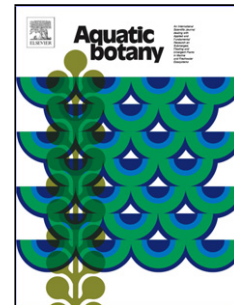


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Temporal changes in the composition and biomass of beached pelagic *Sargassum* species in the Mexican Caribbean

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Highlights

- Since 2014, the Mexican Caribbean has received massive influxes of pelagic *Sargassum* species (sargasso)
- The biomass of beached sargasso varied interannually and seasonally
- Variability was related to presence of sargasso in the ocean and trade winds
- A shift in species and morphotypes occurred from 2016 to 2020

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Abstract

Since 2011, unusually large quantities of pelagic *Sargassum fluitans* and *S. natans* (sargasso) have been washing ashore along the coasts of some African countries and the Greater Caribbean, impacting ecosystems and economies. We estimated biomass and composition of sargasso arriving to a Mexican Caribbean coast from September 2016 until May 2020. In 2016, the beached masses comprised *S. natans VIII* and *S. fluitans III*. *S. fluitans III* was the predominant form throughout the study period, comprising on average >60% of total wet biomass. The relative abundance of *S. natans VIII* decreased in time from 2016 to 2019 (41 to 3 %), although it became prevalent again in the first months of 2020. The third morphological form, *S. natans I*, was not registered until February 2018, and its relative abundance increased from 23% in 2018 to 31% in 2019. The initial composition of *Sargassum* species and morphotypes of the beached sargasso in Mexico differed from that commonly reported in the Sargasso Sea. The total biomass of beached sargasso varied considerably among years and seasons, with peaks during the summer months of 2018 and 2019. Seasonal variations in biomass were explained by 1) presence of sargasso in the Yucatan Current and 2) prevailing trade winds. This study is the first report on biomass and species composition of beached sargasso in the Western Caribbean and may help to understand patterns of the massive influxes; which will aid in the management of this new phenomenon.

Keywords: sargasso, morphotypes, massive influx, Great Atlantic *Sargassum* belt

1. Introduction

The influx of holopelagic *Sargassum* species (hereafter named sargasso) has been recurrent along the tropical Atlantic, African and Greater Caribbean coasts since 2011 (Frazier, 2014). Before 2011, minor sargasso influxes also occurred with the source being the Sargasso Sea, a region located in the North Atlantic, between the United States and Europe/Northern Africa; bound by the currents of the North Atlantic gyre (Lapointe, 1995). The Sargasso Sea is home to a unique pelagic ecosystem supported by two species of holopelagic brown macroalgae, *Sargassum fluitans* (Børgensen) Børgensen and *S. natans* (Linnaeus) Gaillon. This oceanic region serves as a spawning and nursery area for many organisms of ecological and commercial importance – such as jacks (*Caranx* spp.); it also hosts several typical or endemic species, such as the sargassum shrimp (*Latreutes fucorum*) and the sargassum fish *Histrio histrio* (Laffoley et al., 2011).

But since 2011, unusual large quantities of sargasso have been washing-up along the coasts of the Greater Caribbean, and West Africa (Smetacek & Zingone, 2013; Louime et al., 2017; Wang et al., 2019). Large algal masses started to arrive in the Mexican Caribbean in the second half of 2014 and increased during the summer of 2015 (Rodriguez-Martínez et al., 2016). The decaying masses of sargasso on the beach turned the normally blue Caribbean near-shore waters brown (creating so-called Sargasso brown tides; Van Tussenbroek et al., 2017), with severe ecological consequences for affected areas (Maurer et al., 2015; van Tussenbroek et al., 2017; Rodriguez-Martinez et al., 2019).

In contrast to what was previously thought, satellite imagery revealed that the origin of most of the recent large influxes of sargasso into the Caribbean Sea is not the Sargasso Sea, but an area just north of the equator, identified as the North Equatorial Recirculation

Region (NERR) which was never before associated with sargasso blooms (Gower et al., 2013; Johnson et al., 2013; Brooks et al., 2018), and is now known as the Great Atlantic Sargasso Belt (Wang et al., 2019).

To date, scientists recognize two holopelagic *Sargassum* species, *S. fluitans* and *S. natans*; each with distinct morphological forms; first described by Winge (1923) and later defined by Parr (1939). Latter work identified two morphological forms of *S. fluitans* (III, X) and four forms of *S. natans* (I, II, VIII, IX). In 2017, Amaral-Zettler and collaborators demonstrated that the morphological forms of *S. natans* (I and VIII) were genetically distinct, based on consistent differences in mitochondrial and chloroplast genomes.

