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Massive Influx of Pelagic *Sargassum* spp. on the Coasts of the Mexican Caribbean 2014–2020: Challenges and Opportunities

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Abstract: Since late 2014, the Mexican Caribbean coast has periodically received massive, atypical influxes of pelagic *Sargassum* spp. (sargasso). Negative impacts associated with these influxes include mortality of nearshore benthic flora and fauna, beach erosion, pollution, decreasing tourism and high management costs. To understand the dynamics of the sargasso influx, we used Landsat 8 imagery (from 2016 to mid-2020) to record the coverage of sargasso in the sea off the Mexican Caribbean coastline, with a maximum reported in September 2018. Satellite image analysis also showed local differences in the quantity of beached sargasso along the coastline. Over the years, good practice for collection on the beach and for off-shore collection of sargasso have been established through trial and error, and the Mexican Government and hotel industry have spent millions of dollars on removal and off-shore detention of sargasso. Notwithstanding, sargasso also has various properties that could be harnessed in local industries. The stimulation of local industrial growth would offer alternatives to the dependence on tourism, as a circular economy, based on sargasso, is developed.

Keywords: sargasso dynamics; ocean coverage; beach cast volume; sargasso uses

1. Introduction

In 2011, large masses of the pelagic algae species of the genus *Sargassum* (*S. natans* and *S. fluitans*; described as sargasso from here) were reported for the first time floating in the North Equatorial Recirculation Region (NERR) of the southern Atlantic Ocean [1–3]. This new area of drifting algal masses, 8°–23°N and 89°–58° W, was named the Great Atlantic Sargasso Belt by Wang and collaborators [4], and by June 2018, its area had reached almost 3000 km^2, with a biomass of >20 million tons [4]. On reaching the shores of Africa, the Caribbean and the Gulf of Mexico, these drifting masses caused severe environmental, economic and social impacts. In the Mexican Caribbean, massive influxes began to appear in late 2014, peaking in 2015, 2018 and 2019 [5–9].

Suggested causes for the increase in sargasso biomass, include:

a. An increase in the nutrient load in the Atlantic Basin via river discharges, due to deforestation and other land-use changes upstream [4];
b. An increase in Sahara dust [10];
c. A change in upwelling patterns off the north-eastern coast of Africa [4,11];
d. An abnormal wind regime from 2009 to 2010 in the central eastern Atlantic [12,13];
e. An increase in the sea temperature [13]; and,
f. Changes in the mixed layer depth related to nutrient supply [13].

All of which may be ultimately linked to human modification of biogeochemical cycles.

For ecosystems and humans, the most adverse consequences occur when the sargasso reaches the coast (Figure 1). The beached decaying algal masses produce leachates and particulate organic matter, causing sargasso-brown-tides, which deplete oxygen, reduce light and deteriorate water quality [14]. This leads to the death of the nearshore benthic communities (including seagrasses) and fauna [7,14]. Efforts to prevent the sargasso reaching the coast, or to remove it from the beach before the masses decompose, have often been insufficient, or absent. Thus, the accumulation of sargasso on the coast and inadequate clean-up activities have resulted in beach erosion, sand compaction and interfered with marine turtle nesting and hatching [15]. Inland, inadequate disposal of sargasso threatens the aquifer, the only source of freshwater locally, contaminating it with nutrients, salt, metals and other contaminants (see Figure S1).

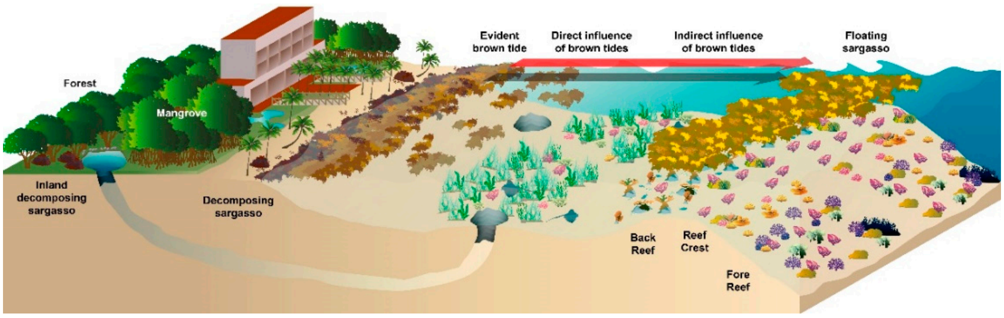

Figure 1. Schematic representation of the Mexican Caribbean coast profile and the impacts of the sargasso influx. Coastal ecosystems include: coral reef (back, crest and fore zones); seagrass meadows, algae and isolated benthic fauna (reef lagoon); beach; mangrove; forest; and underground rivers. When floating sargasso reaches the beach, if left on site, it decomposes after a couple of days, generating leachates and organic matter that reach the sea by wave action, creating brown tides that can affect the flora and fauna close to shore, directly, and the coral reef, indirectly. Inadequate disposal of sargasso in the mangroves and forests may contaminate underground rivers that eventually reach the sea.

The aim of this work is to present a general overview of the massive sargasso influx in the Mexican Caribbean, from physical, ecological, social and economic perspectives. Understanding this challenging phenomenon, its dynamics, impacts, uses and possible value, is necessary for decision making. Stakeholders in the region need this information to design efficient solutions and management protocols and, ultimately, to develop a circular economy with the algae as the key source.

