epibionts (Table S1). For each quadrat containing sufficient biomass, three replicates of each morphotype were used. A portion of dried thalli previously collected and cleaned for tissue nutrient analysis was used to obtain three replicates of each morphotype to assess the organic and inorganic mass fraction of sargasso without associated epibionts. All samples were analyzed using the loss on ignition method [42]. The total dry weight before ignition was subtracted from the mass of ash after ignition and was used as a proxy of organic mass associated with the thalli.

2.6. Heavy Metals

Fresh thalli for each morphotype of sargasso were collected with disposable nitrile gloves using a similar protocol for tissue nutrient content samples described above. These collections were made once a month and independently of biomass surveys and collections of sargasso for nutrient content analysis. Each collection of sargasso made for elemental analysis was placed into plastic bags to avoid potential metal contamination. Collections were made at each of the three sites from 2020 to 2021 (Table S1). Following the commonly used methodology for sargasso, samples collected during this period were sorted at the morphotype level but were not cleaned of any epibionts before being dried at 60 °C and ground using a marble mortar (these samples are called "uncleaned" samples hereafter). This is typically carried out to determine the potential contamination and heavy metal contributions of sargasso that has been washed ashore or collected directly from the ocean. To distinguish between the contributions made by sargasso from its epibionts, dried thalli, previously collected and cleaned of epibionts for nutrient analysis, were used to estimate arsenic tissue concentrations to compare to the field collections made previously (samples noted as "cleaned" samples hereafter for comparison to uncleaned samples). All samples were analyzed using acid digestion (EPA 3050B), and the concentrations of 16 elements (Ag (limit of detection, LOD = 0.01), As (0.25), Ba (0.30), Be (0.03), Cd (0.00), Co (0.01), Cr (1.37), Cu (0.23), Hg (0.07), Mn (0.14), Mo (0.11), Ni (0.09), Pb (0.19), Se (0.09), V (1.08), Zn (0.63)) were measured using inductively coupled plasma mass spectrometry (ICP-MS) analysis (EPA 6020A) at the CREST-CAChE Nutrient Analysis Core Facility at Florida International University.

2.7. Data Analysis

Data were tested for normality (Shapiro–Wilk) and homoscedasticity (Levene's test). If the data violated the parametric assumptions, or if the sample size was too small, non-parametric analysis was used.

Dry weight biomass of sargasso was compared across sampling times at Dania Beach and Crandon Park separately using the Kruskal–Wallis non-parametric test due to the small sample size ($n = 4$). The presence or absence of morphotypes using citizen science observations were calculated to normalized relative frequency (R) using the following equation by Iporac et al. (2022) [16]:

$$R_m = F_m / N, \quad (1)$$

where F is the number of instances where morphotype m was present per total number of observations per month, N. This modified relative frequency is designed to account for multiple morphotypes occurring within the same observation, as was previously noted by geographic locality [16] and over multiple sargasso seasons [15]. A chi-square test was conducted on the normalized frequency data to test for goodness of fit of the observed versus expected frequency of morphotypes. Two chi-square models were tested: One chi-square model was divided by sampling month with a total of 23 months from 2019 to 2021 to test for monthly variations in morphotype composition. Another chi-square model was divided by year to test for interannual differences in morphotype composition, regardless of sampling month.

To test differences in the tissue nutrient content and nutrient molar ratios spatially, temporally, or across morphotypes of sargasso, a one-factor ANOVA was used. Post hoc analysis with Tukey HSD (=0.05) was conducted to assess differences across sites, years, and morphotypes. When data violated normal distribution assumptions, the Kruskal–Wallis or Mann–Whitney non-parametric tests were used to determine significant differences in tissue nutrient content across morphotypes and sites. When significance was detected with non-parametric analyses, post hoc comparisons (=0.05) were carried out using the Dunn test. Differences in the average proportion of organic to inorganic mass fraction across morphotypes in samples with and without associated epibionts were tested using the Kruskal–Wallis non-parametric test.

Sixteen elements (Ag, As, Ba, Be, Cd, Co, Cr, Cu, Hg, Mn, Mo, Ni, Pb, Se, V, Zn) were analyzed for spatial, temporal, and morphotype differences across each elemental concentration. Each element was tested using a one-factor ANOVA followed by post hoc comparisons using the Tukey HSD. If certain elements failed the assumptions, the Kruskal–Wallis non-parametric test was used. In addition, cleaned and uncleaned samples were compared to determine the significance of epibionts to arsenic concentration of sargasso (Mann–Whitney non-parametric test). All statistical analyses were conducted using the packages dplyr, ggplot2, FSA, and vegan in R and RStudio program version 4.1.1 [43].

3. Results

3.1. Biomass

The contribution of sargasso at Dania Beach was variable throughout the sampled months (Figure 2A), with the lowest median value of dry biomass (13.3 g m^{-2}) in March 2019 and the highest median value of dry biomass (784.52 g m^{-2}) in July 2022 (Figure 2A). Across all sampling dates, only the March 2019 collection was statistically distinct as compared to the July 2022 collection (Kruskal–Wallis; $p < 0.05$, Table S2).