The pelagic mats are usually composed of a mixture of species and their morphotypes, but their relative abundance varies by region. *S. natans* I typically dominates in the Sargasso Sea. Schell et al. (2015) found that *S. natans* VIII, a rare form in the Sargasso Sea, dominated in the Antilles Current, the Western tropical Atlantic, and the Eastern Caribbean in 2014 and 2015, with *S. fluitans* III occurring commonly in all regions. Thus, information on the composition of *Sargassum* species/morphotype may provide indications on the origins and transport of sargasso. Information on the composition may also help to increase our understanding of biological or ecological processes of the pelagic masses, since there is some evidence for differences in growth rates (Hanisak & Samuel, 1987), resident fauna (Martin, 2016) and absorption of (toxic) metals (Rodriguez-Martinez et al., 2020) among the *Sargassum* species or morphotypes.

While recent efforts to study sargasso have been focused on the Central West Atlantic and eastern Caribbean (Schell et al., 2015, Amara-Zettler et al., 2017), little is known about what species are involved in these stranding events in the western Caribbean. In this study,

we conducted systematic beach monitoring to estimate the species composition and quantify the massive arrivals of sargasso to the coast of the Mexican Caribbean from 2016 to 2020. This is the first step towards establishing temporal patterns in abundance in this region and better understanding the origin and movements of these species/morphotypes.

2. Material and Methods

Beach surveys

The Puerto Morelos reef lagoon, located on the eastern coast of the Mexican Yucatan Peninsula, was selected as the study site (detailed description in Rodriguez-Martinez et al., 2010). Beach surveys were conducted on a weekly or biweekly basis, from September 2016 to May 2020; with occasional gaps.

Along a ~650 m stretch of coast (between 205210.2°N, 865159.9°W and 205151°N, 865207.8°W), where there was no beach cleaning of algal masses, four points (at intervals of ~150-170m) were selected to account for possible spatial variability at beach-scale.

During the low tide, at each of the four points, the top of a 1m² square quadrat was placed at the wrack line, where the fresh golden sargasso had accumulated during the previous high tides. In the laboratory, all identifiable sargasso thalli were separated and sorted by species or forms according to Parr (1939) and Shell et al. (2015; Fig. 1). The separated material was rinsed in seawater to remove the sand and blotted dry with paper towel to eliminate the excess of water before weighing. Per sample, the wet weight of each species or morphotype was measured using an OHAUSTM 1000g spring scale.

Data analysis

Monthly means were calculated for the biomass and relative abundance (% of species/morphotype biomass of total biomass). Biomass was log transformed to approach normality and homoscedasticity and a univariate ANOVA was applied to test for possible differences between years with months as covariate (and for differences among months with years as covariate). Prevailing wind direction was determined from registrations of wind at 1-minute intervals during the day before sampling (data provided by Servicio Académico de Monitoreo Meteorológico y Oceanográfico, Unidad Académica Sistemas Arrecifales, ICML, UNAM). Presence or absence of drifting algal masses in the open ocean before the coasts in front of Mexico (in the region approximately corresponding with the Yucatan current) were deduced from the online satellite images (monthly averages) provided online (<https://optics.marine.usf.edu/projects/saws.html>; Wang & Hu, 2017). Based on the satellite images, we created the following categories: 0, no visible algal masses; 1, possibly some algal masses; 2, visible algal masses present (Fig. 2c).

We tested for interannual differences in sargasso proportional species composition by running an analysis of similarity (ANOSIM) based on a Bray-Curtis dissimilarity matrix of the arcsine square root transformed data. A similarity percentages test (SIMPER) was used to determine the contribution of each sargasso species to the average between-year Bray-Curtis dissimilarity and to calculate the percent dissimilarity between years.

3. Results and Discussion

During the beach surveys, two species (with one species presenting two morphological forms) of holopelagic *Sargassum* were identified: *S. fluitans III*, *S. natans I* and *S. natans VIII* (Fig.1). According to Parr (1939) *S. fluitans III* has thorns on the stem, while all *S. natans* morphotypes have smooth stems. *S. fluitans III* has oblong floats without spines,

while spines are often present on the floats of *S. natans* I. Both forms of *S. natans* (I and VIII) have spherical floats, with *S. natans* VIII having distinctively wider blades than *S. natans* I (Schell et al., 2015). A fourth morphological form, *S. natans* II, described by Wrinn et al. (2016) with long, thin blades, spherical floats, no thorns on the stem and no spines on the floats was only found once in October of 2018.