2. Study Area

The Mexican Caribbean coast lies on the east of the Yucatán Peninsula (Figure 2). Mangroves, coral reefs, and seagrass beds dominate the seascape, stretching along the entire coastline. In terms of species movement, the flow of energy and matter are inextricably linked with habitat provision. The interactions amongst these factors promote resilience against natural and anthropogenic disturbances, including climate change [16]. The resilience of the coastal ecosystems in this region has been altered over the last 50 years due to inadequate coastal management of urban and tourist developments [17], overfishing and, more recently, the massive sargasso influx.

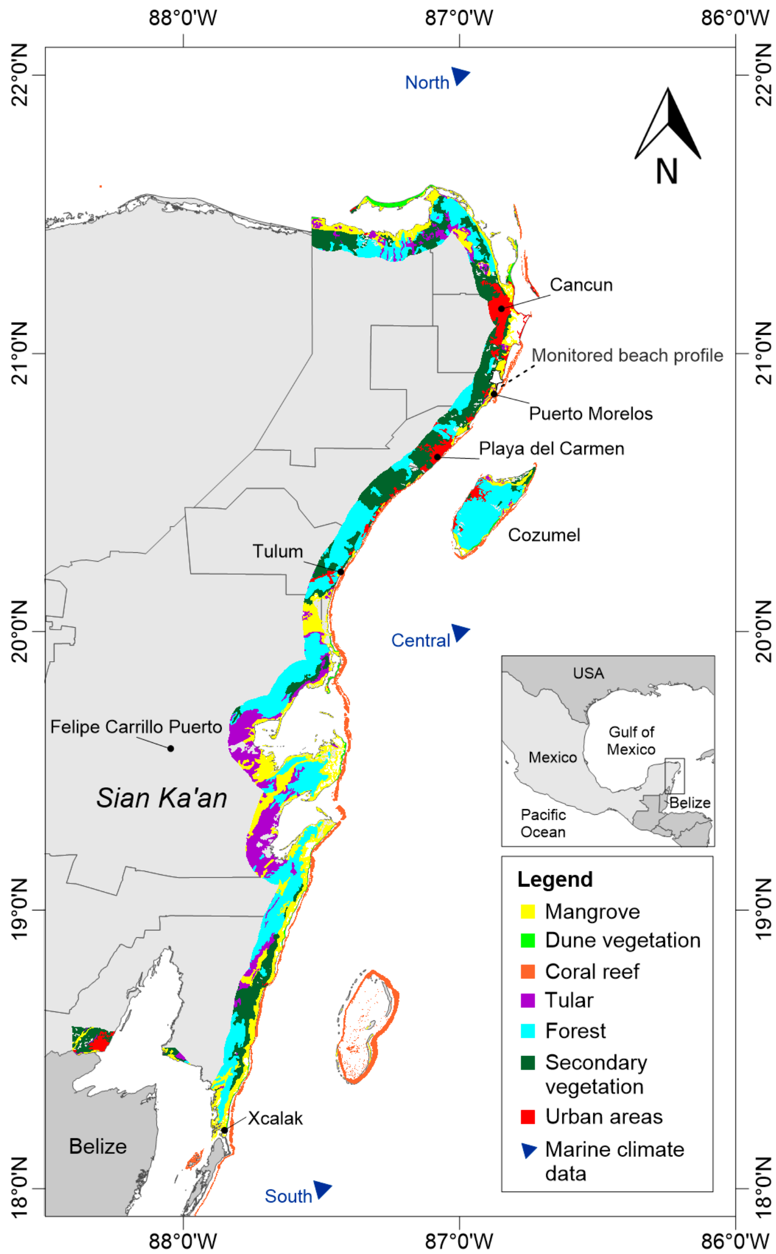

Figure 2. Coastal ecosystems (10 km strip) on the Mexican Caribbean. Data obtained from [18,19].

2.1. Marine and Atmospheric Climates

The winds of the Mexican Caribbean coast are influenced by the Trade Winds, and by mild, cold fronts in the winter, lasting 3–10 days [20]. Monthly average sea surface temperatures ranged from 25.1 °C to 29.9 °C, from 1993 to 2005 [21]. The Yucatan current flows northward along the narrow continental shelf and during the Trade Wind season surface waters are transported into the reef area.

Marine climate data, 1979–2019, obtained from Era5 climate reanalysis [22], were analyzed for three points on this coast (coordinates 22° N 87° W, 20° N 87° W and 18° N 87.5° W). These points were considered representative of the northern, central and southern sections of the area, (Figure 2).

Charts showing the prevalent wind and wave power are presented in Figure 3. It can be observed that the predominant waves and winds are east–southeast in the north, and east in the south. Wave power values are mainly lower than 5 kW/m in the northern region. On the other hand, more energetic conditions are found in the south, where values of up to 20 kW/m occur with a probability of 60%. The same pattern is seen for wind power: more energetic conditions in the south than in the north.

The seasonal variation of wave and wind power is shown in Figure 4, represented as the number of events that exceeded 10 kW/m and 0.5 kW/m^2, respectively. The most powerful winds and waves occurred in the period from November to April (winter). The differences between the three sections of the coast were greater in the May–October periods than those of November–April.