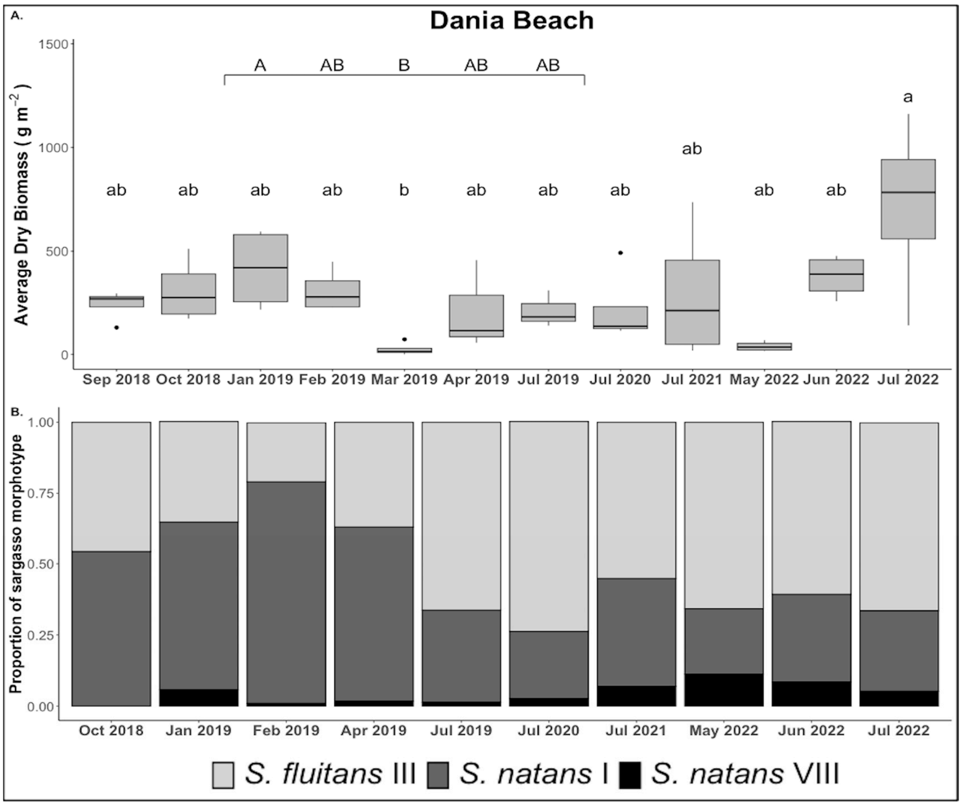

Figure 2. *Cont.*

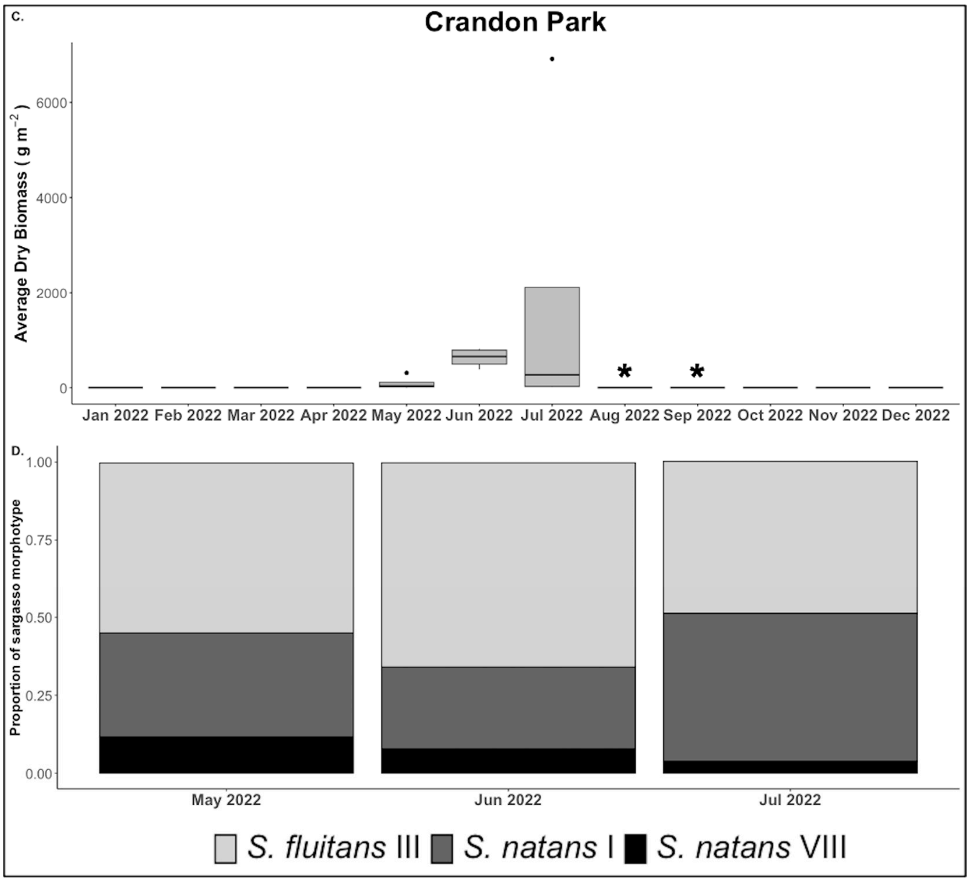

Figure 2. (**A**) Box and whisker plots showing dry weight of sargasso biomass landings collected from Dania Beach from September 2018 through July 2022. Surveyed months at Dania Beach contain one survey (N = 4) and were shown only when sargasso was present and volunteer surveys were successfully conducted. The horizontal bar within the box represents the median, the upper and lower boundaries of the box represent the lower and upper quartile, and the whiskers represent the extreme values; circles are the outliers. Different common letters indicate post hoc analysis (Dunn test) when dry biomass differed across sampling times, while capital letters indicate post hoc analysis (Dunn test) for sampling times across 2019 only. (**B**) Proportion of dry weight of biomass of each morphotype of sargasso collected from Dania Beach. Surveys for morphotype distinctions at this site began in October 2018 and were conducted for each subsequent biomass sampling. (**C**) Box and whisker plot showing dry weight of sargasso biomass collected from Crandon Park from January 2022 to December 2022. Surveys were conducted every month regardless of the presence of sargasso to show seasonality at Crandon Park. Horizontal lines represent no sargasso present. Asterisks (*) indicate dead sargasso with no new landings of fresh specimen present on the shoreline. These surveys were reported as no sargasso present. The horizontal bar within the box represents the median, the upper and lower boundaries of the box represent the lower and upper quartile, and the whiskers represent the extreme values; circles are the outliers. (**D**) Proportion of dry weight of biomass of each morphotype of sargasso collected from Crandon Park.

Intra-annual differences were detected in 2019, the year with the most frequent sampling (Kruskal–Wallis; $p < 0.05$, Table S2). Comparing total biomass observed in the month of July over four years, July 2019 had a median biomass of 180.7 g m^{-2} (average 209.4 $\pm$ 51.88 g m^{-2}), July 2020 had a median of 135.5 g m^{-2} (average of 219.31 $\pm$ 91.21 g m^{-2}), July 2021 had a median of 211.6 g m^{-2} (average of 294.42 $\pm$ 166.41 g m^{-2}), and July 2022 had a median of 783.8 g m^{-2} (average of 717.52 $\pm$ 214.74 g m^{-2}). Biomass values reported for the month of July across these years were not statistically different (Kruskal–Wallis; $p = 0.268$, Table S2). *S. natans* I was the most abundant morphotype landing on Dania Beach until July 2019, when *S. fluitans* III was observed as most abundant (Figure 2B). *S. fluitans* III was also most abundant in samplings from July 2020 and 2021. Throughout all sampled times, *S. natans* VIII was the least abundant morphotype.

In 2022, the year Crandon Park biomass surveys were conducted, sargasso accumulations on shorelines occurred from May to July, with the lowest median value of dry biomass of 33.4 g m^{-2} reported in May (average 94.3 g m^{-2}). The peak of sargasso arrival at Crandon Park in 2022 was observed in July, with the highest median of 271.4 g m^{-2} (average 1868.9 g m^{-2}) estimated on the shoreline. There were no intra-annual differences detected among sampling times at Crandon Park (Kruskal–Wallis; $p = 0.098$; Table S2). Comparing sargasso landings at Crandon Park and Dania Beach in July 2022, Crandon Park received a higher median biomass with higher variation (ranging from 21.8 g m^{-2} to 6912.2 g m^{-2}) in the biomass landings than the amount on the Dania Beach shorelines (Figure 2C). Similar to Dania Beach, *S. fluitans* III was observed as the most abundant morphotype and *S. natans* VIII the least abundant morphotype landing at Crandon Park (Figure 2D). At both Dania Beach and Crandon Park, a strong linear relationship was detected between wet biomass and dry biomass of processed sargasso samples ($R^2 = 0.96$, $p < 0.05$, Figure S1).