The composition of species and morphological forms of sargasso that arrived on shore varied significantly over time (ANOSIM $R = 0.7044$, $p < 0.001$, Fig. 2a). SIMPER analysis showed that 2016 and 2019 were the most dissimilar years (38.14% dissimilarity) while 2018 and 2019 were the most similar (11.1% dissimilarity). Differences in *S. natans* I and *S. natans* VIII contributed the most to dissimilarity between 2016 and 2019, contributing 17.6% and 16.2%, respectively.

In 2016 and the first half of 2017, mostly *S. fluitans* III and *S. natans* VIII were found, and *S. natans* I was rare. From 2018 onwards, *S. natans* I became more abundant, and this form comprised on average 23% of the total sargasso in 2018, increasing to 31% in 2019.

Simultaneously, we observed a progressive reduction in *S. natans* VIII, whose average contribution decreased from 41% to 3% in 2016 to 2019, respectively. At the beginning of 2020, there was a rise again in *S. natans* VIII, reaching 30% of the total wet biomass, time during which the presence of *S. natans* I was reduced to 2% (Fig. 2A). *S. fluitans* III was present throughout the study period and usually dominated the pelagic masses, comprising on average ~60% of the total biomass (Fig. 2a).

Especially the presence of *S. natans* VIII was notorious, because historical data from Winge (1923), Parr (1939), and a > 20-year data set from the Sea Education Association's research cruises in the Sargasso Sea and eastern Caribbean, did not document *S. natans* VIII

until 2014 (Schell et al., 2015). *S. natans* VIII was found to be genetically distinct from *S. natans* I by Amaral-Zettler et al. (2017), excluding phenotypic changes in morphology as an explanation for the sudden appearance of this morphological form.

In 2015, during the peak arrival of sargasso (August) in the Mexican Caribbean, the senior author (B.I. van Tussenbroek) identified *S. natans* VIII as the predominant form (~75% of the total volume arriving to the shores of Puerto Morelos), and the identification of the species was corroborated through photographic records and herbarium specimens.

Shipboard observations from the Antilles Current, Eastern Caribbean, and western tropical Atlantic also registered dominance of *S. natans* VIII during 2014 and 2015 (87.3-95.3% of the algal masses; Schell et al., 2015).

Dissimilarity between the composition of *Sargassum* species and their morphological forms in the Sargasso Sea and the Great Atlantic Sargassum Belt (at least between 2014 and 2017), raises questions concerning the connectivity between these two regions of oceanic concentration of sargasso. Satellite data have shown large quantities of sargasso moving north from the North Equatorial Recirculation Region (NERR) into the Caribbean and Gulf of Mexico (Gower et al., 2013; Wang et al., 2019). Brooks et al. (2018) suggested that the Sargasso Sea potentially acted as a sink of this sargasso passing through the NERR and Caribbean, without an established connection between the North and the tropical Atlantic. If this were a consistent pattern, and all sargasso arriving to Mexico has its origin in the Great Atlantic Sargassum Belt, then it is difficult to explain how *S. natans* I was slowly introduced into the beached sargasso in our study. Johns et al. (2020) in contrast, more recently suggested that the transport of sargasso from the Sargasso Sea into the eastern North Atlantic and subsequently the NERR during 2011, could be explained by wind-

induced drift and an extreme negative phase of the winter 2009–2010 North Atlantic Oscillation. But under this scenario, a similar composition of the pelagic masses in both regions of concentration of sargasso could be expected, which was not the case. Possibly, the sargasso beached in Mexico had multiple origins. Alternatively, or complementary, changes in species/morphotype composition could also be reflective of environmental conditions, since *Sargassum* species have been found to have different thermal tolerances and growth rates (Hanisak and Samuel 1987). Further research is needed to clarify this.

We found large interannual differences in the total biomass of beached sargasso. Whereas little sargasso arrived on shore in 2016 and 2017 after a peak year in 2015, beached masses increased again in 2018 (Figure 2b). Mean biomass of beached sargasso on a single day, varied significantly among years ($F = 5.611$, $df = 4$, $p = 0.001$). Of the years in which a yearly cycle was completed (with occasional gaps), mean daily arrived biomass was highest in 2018 (17.3 ± 1.8 SE wet kg m^{-2}), and lowest in 2017 (3.1 ± 0.7 SE wet kg m^{-2}). These interannual variations are explained by the extension of pelagic masses in the Yucatan current in front of the Mexican coast (Fig. 2c), which come from the Great Atlantic Sargassum Belt. Until present, it is not precisely known which factors explain the quantity of sargassum in this region but presence of seed population in the NERR, sea surface temperatures, winds strength and mixed layer depth related to nutrient supply, are thought to play a role (Wang et al., 2019; Johns et al., 2020).