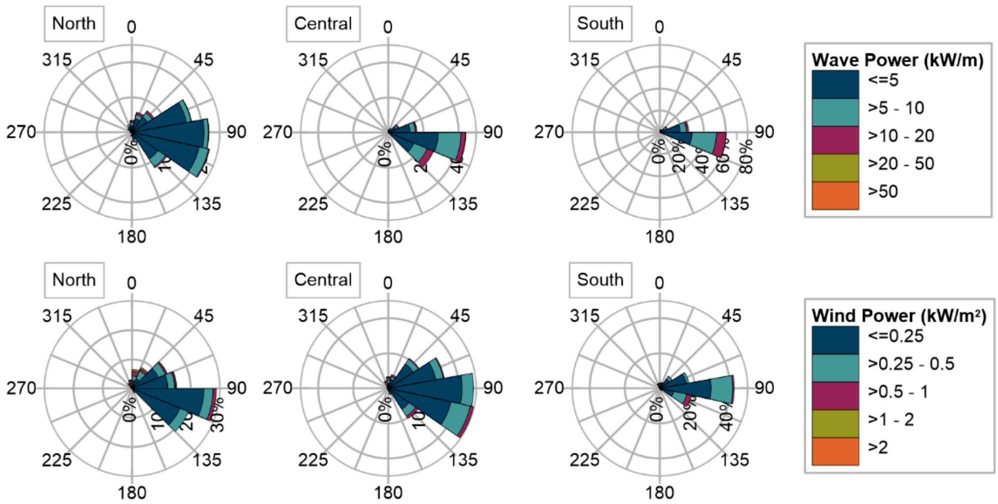

Figure 3. Prevalent wave (**top**) and wind (**bottom**) power charts for January 1979–December 2019 for three points along the Mexican Caribbean coast. Data obtained from Era5 climate reanalysis [22].

2.2. Geomorphological Features

The karst aquifer of the Yucatan Peninsula is one of the most extensive aquifer systems in the world, extending ≈165,000 km^2 across Mexico, Guatemala and Belize. The eastern coast of the peninsula is composed of carbonated marine sediments of the Tertiary and Quaternary periods, and is characterized by continuous radial underground flows towards the coast [23] (Figure S2). The underground water moves through the pores, fractures and dissolution ducts in the limestone until it reaches the coast via submarine groundwater discharges [24]. The flow capacity of the submarine groundwater discharges from the mainland to the coast affecting the marine geochemical cycles of the elements [24]. The underground water also transport different compounds and particles that eventually flow into the marine environment [24–26].

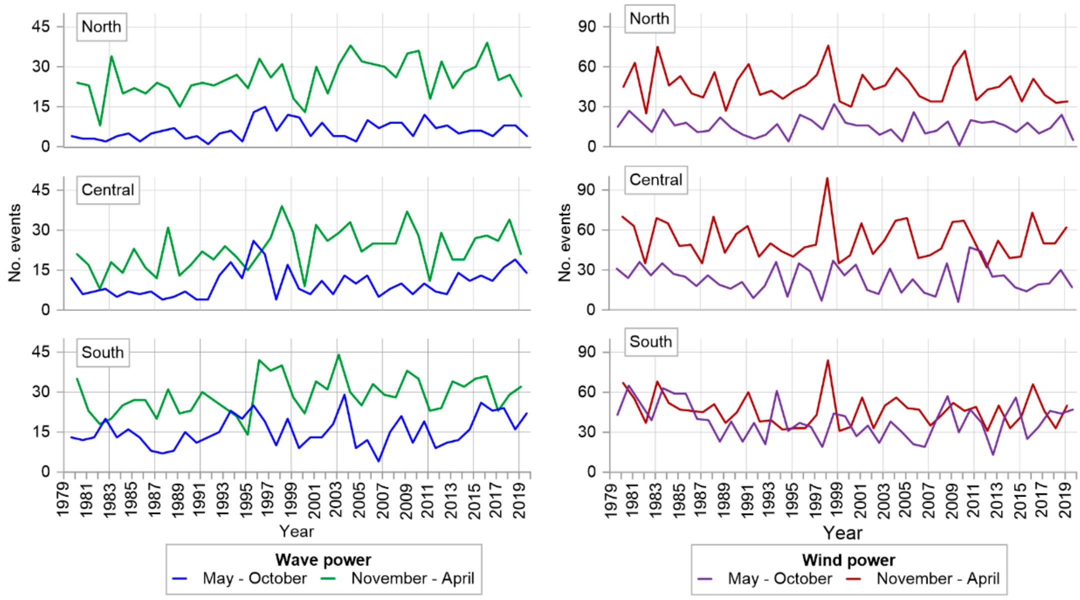

Figure 4. Number of events in which wave power exceeded 10 kW/m (**left**) and wind power exceeded 0.5 kW/m^2 (**right**) over six-month periods (May–October and November–April) from January 1979 to December 2019, for three points along the Mexican Caribbean (see Figure 2). Data obtained from Era5 climate reanalysis [22].

2.3. Coastal Ecosystems

Extended fringing reefs border most of the coastline of the region, and are usually separated from the beach by wide reef lagoons, sometimes hundreds of meters wide [27]. The reef lagoon is shallow and the floor is usually sandy, colonized by extensive beds of seagrasses, and sporadic coral communities. Although they are generally considered to be one continuous system, the coral reefs of the region have different geomorphological structures.

The coral reefs of the southern Mexican Caribbean are the most well-developed in the region, with large areas of spur and groove formations in the fore reefs. In the central region, the shelf widens, and the fore reefs have gentle slopes with high relief at several sites. In the northern section the reefs are smaller, with identifiable reef lagoons, back reefs and fore reefs [27,28].

In the last 40 years, the coral cover along this coast has decreased significantly. This is due to combined local and global anthropogenic impacts: coastal development and associated pollution, rising sea temperatures, which have increased coral diseases and bleaching episodes, and the occurrence of hurricanes [28–30]. In the northern section, for example, coral cover has declined by 50% since the late 1970s, mainly due to significant loss of important, framework-building, coral taxa [31].