3.2. Volunteer-Contributed Monitoring of Morphotypes

Most months sampled through community-contributed photos at Dania Beach demonstrated *S. fluitans* III as the most dominant morphotype found (Figure 3). The morphotype composition did not seem to be dependent on sampling month, χ^2 (44, N = 206) = 418.0, $p = 0.13$. However, the composition of sargasso morphotypes varied by year, χ^2 (4, N = 206) = 418.0, $p < 0.001$. The 2019 sargasso season observed a higher-than-expected frequency of *S. natans* I, while the 2021 season observed a lower-than-expected frequency of *S. natans* I and higher-than-expected frequency of *S. natans* VIII (Figure S2).

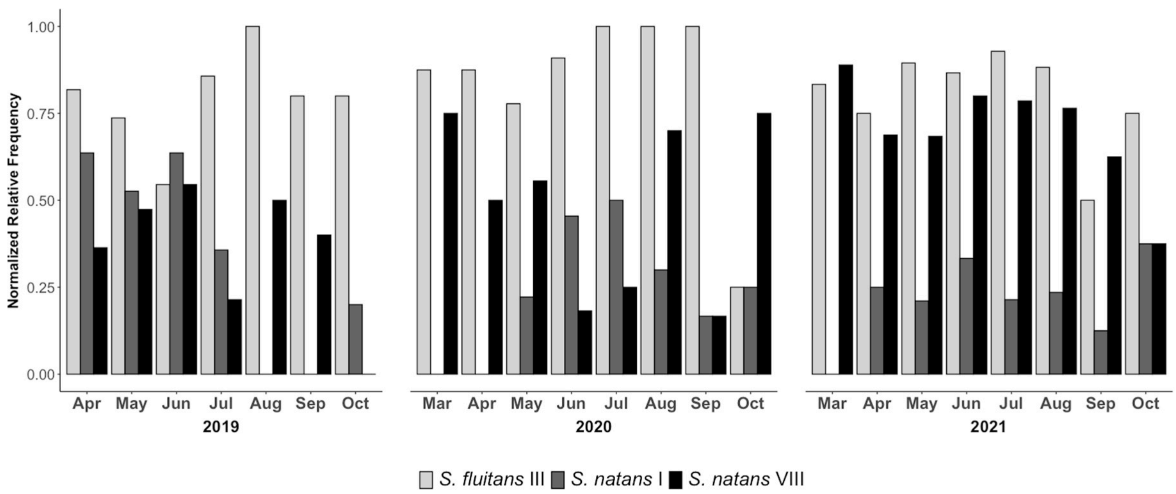

Figure 3. Normalized relative frequency of sargasso morphotypes present at Dania Beach from 2019 to 2021 using citizen science observations from "*Sargassum* Watch".

3.3. Nutrient Content

Carbon, nitrogen, and phosphorus tissue concentrations were not significantly different among morphotypes (Kruskal–Wallis; $p = 0.111$; ANOVA, $F_{2,93} = 2.9$, $p = 0.062$; ANOVA, $F_{2,93} = 1.7$, $p = 0.184$, respectively; Table S3). From these results, morphotypes were grouped together in subsequent analyses for general comparisons of sargasso nutrient content among sites and sampling dates (Figures 4, S3, and S4). Previously published average values for nutrient contents of macroalgae, benthic *Sargassum*, and sargasso from other regions are presented in each figure for reference. There were no statistical differences observed for C:N and C:P ratios among morphotypes (ANOVA, $F_{2,93} = 2.8$, $p = 0.066$; ANOVA, $F_{2,93} = 2.3$, $p = 0.102$, respectively; Table S3); however, there was a difference in N:P ratio among morphotypes (ANOVA, $F_{2,93}$= 4.4, $p < 0.05$; Table S3), with *S. fluitans* III being almost 1.5 times higher than *S. natans* VIII. The average values obtained for tissue nutrient content and tissue C:N:P ratios of sargasso observed in South Florida are shown in Table S4.

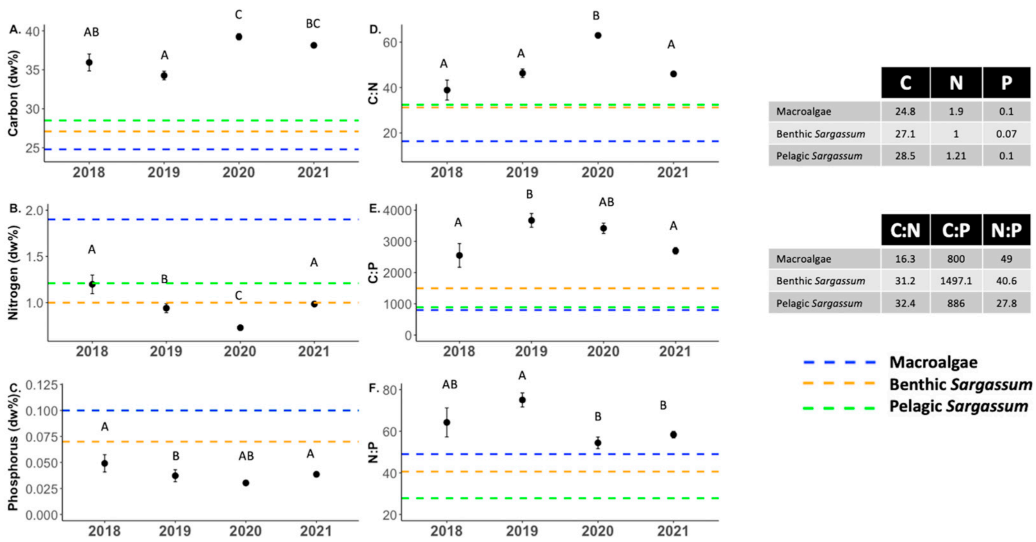

Figure 4. (**A**–**C**) Annual average carbon, nitrogen, and phosphorus tissue contents of sargasso and (**D**–**F**) annual average carbon, nitrogen, and phosphorus molar ratios of sargasso collected at all three sites from 2018 to 2021. The black dots represent this study, with error bars indicating standard error of the mean (SEM). The blue dashed line represents the average nutrient content value for macroalgae reported by Duarte in 1992 [44]. The orange dotted line represents the average nutrient content value for benthic *Sargassum* obtained by averaging published values of nutrient content for *Sargassum* spp. [45–47]. The green dashed line represents the average nutrient content value for sargasso reported by Lapointe et al. 2021 [21]. The green dashed line in panel (**C**) is overlapping with the value reported by the blue dashed line for macroalgae. Different letters indicate post hoc analyses (Dunn test) when nutrient content differed among years.