We also recorded a clear seasonal pattern in beached biomass, with pronounced monthly differences ($F = 3.855$, $df = 11$, $p = 0.002$), peaking during July (39.2 ± 5.7 SE wet kg m^{-2}) and August (42.0 ± 6.7 SE wet kg m^{-2}), and being negligible in December (0.11 ± 0.02 SE wet kg m^{-2}) and January (0.99 ± 0.12 SE wet kg m^{-2}) (Fig 2b). We observed that

Sargasso-brown-tides (Sbt) occurred when $\sim \geq 20$ wet kg m⁻² arrived at the shore. Sbt were absent in 2016 and 2017. In 2018, first Sbt were registered in March, whereas in 2019, Sbt was not formed until late April, when regular daily arrivals above 20 wet kg m⁻² were registered. Seasonal pattern in influx can be explained by more sargasso being carried in the Yucatan current during Spring and Summer. From January to May the North Equatorial Counter Current (NECC) breaks down and surface flow is westward into the western tropical Atlantic transporting sargasso into the Southern Caribbean Sea (Franks et al., 2016, Wang et al., 2019), with its subsequent arrival to the Mexican coast after 2 to 3 months. Local wind regimes also play a role in temporal variability in the quantity of beached sargasso in our study. The southeast trade winds transport the sargasso masses accumulated in the Yucatan current (running parallel to the Mexican Caribbean shore) towards land, whereas the northerly winds that dominate in autumn and winter inhibit onshore transport (Fig 2c). At times when sargasso is abundant in the Yucatan current, but when the prevailing direction of the winds did not come from NEE to S, algal biomasses on the beach were low or zero (indicated by arrows in Fig. 2c).

To avoid further damage to ecosystems and local populations and economies, Sbt caused by the accumulation of massive quantities of seaweeds on the shores should be prevented by either intercepting sargasso in the near-shore sea or beach cleaning, which requires considerable effort and infrastructure. But the irregular and unpredictable massive arrivals pose a serious challenge for capture, cleaning and processing of sargasso. Systematic monitoring of composition of biomass of beached sargasso could illuminate patterns across the region and contribute to better understanding of the massive sargasso influxes into the

tropical Atlantic, thereby aiding the region to adapt to this new major threat to ecosystems and livelihoods.