In the shallow reef lagoons between the crests of the fringing reefs and the shoreline, the sediments are covered by extensive seagrass beds. Seagrass meadows are also found in more landlocked waters, such as the Nichupte lagoon system and Chetumal Bay. The transparent waters of the reef lagoons were originally oligotrophic, an environment with considerable light. The rooted vegetation in the reef lagoon is mainly comprised of the dominant foundation species *Thalassia testudinum*, accompanied by the seagrass *Syringodium filiforme* or *Halodule wrightii*.

The densities of the latter species was low, when it was intermixed with *T. testudinum*, but has been increasing over recent decades, due to gradual eutrophication [32]. Rhizophytic algae usually accompany the seagrasses [33]. Most of these algae are calcareous and they are important producers of calcareous sand [34]. In these coastal systems, seagrass meadows play a pivotal role in sustaining food webs through processes such as primary productivity [32], sediment stabilization [33,35], and carbon sequestration [36].

Before the onset of tourist development in the 1960s, there were often strands of sand dunes parallel to the coastline [37], with some reaching heights of 7–12 m in Cancun [38] and 3–4 m in Puerto Morelos [39]. Good condition coastal dunes are presently only found in protected areas, such as the Biosphere Reserve of Sian Ka'an [40]. Sediment transport and wave activity cause periodic disturbances and create topographic microenvironments where beach and dune vegetation becomes established [41], providing habitat for at least 456 species of plants belonging to 79 families [37].

Different types of mangrove ecosystems dominate the wetlands parallel to the coastline. The type of mangrove depends on the salinity and on the amount of nutrients present. Fringe mangroves, of tall trees, are commonly found along the edge of coastal lagoons, while dwarf mangrove forests are short trees (<5 m) interspersed with seasonally flooded lagoons of shallow water, occurring in low-lying areas parallel to the shoreline, extending from the landward edge of the beach ridge to a steep Pleistocene coastal ridge, which was once an ancient shoreline [42]. Four species of mangrove occur in this region: *Rhizophora mangle*, *Avicennia germinans*, *Laguncularia racemose* and *Conocarpus erectus*. The forests in the area vary from semi-evergreen (25–50% dry season leaf loss) to semi-deciduous (50–75% dry season leaf loss) and are of low (10–15 m), medium (15–30 m), and high-stature (30–35 m) [43,44]. Common upland species include *Brosimum alicastrum*, *Manilkara zapota*, *Talisia olivaeformis*, *Bursera simaruba*, *Lonchocarpus longistylus*, *Nectandra salicifolia*, *Psidium sartorium*, *Vitex gaumeri*, *Caesalpinia gaumeri* [45,46].

2.4. Socioeconomic Characteristics

Until the 1960s the Mexican Caribbean coast was sparsely populated, with small urban centres and local small-scale economic activities such as logging, rubber exploitation and fishing [47]. Since the late 1960s, tourist development in the area has resulted in explosive population growth, with a population exceeding 1.5 million in 2015 [48]. The economy of the area depends almost entirely on the tourism industry. The tourist corridor along this coast is the main beach destination in Mexico, receiving > 15 million visitors in 2018 [49]. The national tourism industry contributes 8.7% to the Gross Domestic Product of Mexico, with 40% of this coming from the Mexican Caribbean [50]. Extensive urbanization and construction of tourism infrastructure have induced significant changes in land use, displacement of coastal dunes and vegetation, and deforestation.

According to Cruz et al. [51], 4% of the Mexican Caribbean coast has a high degree of anthropization. This corresponds to the areas with high tourist development, considerable infrastructure and a high population density. A total of 12% of this coast has a low degree of anthropization, 12% moderate and 72% no anthropization. However, the impact of the highly urbanized parts reaches far beyond the actual physical occupation of the coastline.

3. Materials and Methods

3.1. Sargasso Dynamics

Understanding the spatial distribution of sargasso in the open sea and its correlation with the sargasso landings (locations and quantities), is essential to developing reliable and precise forecasting tools, required to design management strategies.

Mats of sargasso have been detected for over a decade now, using remote sensing products and other detection approaches with various spectral, temporal, and spatial resolutions [52,53].

Satellite images of high spatial resolution, such as Sentinel 2 or Landsat 8, which provide high quality images (≈185 km × 185 km) over a broad spatial area are commonly used. Regarding the temporal resolution, Landsat 8 provides one image every 16 days and Sentinel 2, with satellites, gives an image every 5 days. After digital processing, the results are very reliable, and there is little chance of confusing sargasso with other floating features [54].

In this work a dataset from January 2016 to August 2020 was used to track the movement of sargasso in the open sea off the Mexican coast from Cancun, in the north, to Xcalac, in the south (Figure 2). The area covered by sargasso was detected using Landsat 8 imagery [55] (n = 321; spatial resolution = 30 m) in three sensor scenes (reference index in Landsat grid: path/row 018-046, 018-047 and 019-046). The images were corrected for atmospheric conditions and the sargasso was detected following Cuevas et al. [54].

In this work a dataset of Landsat 8 (Operational Land Imager, OLI) satellite imagery [55] from January 2016 to August 2020 (one image every 16 days) was used to detect sargasso in the open sea off the Mexican coast from Cancun, in the north, to Xcalac, in the south (Figure 2). The Landsat 8 imagery (n = 321; spatial resolution = 30 m) included three scenes (reference index in Landsat grid: path/row 018-046, 018-047 and 019-046). Following Cuevas et al. [54], the satellite images were corrected for atmospheric conditions (dark object subtraction, DOS, model), to calculate a set of vegetation and algae indices for each image (Normalized Difference Vegetation Index, NDVI; Soil-Adjusted Vegetation Index, SAVI; Floating Algae Index, FAI). This set of indices in conjunction with the Landsat blue bands (450–510 nm) and near infrared (850–880 nm) were used for visually define "training" sites of sargasso matts. The latter sites were used for a supervised classification with the Random Forest algorithm to detect the sargasso cover. The result was transformed to vector format to calculate the area covered with sargasso. For each date, the total area of sargasso cover was calculated for the study area.