When pooled across all sites, carbon, nitrogen, and phosphorus concentrations were statistically different from 2018 to 2022 (Kruskal–Wallis; $p < 0.001$), with sargasso arriving in 2020 having the highest carbon content and lowest nitrogen and phosphorus contents (Figure 4). At Dania Beach, the site measured annually from 2019 to 2021, there were significant temporal differences in the nutrient contents and nutrient ratios (Kruskal–Wallis; $p < 0.001$ for all). Carbon, nitrogen, and phosphorus tissue contents reported in 2019 at Dania Beach were significantly different from the nutrient contents observed at the same site in 2020 and 2021 (Figure S3). In 2019 and 2021, all three sites were surveyed to determine spatial differences in sargasso nutrient contents. In 2019, there were no statistical differences in carbon and nitrogen across sites (Kruskal–Wallis; $p = 0.069$ and $p = 0.192$, respectively), however, there was a difference in the phosphorus content (Kruskal–Wallis; $p < 0.01$) of sargasso between Crandon Park and Bill Baggs, while both sites had similar values to Dania Beach. In 2021, there was no difference in tissue nutrient content (Kruskal–Wallis; $p = 0.077$, $p = 0.520$, and $p = 0.123$) or nutrient ratios (Kruskal–Wallis; $p = 0.104$, Kruskal–Wallis; $p = 0.111$, Kruskal–Wallis; $p = 0.382$, respectively) across sites (Figure S4).

3.4. Organic versus Inorganic Mass Fraction

Among sargasso morphotypes, there were no statistical differences in the proportion of inorganic to organic mass fraction among sargasso morphotypes for cleaned (Kruskal–Wallis; $p = 0.4413$) and uncleaned samples (Kruskal–Wallis; $p = 0.4577$). However, the proportion of inorganic mass was higher in uncleaned samples of sargasso compared to cleaned samples of sargasso (Kruskal–Wallis; $p < 0.001$) (Figure 5). A strong linear relationship between organic and inorganic mass was observed among clean and unclean samples of sargasso with equal proportions (Figure S5).

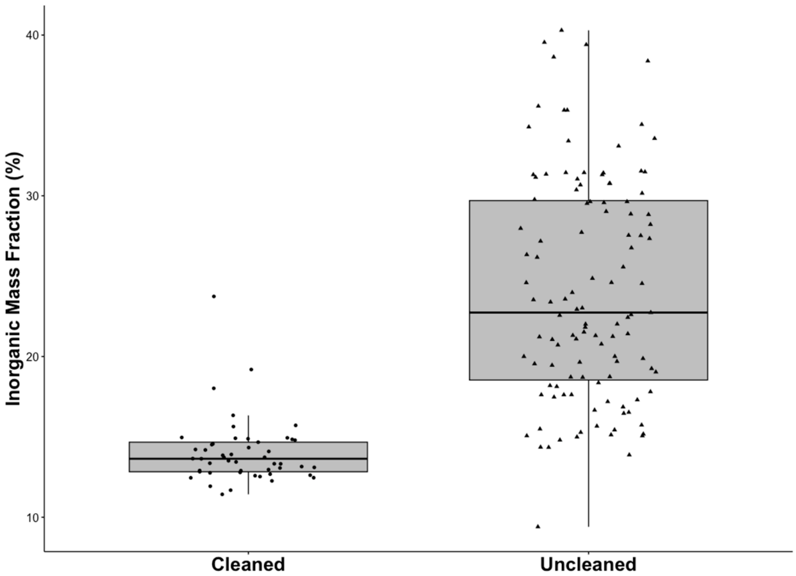

Figure 5. Box and whisker plot showing percent of inorganic mass fraction of cleaned sargasso to remove associated epibionts versus uncleaned samples of sargasso to include all associated epibionts collected from all three sites from 2019 to 2022. The horizontal bar within the box represents the median, the upper and lower boundaries of the box represent the lower and upper quartile, and the whiskers represent the extreme values. Circles indicate each thalli of sargasso analyzed with all associated epibionts removed, while triangles indicate sargasso thalli analyzed with epibionts attached. Statistical analyses (Mann–Whitney) showed differences across inorganic mass fraction of cleaned versus uncleaned samples of sargasso ($p < 0.001$).

3.5. Heavy Metals

All 16 metals tested were present in sargasso tissue during our sampling, with As, Ba, Cd, Co, Mn, Ni, and Se detected above the LOD in 100% of the samples. Five other metals were present above LOD in more than 50% of the samples tested: Zn (96%), Cu (95%), Mo (80%), Pb (51%), and V (57%). The remaining four metals, Ag, Be, Cr, and Hg, were found above the LOD in less than 10% of the samples. Seven metals were detected in samples but below the LOD: Ag (4%), Be (50%), Cr (97%), Hg (37%), Mo (20%), Pb (49%), and V (41%). Be was the only element consistently under the LOD in all samples. Ag, Be, and Hg were not detected in 88%, 50%, and 60% of the samples, respectively. Cu, V, and Zn were the other metals not detected in less than 5% of the samples tested.

From the elements observed, the seven found with the highest concentration in sargasso tissue were As > Ba > Mn > Zn > Cu > Ni > V (Figure 6). All three morphotypes of sargasso contained no statistically significant differences in the quantities of heavy metal concentrations accumulated in their tissue (ANOVA, $F_{2,885} = 0.166$, $p = 0.847$). As was found to be the element with the highest concentration consistently across all morphotypes. Concentrations of Ag, As, Cd, Co, Mn, Mo, and Se varied across morphotypes (Table 1). There was spatial variation in the concentrations of As, Cd, Cr, and Mo in sargasso tissue observed between Dania Beach and Crandon Park in May 2021 (ANOVA, $F_{1,16} = 13.16$, $p < 0.01$; $F_{1,16} = 11.42$, $p < 0.01$; $F_{1,16} = 5.15$, $p < 0.05$; and $F_{1,16} = 20.92$, $p < 0.001$, respectively; Table S5). In June 2021, there was spatial variation in Ba, Cd, Cu, Ni, Se, V, and Zn concentrations between Dania Beach and Bill Baggs (Kruskal–Wallis; $p < 0.01$; ANOVA, $F_{1,15} = 12.26$, $p < 0.01$; $F_{1,15} = 9.644$, $p < 0.01$; $F_{1,15} = 5.25$, $p < 0.05$; $F_{1,15} = 13.43$, $p < 0.01$; Kruskal–Wallis, $p < 0.01$; and ANOVA, $F_{1,15} = 5.77$, $p < 0.05$, respectively; Table S5). At Dania Beach, the site measured the most frequently, there was temporal variation in the concentrations of Ba, Cd, Co, Cr, Mo, Se, and Zn (Table S5).