Conflict of interest: none

Acknowledgments

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Figures captions

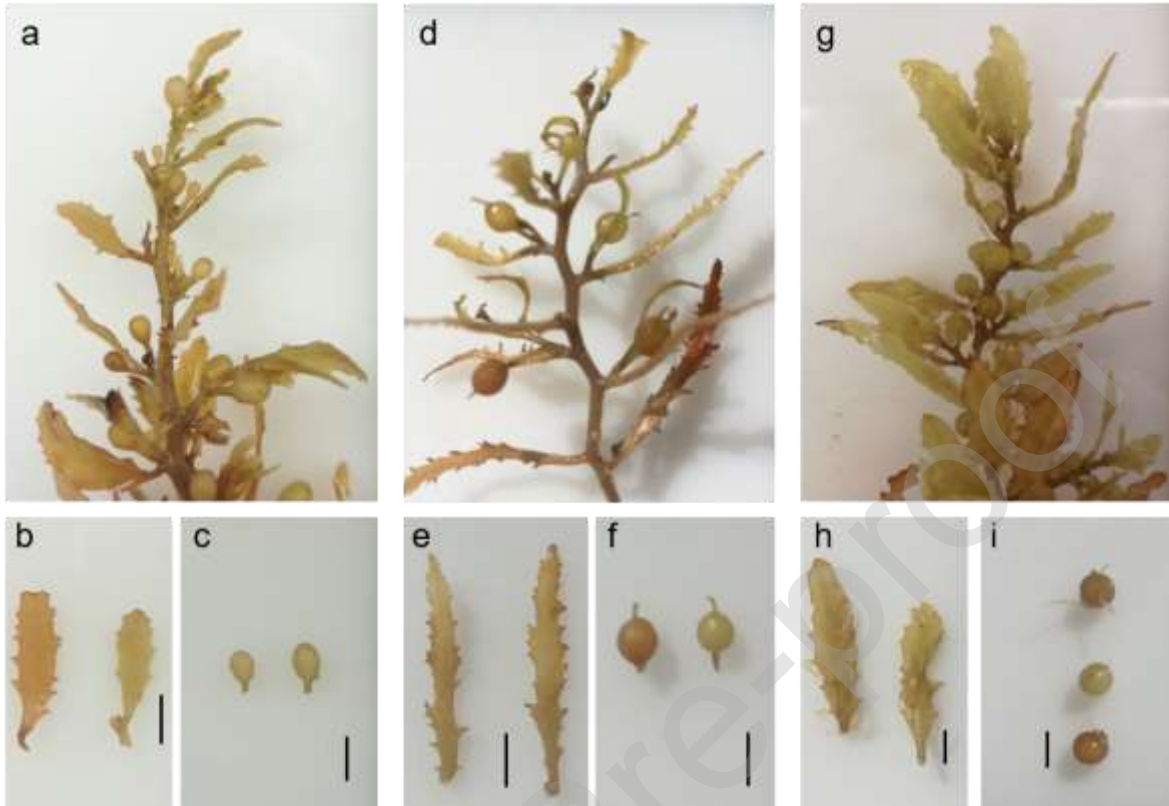


Figure 1. General appearance, blades and floats of the pelagic species and forms of *Sargassum* collected during the beach surveys in Puerto Morelos, Mexican Caribbean. (a-c) *S. fluitans* III, (d-e) *S. natans* I, (g-i) *S. natans* VIII. Scale bars are 5 mm.

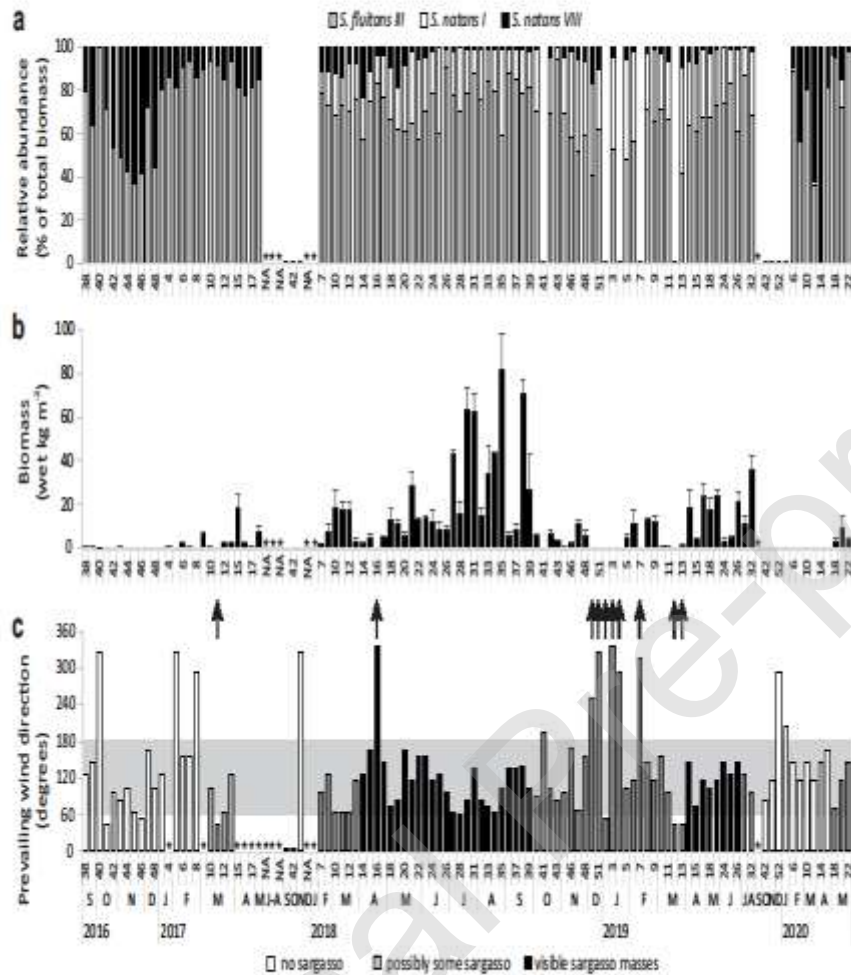


Figure 2. (a) Relative abundance of each pelagic *Sargassum* species/morphotype beached at Puerto Morelos, Mexico, (b) Mean (\pm SE, n=4) biomass of freshly beached sargassum, (c) Prevailing wind direction on the day before collection. The coloring of the bars indicates the categories of quantity of sargassum in the ocean before the Mexican coast. The grey area indicates the range of directions of winds that transport sargassum from the ocean towards the

shore. The arrows indicate days that abundant sargasso was present offshore, but the direction of the winds was not adequate for transport towards the coast. * no data.

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