3.2. Impacts of the Massive Influx of Sargasso

In order to determine the impacts of the massive sargasso influx on the beach morphology, the beach profile and coastline displacement at Puerto Morelos, were monitored from 2008 to 2019. Using the beach profile elevations obtained with differential GPS, the volume of dry beach per meter was calculated as the area under the curve of the beach profile to $Z > 0$ m. The profile monitored was always referenced to the same landmark, measured perpendicular to the coastline.

A literature review was also performed, to identify the most recently reported impacts, on coastal ecosystems and socioeconomics, of the sargasso arrivals in the Mexican Caribbean. The impacts on ecosystems include the effects of Sargasso Brown Tides in nearshore waters, the ecosystem services of support that the sargasso provides, and the contamination of coastal aquifers as a result of the disposal of sargasso. Socioeconomic issues include sargasso collection and disposal practices, and the potential uses of sargasso.

4. Results and Discussion

4.1. Sargasso Dynamics

The maximum total coverage of oceanic sargasso mats for the period was 22,900 ha, recorded in September 2018, followed by 19,000 ha in April 2019 (Figure 5). Coverage was minimal from February to December 2016 (average area of 19 ha), and from November 2019 to April 2020 (average area of 44 ha). From February 2018 to June 2019, the presence of sargasso varied in abundance. In 2020, sargasso coverage was practically zero until the first sargasso mats were detected in May, increasing in July (6500 ha), and then falling in August. These results coincide closely with the temporal patterns of beached sargasso recorded on a small stretch of beach at Puerto Morelos by Garcia-Sánchez et al. [8] (Figure 6).

These temporal patterns also coincide with the quantities of sargasso removed from the beaches by hotels in the northern section of the Mexican Caribbean (data provided by nine hotels). During the peak month, September 2015, an average of 2.4×10^3 m^3/km of sargasso was removed from these beaches [5]. In 2016 and 2017, the influx of sargasso significantly decreased, and most hotels did not provide reports on the small quantities removed. In the peak months of 2018 (March to August), 4.5×10^3 m^3/km was removed on average per month, with quantities varying greatly among beach sections from 0.7×10^3 to 31.5×10^3 m^3/km. In 2019, on average 2.8×10^3 m^3/km was collected per month during the peak months (February to July), varying among beach sections from 1.9×10^3 to 19.5×10^3 m^3/km. Yearly averages were 3.2×10^3 and 1.7×10^3 m^3/km/month for 2018 and 2019, respectively.

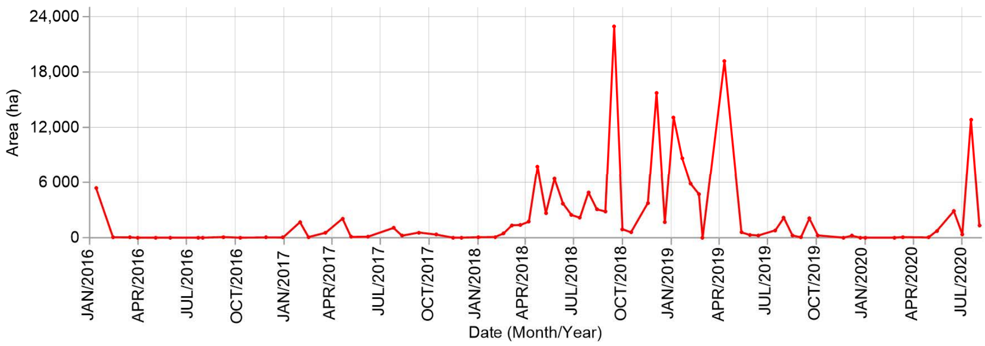

Figure 5. Time series of sargasso cover in the study area, detected by Landsat 8 imagery, 2016–2020.

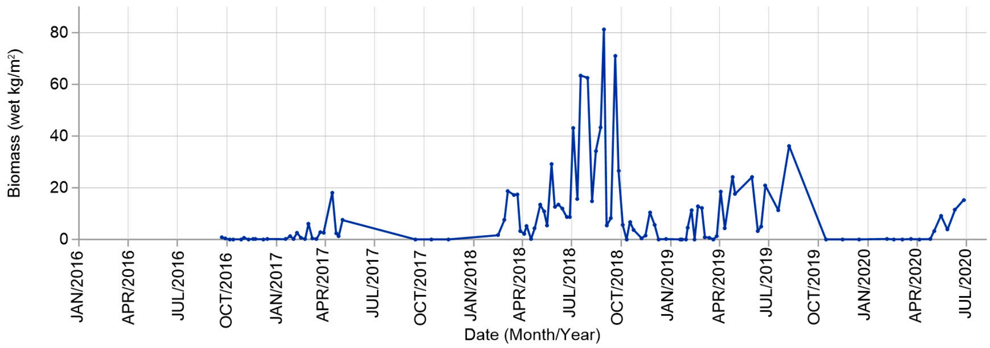

Figure 6. Biomass of beached sargasso on a short section of beach at Puerto Morelos (adapted from [8]).