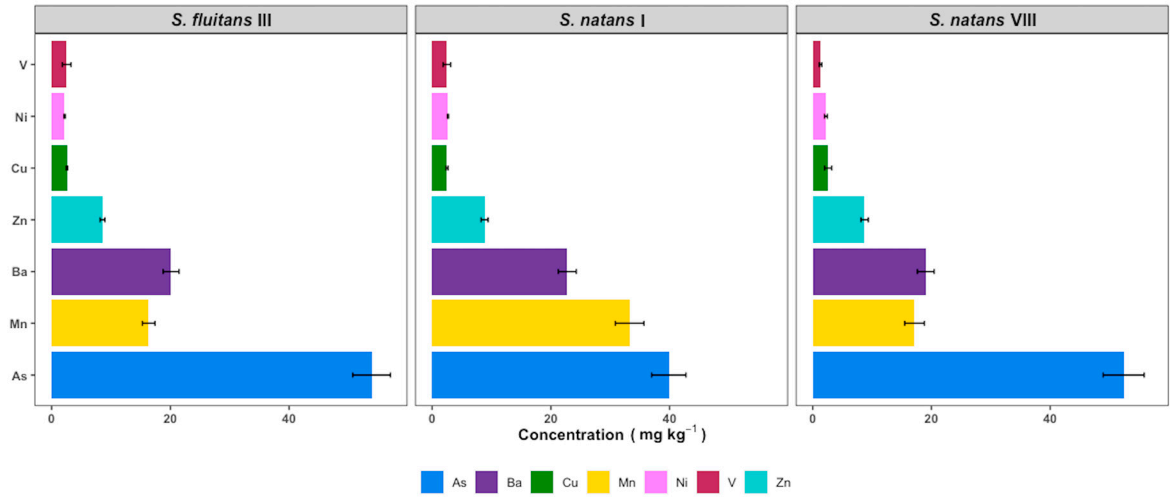

Figure 6. Element concentrations of sargasso collected at all three sites sorted from lowest to highest average elemental concentrations separated by morphotype: *S. fluitans* III, *S. natans* I, and *S. natans* VIII. Error bars indicate standard error of the mean (SEM).

Table 1. Average element concentrations and ranges (max.–min.; in parentheses) of each sargasso morphotype collected from three sites in South Florida from 2020 to 2021 reported in mg kg^{-1} dw. ND indicates that the element was not detected. *p*-values demonstrate the summary of statistical analyses using ANOVA or Kruskal–Wallis, and post hoc analysis is shown in the last column.

Element	Limit of Detection (LOD)	(a) *S. fluitans* III	(b) *S. natans* I	(c) *S. natans* VIII	*p*-Value	Multiple Comparison Test
Ag	0.01	ND	0.47 (0.5–0.5)	0.06 (<LOD–0.1)	**0.0243**	b > c
As	0.25	53.90 (28.8–80.1)	39.86 (15.1–59.0)	52.38 (34.9–83.4)	**0.0047**	(a=c) > b
Ba	0.30	20.11 (14.7–34.4)	22.75 (32.7–42.6)	19.04 (9.8–33.6)	0.177	
Be	0.03	0.00 (<LOD)	0.00 (<LOD)	0.00 (<LOD)	0.1990	
Cd	0.00	0.43 (0.3–0.6)	0.50 (0.3–0.8)	0.34 (0.3–0.5)	**<0.001**	(a=b) > c
Co	0.01	0.60 (0.5–0.8)	0.66 (0.5–0.9)	0.41 (0.3–0.7)	**<0.001**	(a=b) > c
Cr	1.37	0.40 (0.1–0.9)	0.50 (<LOD–1.5)	0.47 (<LOD–2.9)	0.7160	
Cu	0.23	2.58 (<LOD–3.6)	2.51 (1.2–4.3)	2.60 (1.0–14.4)	0.9850	
Hg	0.07	0.00 (<LOD)	0.01 (<LOD)	0.00 (<LOD)	0.644	
Mn	0.14	16.36 (9.9–25.3)	33.28 (16.2–53.0)	17.16 (7.1–30.8)	**<0.001**	b > c > a
Mo	0.11	0.14 (0.1–0.3)	0.19 (0.1–0.4)	0.12 (0.1–0.2)	**<0.001**	b > (a = c)
Ni	0.09	2.17 (1.3–3.2)	2.65 (1.8–3.6)	2.23 (0.8–5.4)	0.0991	

Table 1. *Cont.*

Element	Limit of Detection (LOD)	(a) *S. fluitans* III	(b) *S. natans* I	(c) *S. natans* VIII	*p*-Value	Multiple Comparison Test
Pb	0.19	0.19 (0.1–0.4)	0.26 (0.1–0.5)	0.24 (0.1–1.1)	0.266	
Se	0.09	0.74 (<LOD–1.2)	0.83 (0.5–1.1)	0.55 (0.2–0.9)	**<0.001**	(a = b) > c
V	1.08	2.54 (<LOD–13.6)	2.47 (0.7–11.2)	1.33 (<LOD–4.5)	0.2830	
Zn	0.63	8.56 (5.5–12.0)	8.83 (4.6–14.8)	8.75 (4.2–15.5)	0.9360	

Significant differences are indicated in bold. Post hoc results for one-way ANOVA were determined by a Tukey (HSD) test ($\alpha = 0.05$), and results for Kruskal–Wallis were determined using a Dunn test ($\alpha = 0.05$).

Eight of the metals observed (As, Cu, Co, Mn, Mo, Pb, Ni, Zn) in more than 50% of the samples were potentially toxic above a certain threshold concentration. The concentration of As in 70% of the samples was above the maximum allowable limit for seaweed used as animal fodder under European regulations [48]. None of the other potentially toxic metals were found in sargasso tissue at a concentration above international acceptable limits (Table S6). There was no statistical difference in As concentration across sampling times within the same year (May to July 2021), but a temporal difference was detected between 2020 and 2021 at Dania Beach. Analysis of sargasso tissue containing epibionts and sargasso tissue with epibionts removed before analysis showed that the As concentration in uncleaned samples was significantly higher than in cleaned samples (Kruskal–Wallis; $p < 0.001$) (Figure 7). There were no statistically significant differences spatially or across morphotypes in both cleaned (Kruskal–Wallis; $p = 0.271$ and $p = 0.069$) and uncleaned samples (Kruskal–Wallis; $p = 0.0529$ and $p = 0.531$).