Figure 7 shows the highest recorded area of sargasso in the open sea, September 2018. High spatial variability is observed. The waters adjacent to the coastline between Tulum and Playa del Carmen had the largest amount of sargasso, including waters off the east coast of Cozumel Island. The area between Puerto Morelos and Cancun had less, while in the south, from Tulum to the Biosphere Reserve of Sian Ka'an, much lower quantities were detected. Spatial variability has also been reported in beached sargasso, e.g., Rodríguez-Martínez et al. [5], where the volumes collected by six hotels in the northern region of the study area (between Cancun and Playa del Carmen) are documented.

Based on the same Landsat 8 imagery, a prevalence index of sargasso was developed for the study area (Figure 8). The index was obtained from January 2016 to August 2020 in a 64,904 km^2 grid, divided into 2 km diameter hexagons. The frequency was quantified as the number of images in which sargasso areas, larger than 1800 m^2, were present in each hexagon from the total of 321 (one image every 16 days, the revisiting time of Landsat 8). As shown in Figure 8, the frequency was normalized from zero to one, based on the maximum number of images in which the above condition was true (16 of the 321 images). The results show the areas where large masses of sargasso were more frequently found (prevalence index close to one).

4.2. Impact on Ecosystems

When pelagic masses of sargasso float in the open sea, they serve as a habitat for numerous animal and plant species and are generally considered beneficial to the biodiversity of the high seas [56–59]. However, we do not yet know all the impacts of these unusually large masses drifting in the western tropical Atlantic. If these masses were to remain at sea, or if only small quantities were to arrive at the shore, ecological problems would be minor. Small quantities of wrack on a beach, are usually beneficial, improving the consistency of the sand and providing food for small animals, such as talitrid amphipods [60], and thereby birdlife. However, the massive beaching events of this algae have had major consequences for the ecological and socio-economic systems of the Caribbean, especially as this a new phenomenon; there are no records of such massive arrivals of sargasso in this region.

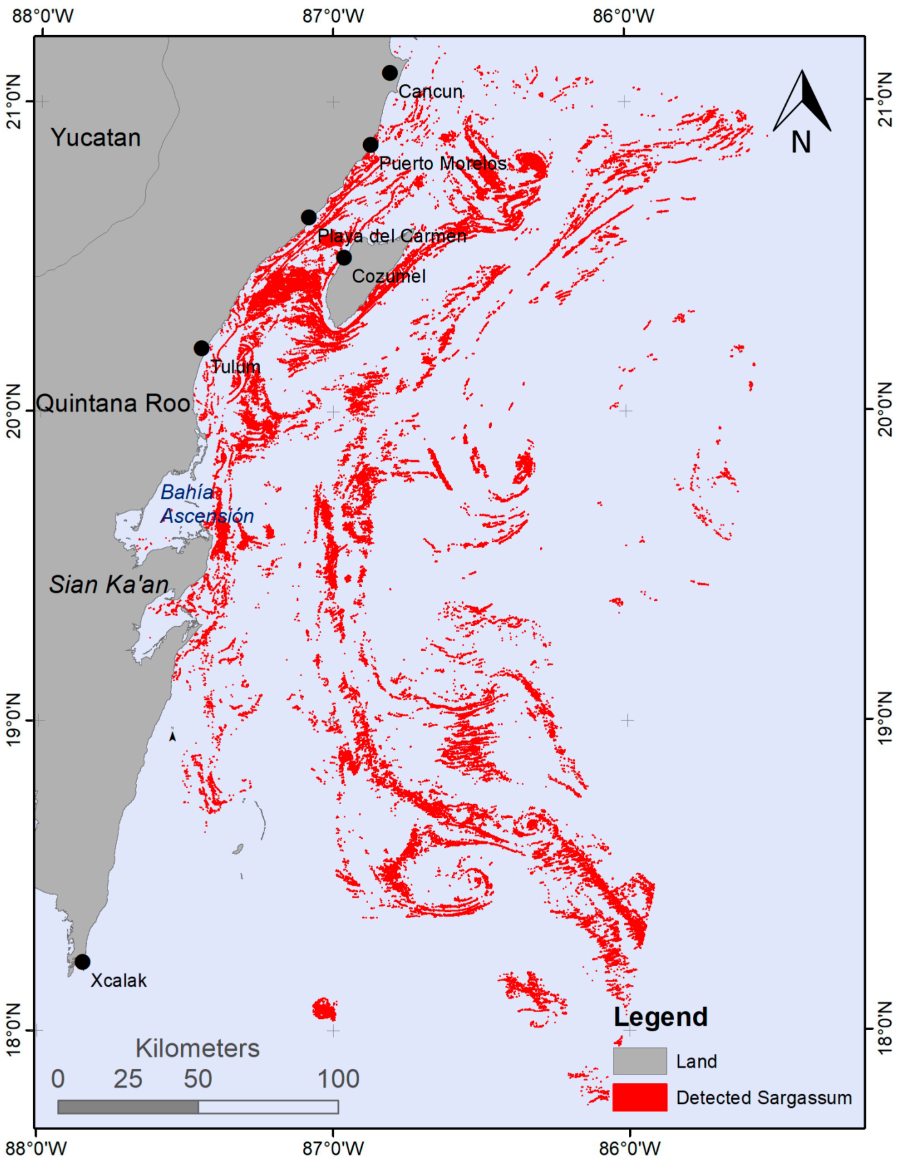

Figure 7. Sargasso cover in the open sea off the Mexican Caribbean coast in September 2018, detected with Landsat 8 imagery.