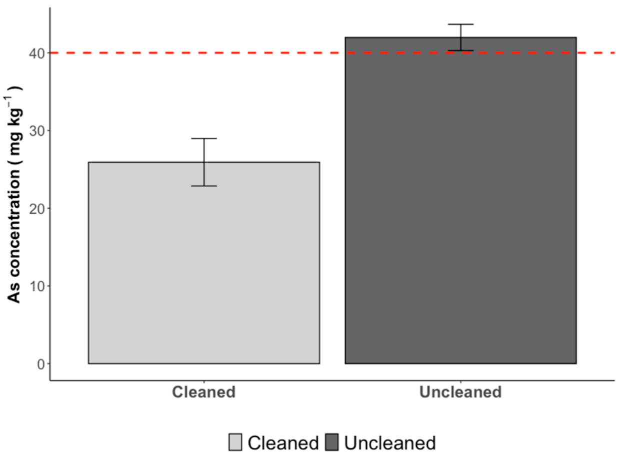

Figure 7. Average arsenic concentration of cleaned sargasso to remove associated epibionts versus uncleaned samples of sargasso to include all associated epibionts collected from all three sites in 2021. Error bars indicate standard error of the mean (SEM). The red dashed line represents the maximum limit for seaweed intended as animal fodder as reported in [13,48]. Statistical analyses (Mann–Whitney) showed differences across arsenic concentration of cleaned versus uncleaned samples of sargasso ($p < 0.001$).

4. Discussion

Long-term and regional-scaled monitoring efforts of sargasso over multiple locations are needed to detect variations in biomass accumulation among affected localities [16]. This is the case for South Florida, where biomass accumulations vary between Dania Beach and Crandon Park, with Crandon Park having extremely high variability across quadrats measured on the same day compared to biomass landings at Dania Beach within the same month (Figure 2). These large site variations may be due to both differences in the pelagic nature of sargasso morphotypes and differences in topography and hydrodynamic processes occurring at each beach. Comparing Dania Beach to the Mexican Caribbean from 2018 to 2019, the Mexican Caribbean can receive anywhere between two to 18 times the amount of dry biomass onshore as Dania Beach within the same week [15]. However, similarly monitored months (May 2019, July 2020, and May 2021) in northwest Cuba from 2019 to 2021 noted no biomass available for collection [38]. Future standardized monitoring efforts, particularly with a high temporal resolution, are needed for a truly rigorous comparison of accumulation differences across regions. Distance from the GASB and local conditions in wave and wind patterns can all have an influence on the distribution and abundance of biomass among localities across the tropical Atlantic [18,49,50]. South Florida obtaining a comparatively lower biomass than the Mexican Caribbean is consistent with satellite imagery observations at a regional level [19]. However, with in situ biomass monitoring for this study, we were able to detect variations in biomass accumulations within South Florida that may not have been as easily detected with remote sensing. While Southeast Florida's main current is the Gulf Stream that runs parallel to the shoreline, other smaller currents can influence the variations in biomass between Crandon Park and Dania Beach [36]. Our study is a contribution at the in situ level providing ground-proof data for modelers and specific characteristics of sargasso arriving in South Florida for managers.

Morphotype composition was assessed in a single day through in situ biomass collections representing a month and through frequency collections by volunteers through a citizen science program. Both methods demonstrated *S. fluitans* III as the most dominant morphotype found washed ashore. Three sampling dates (July 2019, July 2020, and July 2021) shared both in situ biomass and volunteer-contributed frequency data of morphotypes; two of those three dates shared the same result of more *S. natans* I than *S. natans* VIII between citizen science and in situ biomass data. The sampling date with a disagreement in morphotype composition (July 2021) also had only one sampling date for the whole year, demonstrating more *S. natans* I than *S. natans* VIII. In contrast, the citizen science data demonstrated a higher *S. natans* VIII frequency than *S. natans* I throughout the 2021 sargasso season. This comparison between monitoring methods demonstrates how multiple methods are needed to cross-validate the information collected. While citizen science data can allow for more frequent collection and accumulation of morphotype data, the resolution can be lower than a more in-depth collection and comparison of in situ biomass as a measurement of abundance. Validation of morphotypes through photos requires training and protocols to recognize both the overall structure and minute details of sargasso, which is challenging considering the large amount and varying quality of photos uploaded [16].

The monitoring of morphotypes in Florida compared to the broader Caribbean demonstrates the variability in morphotypes based on seasonality and oceanographic conditions from sargasso source to landing site. Months with peak sargasso influxes (usually from May to August) showed that the compositions from Florida and the Caribbean are consistent with *S. fluitans* III as the most abundant morphotype, while off-season morphotype compositions varied across the Tropical Atlantic [15,38,51,52]. Morphotype composition associated with sargasso inundation events seemed to be dependent on the source of sargasso and the seasonality during the transport and landing of sargasso. Monitoring of sargasso and drifters from Barbados demonstrated two subregions within the GASB where landed sargasso could have originated; most months surveyed showed *S. fluitans* III as the abundant morphotype, although one month showed abundant *S. natans* VIII [52]. Northwest Cuba during the off-season months showed *S. natans* I as the most abundant morphotype, indicating that the sargasso landings were more similar to the sargasso composition found in the Sargasso Sea at the time of sampling, although the morphotype composition during the peak season months sampled was similar to other locations during the same peak season, likely sourced from the GASB [38]. During off-season sampling months in South

Florida (January–February 2019), abundant *S. natans* I could be indicative of sargasso from the Sargasso Sea, similar to Northwest Cuba the year after, while the Mexican Caribbean continued to have abundant *S. fluitans* III even after peak season months [15]. Florida's position relative to the GASB and the Gulf Stream are potential factors that can lead to similar morphotype compositions with the broader Caribbean during the peak season but differences during the off season. However, tracking the movement of sargasso from source to sink requires remote sensing and modeling of wind and water currents [52] and comparison of molecular markers of landed sargasso over different sargasso seasons and locations [28].

Carbon, nitrogen, and phosphorus content did not differ across morphotypes or spatially but showed temporal variations at Dania Beach (Figure 4). Despite distinct morphological, physiological, and genetic differences across sargasso morphotypes [39,53,54], the lack of differences in nutrient content across morphotypes in our study is similar to the lack of distinctions found between *S. fluitans* and *S. natans* (without morphotype distinction) in studies conducted by Lapointe et al. (2021) [21] and McGillicuddy et al. (2023) [26]. However, Changeux et al. (2023) [55] reported local variations of %N across morphotypes sampled in the Mexican Caribbean region. The lack of differences across morphotypes in our study could be due to the short geographic distance between samples compared with studies whose sample designs had extensive areas, such as oceans and shorelines. There was also no spatial variation in nutrient content (CNP) values at our sites despite spatial variations in %C of sargasso reported by Vasquez-Delfin et al. (2021) [56] in the Mexican Caribbean region. These differences in local variations spatially and across morphotypes in the Mexican Caribbean region could be due to differences in origin and travel pathways of sargasso landings in South Florida, mainly impacted by the Gulf Stream rather than the North Equatorial Recirculation Region that would affect the tropical Atlantic [34,52]. The temporal variation in nutrient contents of sargasso arriving at Dania Beach from 2018 to 2021 (Figure 4) can be attributed to the high annual variability in biomass and origin of sargasso mentioned above. The highest nitrogen and phosphorus contents were observed in 2018 and 2021, which corresponds to the two years considered to have major sargasso events across the entire Atlantic region.

The carbon content across the species of the genus *Sargassum* is highly variable, ranging from 15 to 37% [57]. The values of carbon within our study fell within this range but had much higher %C (36.2) and lower %N (0.97) and %P (0.04) content compared to macroalgae [44], published values for benthic *Sargassum* in the Atlantic region [45–47], sargasso from the north Atlantic region [21], sargasso from the north Sargasso Sea [26] and sargasso reported in the Mexican Caribbean [54,55]. The CNP values in this study were consistently similar to CNP values of sargasso reported in the south Sargasso Sea [26], with our study having higher %C values, suggesting that sargasso landings in South Florida may be dominated by individuals originating from the Sargasso Sea rather than the GASB. Our study reported the highest %C values of other published values for sargasso. Carbon content in macroalgae is typically influenced by many factors, such as species-specific differences, seasonality, and varying environmental parameters [57]. High carbon tissue content in South Florida sargasso may indicate landings of older and senescent thalli. High carbon values may also be related to the high level of alginates, a group of linear polysaccharides contained in sargasso cell walls, and other products rich in carbohydrates that require carbon and can account for 56–78% of DW in sargasso [58,59]. The monitoring of nutrient content in sargasso can provide estimations of sargasso contributing to eutrophication of a coastal system as it accumulates and decomposes [7]. The combination of its high biomass and its nutritional content has promoted exploration for commercial viability of sargasso for various purposes, including composting, incorporation into construction materials, paper production, and even shoe manufacturing [60].

Across molar ratios, only sargasso N:P ratios varied across morphotype and between sites and were significantly higher than values of sargasso reported across the Atlantic region, indicating a high N content relative to P content for individuals landing in South

Florida. Despite being collected in the neritic zone, the C:N values of sargasso for this study (46.8) were similar to the C:N of oceanic sargasso (47) reported by [24] and sargasso from the south Sargasso Sea (48.7) reported by [26]. Comparative studies show high C:P values in the south Sargasso Sea, however, our values were much higher than values previously reported [24,26]. The high nutrient ratios among morphotypes suggest an oligotrophic origin of the sargasso landing in South Florida, such as the Sargasso Sea versus areas with higher local nutrient availability like the Amazon and Orinoco Rivers, or areas influenced by upwelling or deposition of Saharan dust off the coast of Africa [10,50]. Our study is limited in definitively indicating the origin of sargasso landings in South Florida, and future studies should include oceanographic backtracking with drifters [52] and epibiont species diversity comparisons between the GASB and the Sargasso Sea. It is likely that the origins of sargasso during off-season months could be dominated by the Sargasso Sea, whereas landings occurring during the peak season in South Florida could be a mix from the GASB and Sargasso Sea with seasonal variability. Furthermore, studies on nutrient uptake rates and other physiological studies of sargasso along with analyses of the availability of nutrients in the water column need to be explored to understand sargasso utilization of available nutrients and the potential mechanisms of nutrient uptake in sargasso.

Sargasso contains a variety of calcareous epibionts that have a small contribution to carbonate sediments, which can support biogenic sediment production similar to the large contributions made by seagrass epibionts [61]. This process in South Florida is primarily driven by green calcareous algae, contributing 56–80% DW inorganic carbon to these sediments [62]. However, long-term studies showed that the abundance of these foundational species were declining and were projected to decline even further from ocean acidification [62,63]. The increased accumulation and decomposition of sargasso may be able to subsidize carbonate sediments in South Florida. Ash content for the genus *Sargassum*, shown as the inorganic mass fraction in this study, has varied by region in previous studies, with values ranging from 21% to 36% DW [64], and values for sargasso typically higher than 30% DW of biomass [65,66]. Uncleaned sargasso from South Florida had an average of 24% DW inorganic mass, which was lower than the values expected for sargasso but higher than averages reported in Mexico and the Dominican Republic [61,66]. These lower values may be related to South Florida being in the northern limits of the distribution of the sargasso bloom in relation to the GASB along with differences in the morphotype composition and age of thalli landings. Cleaned biomasses of sargasso, where all epibionts were removed from the thallus, had a much lower average of 14% DW inorganic mass fraction. This difference in the inorganic mass fraction between cleaned and uncleaned sargasso may suggest a high community of calcifying epibionts associated with sargasso landings in South Florida and may suggest a high residence time floating in the open ocean before landing. The presence of sargasso provides a substrate and increases the habitat availability for these calcifying epibionts. Our study showed similar ash contents across morphotypes of both cleaned and uncleaned sargasso, despite previous studies demonstrating variations in associated calcareous epibionts among morphotypes due to structural differences in the thalli [22].

The seven metals found in highest concentrations in sargasso tissue in our study were similar to the highest concentrated elements previously reported in sargasso tissue from the middle tropical Atlantic Ocean basin [30,67]. The sargasso tissue collected in South Florida had high spatial and temporal variations in metal concentrations, likely due to variations in the environmental history of sargasso thalli based on its origin and dispersal pathway before landing. This high spatial and temporal variability of elemental concentrations, particularly with intra-annual variations in these metals, was also found in sargasso tissue landings in the Mexican Caribbean region [68]. Sargasso landings in South Florida contained similar quantities of heavy metals across all three morphotypes, which was consistent with other reports of heavy metal concentrations at the morphotype level [13,67] but differed from sargasso landings in Jamaica, where *S. natans* VIII consistently had a lower quantity of metals compared to *S. fluitans* III and *S. natans* I [69].

Arsenic (As) is consistently the highest concentrated element found in sargasso tissue across the Atlantic region [13,30,67]. In our study, 70% of sargasso samples (83% *S. fluitans* III, 52% *S. natans* I, and 74% *S. natans* VIII) contained As contents higher than the European maximum allowable limit of As content for seaweed used as animal fodder (40 ppm DW) and other limits for agricultural soil in other countries [14]. The average As content in our study (52.7 mg kg^{-1}) was within the range of values reported across the Atlantic region (Table S6), with a maximum value of 119 mg kg^{-1} reported in August 2019. Concentrations of As in sargasso tissue previously reported in Jamaica, Mexico, Turks and Caicos, and across the north Tropical Atlantic Ocean has varied seasonally, annually, spatially, and across morphotypes [13,65,69,70]. Our study showed no differences in As concentrations across sampling times within the same year (May to July 2021) but a statistically significant temporal difference between July 2020 and July 2021 at Dania Beach and a significant spatial difference between Dania Beach and Crandon Park in May 2021. This spatial difference in As was not consistent in June 2021 between Dania Beach and Bill Baggs. In previous studies, As concentrations were found to be higher in *S. natans* I in Jamaica [69] and Turks and Caicos [65], while *S. natans* VIII had the highest As concentration in Mexico [13] and the northern Tropical Atlantic [70]. This was inconsistent in our data, which showed *S. natans* I being significantly lower in As concentration than both *S. fluitans* III and *S. natans* VIII. Despite not having statistical differences in As concentrations from *S. natans* VIII, *S. fluitans* III had the highest total As despite having the highest average phosphorus values. Notably, cleaned samples of sargasso where all epibionts were removed had a 1.5 times lower total As concentration than sargasso samples that contained epibionts. This suggests a substantial contribution of total As by the epibiotic community associated with sargasso landings in South Florida. Thus, in order to explore the valorization potential for sargasso, the epiphytic community associated with each morphotype should be considered in future As estimations of both inorganic and organic species of As. Despite lower As concentrations in sargasso when epibionts were removed, the challenge of eliminating associated epibionts could still hinder its commercial viability.