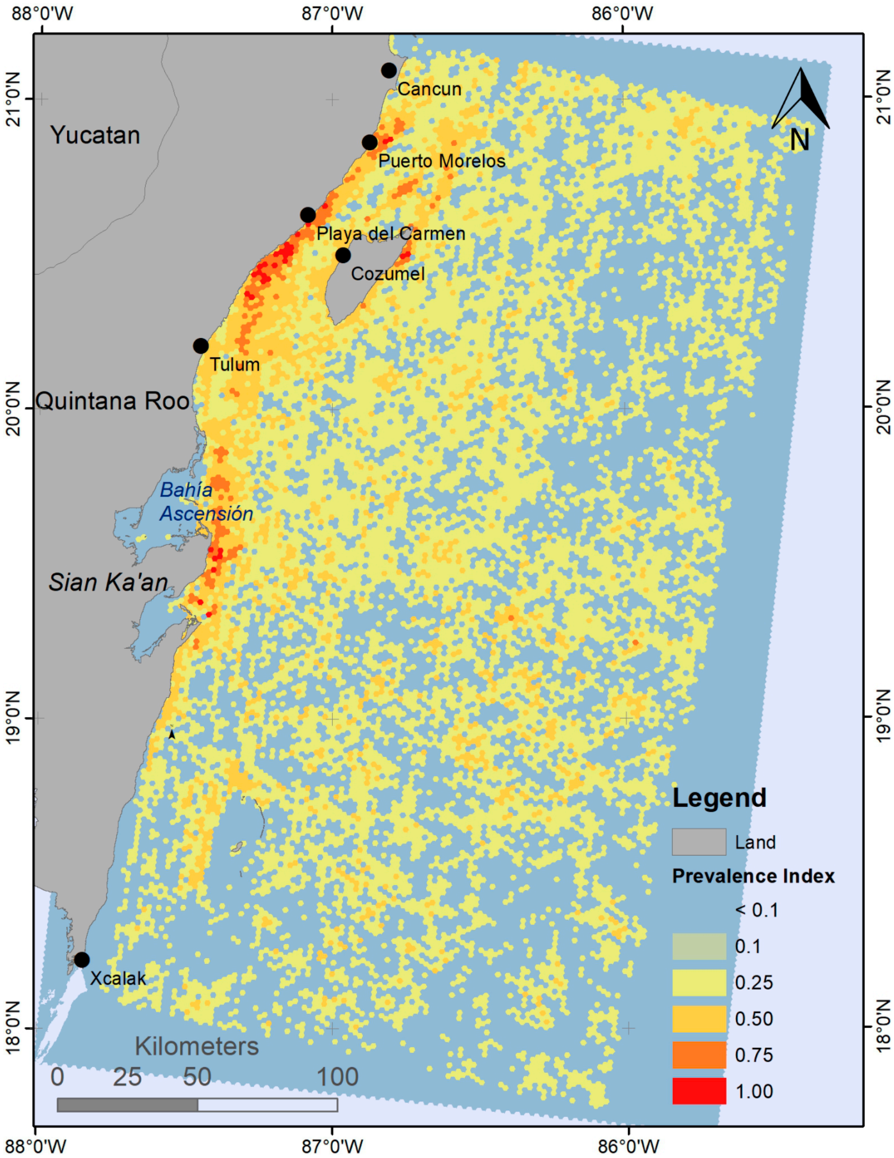

Figure 8. Prevalence index of sargasso in the Mexican Caribbean, January 2016–August 2020, detected with Landsat 8 imagery.

4.2.1. Beaches and Coastal Dunes

Apart from the unpleasant smell and negative visual impact on the beach (Figure 9), the accumulated sargasso may also cause beach erosion, depending on local conditions. This is especially true for enclosed embayments, areas with piers, marinas, and other infrastructure, where sargasso accumulates. Clean-up activities that include the use of heavy machinery, also increase beach erosion (Figure 10a–b) as the machines also remove large amounts of sand (Figure 10c). On beaches where the sargasso is left to decompose, leachates (Figure 10d) and organic matter are produced. Although current guidelines indicate that sargasso must be removed within 72 h to prevent this, with high temperatures and large sargasso volumes, leachate production can begin after 24 h [61]. The effects of this still need to be evaluated.

Results of the monitored beach profile show that in March 2008, the width of the dry beach was 31 m and the estimated sand volume was 28 m^3/m, and both parameters remained relatively stable until 2012 (Figure 11). But by October 2018, the beach width decreased to 16 m and the sand volume to 15 m^3. By June 2019 these features had fallen to 15 m and 13 m^3. Although it is known that the beach has a natural cycle of erosion and accretion linked to seasonal changes, the comparison of June

2008 and June 2019, shows that 54% of the beach volume was lost and that the coastline receded 16 m. The increase in the width of the beach in October 2018, ~8 m (Figure 11), was due to sediment accretion induced by the swells associated with Hurricane Michael (see Figure S3). After this storm, the coastline continued to retreat. In this beach section, the sargasso has not been removed regularly; therefore, the decrease in the size of the beach is probably caused by a combination of the undertow generated by the accumulated sargasso, and the loss of near-shore seagrass meadows, that fix the sands in the shallow subtidal lagoon (see Section 4.2.2). This profile is on the same beach where the temporal variations in sargasso arrivals were studied (Figure 6) and is very near to the beach pictured in Figure 9 (for location, see Figure 2).