5. Conclusions

Compared to other regions across the Tropical and Western Atlantic, sargasso landings in South Florida are relatively low. South Florida's position in the northern limits of the movement of sargasso influenced by the GASB and its influence by larger currents like the Gulf Stream may contribute to the arrival of sargasso from multiple origins, as proposed in other studies. The morphotype composition of landed sargasso in South Florida is consistent with other sites across the Tropical Atlantic and GASB during peak season, with *S. fluitans* III as the dominant morphotype. However, the *S. natans* I morphotype dominates in South Florida during the off season, suggesting a greater influence from the Sargasso Sea during this time. In situ monitoring can be combined with data collected from citizen science programs to increase the frequency of sargasso observations.

Tissue nutrient content and heavy metal content of sargasso showed no statistical differences across the three morphotypes despite the distinct morphological, physiological, and genetic differences previously observed. The nutrient content of sargasso landings in South Florida was more similar to individuals from the Sargasso Sea than individuals within the GASB. The inorganic content of sargasso and its associated epibionts combined with the high biomass landings may have significantly contributed to the accumulation of carbonate sediments. Heavy metal contents in sargasso varied spatially and temporally, likely due to differences in environmental history. The arsenic concentration was consistently the highest concentrated element in sargasso tissue, with 70% of samples above the European maximum allowable limit of As content for seaweed used as animal fodder. Cleaned samples of sargasso in which all epibionts were removed contained significantly less arsenic, suggesting that a significant contribution of arsenic content may be due to the epiphytic community associated with sargasso.

The results of this study suggest that South Florida has some differences from the Caribbean at large; however, experiments on nutrient and metal uptakes are needed to understand the potential physiological mechanisms behind those differences and evaluate the local contribution compared with oceanic sources.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/phycology4020013/s1, Table S1: Summary of collections and analyses of sargasso conducted at Dania Beach, Crandon Park, and Bill Baggs during the survey period (2018 to 2022); Table S2: Results of parametric and non-parametric analyses on biomass of sargasso at Dania Beach and Crandon Park; Table S3: Results of parametric and non-parametric analyses on nutrient content of sargasso in South Florida; Table S4: Percent carbon, nitrogen, phosphorus, and nutrient ratios (mean ± standard error) for dry weight values of sargasso in South Florida; Table S5: Results of parametric and non-parametric analyses on elemental concentrations of sargasso at all three sites. Dashes indicate more than two elemental concentrations were not present; Table S6: Element concentrations (mean ± SD) of sargasso in South Florida reported in mg kg^{-1} dw from this study are indicated in blue rows. Element concentrations (mean ± SD or range) of sargasso from previous studies reported in mg kg^{-1} dw or ug g^{-1} dw conducted in other countries are indicated in yellow rows. Maximum levels permitted by different countries in agricultural soils reported in ppm or mg kg^{-1} dw are indicated in green rows; Figure S1: Relationship between wet weight and dry weight measurements taken for sargasso at both Dania Beach and Crandon Park for all sampling times; Figure S2: Interannual relative frequency of sargasso morphotypes collected from citizen science data at Dania Beach from 2019 to 2021; Figure S3: (A–C) Annual average carbon, nitrogen, and phosphorus tissue contents of sargasso and (D–F) annual average carbon, nitrogen, and phosphorus molar ratios of sargasso collected at Dania Beach from 2019 to 2021. The blue dashed line represents the average nutrient content values for macroalgae reported by Duarte in 1992 [43]. The orange dotted line represents the average nutrient content value for benthic *Sargassum* obtained by averaging published values of nutrient content for *Sargassum* spp. [44–46]. The green dashed line represents the average nutrient content value for sargasso reported by Lapointe et al. in 2021 [21]. The green dashed line in panel (C) is overlapping with the value reported in the blue dashed line for macroalgae. Different letters indicate post hoc analyses (Dunn test) when nutrient content differed across years; Figure S4: (A–C) Annual average carbon, nitrogen, and phosphorus tissue contents of sargasso and (D–F) annual average carbon, nitrogen, and phosphorus molar ratios of sargasso collected at all three sites in 2019 and 2021. The blue dashed line represents the average nutrient content values for macroalgae reported by Duarte in 1992 [43]. The orange dotted line represents the average nutrient content value for benthic *Sargassum* obtained by averaging published values of nutrient content for *Sargassum* spp. [44–46]. The green dashed line represents the average nutrient content value for sargasso reported by Lapointe et al. in 2021 [21]. The green dashed line in panel (C) is overlapping with the value reported in the blue dashed line for macroalgae. Different letters indicate post hoc analyses (Dunn test) when nutrient content differed across sites and years; and, Figure S5: Relationship between organic and inorganic mass of sargasso in (A) cleaned and (B) uncleaned specimens of sargasso.

Author Contributions: Conceptualization, D.C.H., N.K.B., L.A.R.I., S.O. and L.C.-V.; methodology, D.C.H., S.O. and L.C.-V.; formal analysis, D.C.H.; investigation, D.C.H.; data curation, D.C.H.; writing—original draft preparation, D.C.H. and L.A.R.I.; writing—review and editing, D.C.H., N.K.B., L.A.R.I., J.E.C. and L.C.-V.; visualization, D.C.H.; supervision, L.C.-V.; project administration, L.C.-V.; funding acquisition, S.O. and L.C.-V. All authors have read and agreed to the published version of the manuscript.

Funding: This material is based upon work supported by the National Science Foundation under Grant No. HRD-1547798 and Grant No. HRD-2111661. These NSF Grants were awarded to Florida International University as part of the Centers of Research Excellence in Science and Technology (CREST) Program. Additional support was provided by the National Save the Sea Turtle Foundation Grant No. AWD000000011522 from the Institute of the Environment at Florida International University and the FIU Kelly Foundation Tropical Botany Scholarship. This is contribution #1710 from the Institute of Environment at Florida International University.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors would like to thank all volunteers for their contribution to data collection on the Epicollect5 database. We would like to thank all undergraduate research volunteers who assisted with processing data.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analysis, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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