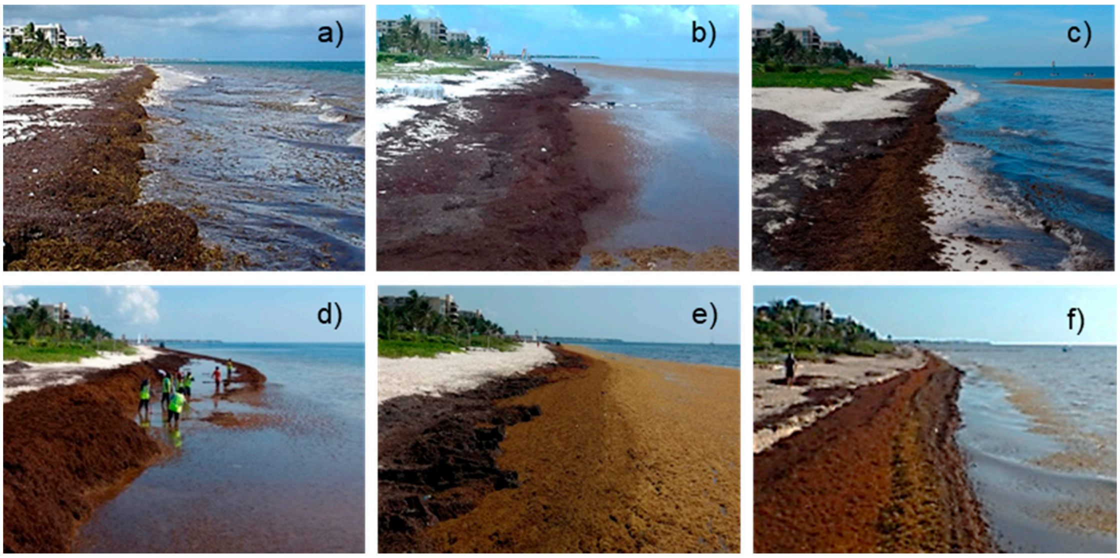

Figure 9. Sargasso accumulation and decomposition on a beach at Puerto Morelos: (**a**) October 2014, (**b**) August 2015, (**c**) July 2017, (**d**) August 2018, (**e**) October 2019 and (**f**) July 2020.

Figure 10. Removing beached sargasso from the Mexican Caribbean: (**a**–**c**) on the beach, and (**d**) in coastal waters. (**e**) Sand recovery in one of the hotels (huge amounts of sand are removed during sargasso clean-up activities on the beaches). (**f**) When large amounts of sargasso are left on the beach pools of leachates can be produced.

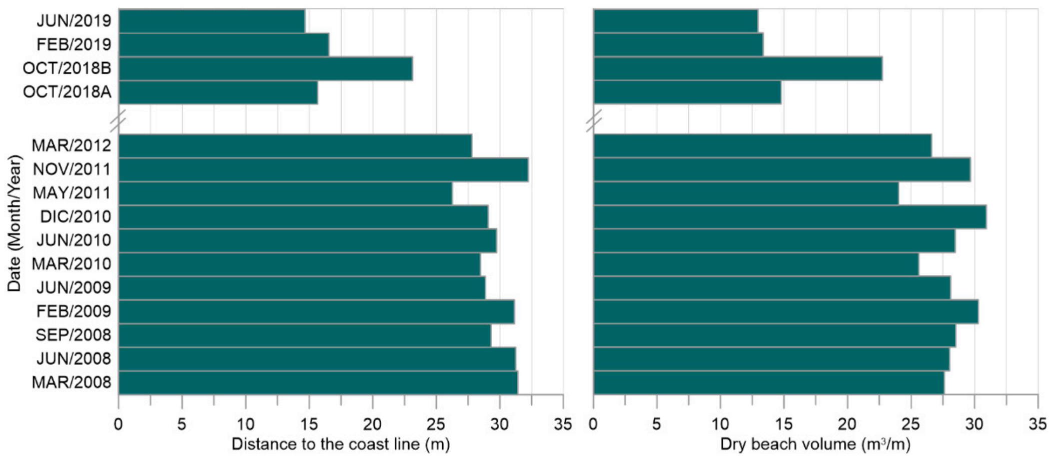

Figure 11. Coastline width retreat and dry beach volumes from 2008 to 2019, for a beach at Puerto Morelos.

On the positive side, sargasso has favored the growth of vegetation on some beaches and dunes (Figure 12), possibly through the input of nutrients, organic matter, phytohormones and alginates (that help to bind sediments) [62–64]. A few local hotel owners have initiated small-scale trials to enhance dune formation, employing sand mixed with sargasso. Anecdotal information indicates that native and exotic plants have colonized the 3–4 m high piles of dumped sargasso naturally, over time, when left undisturbed.

Figure 12. Dunes in Puerto Morelos, with plant growth favoured by sargasso. (**a**) View to the North, and (**b**) view to the South, of the same location.

Four species of sea turtle nest along this coast; the green turtle (*Chelonia mydas)*, loggerhead (*Caretta caretta)*, hawksbill turtle (*Eretmochelys imbricate)*, and leatherback (*Dermochelys coriacea)*, in descending order of abundance, [65–67]. The females lay their eggs mostly in dune zones [68], and they have been seen crossing the beached masses of sargasso to nest on the upper part of the beach; thus to date, there is no evidence that nesting behavior in the region has been significantly impacted by sargasso. However, during the incubation period of the eggs, decomposing sargasso can induce temperatures that are lethal for the embryos. This has been documented by personnel from the Puerto Morelos National Park who measured the thermal conditions in a nest inside a nursery approximately 1 meter away from where collectors had temporarily piled up sargasso away from the waterline (pile of ~3 m high) [69]. It is also well known that even small changes in temperature of the sand interfere with the sex ratios of hatchling turtles and their viability; thus, the demographic balance of future turtle populations could be altered by sargasso induced temperature changes. Accumulations of sargasso on the beach could also affect the newly hatched sea turtles as they cross over the piles on their way to the sea. This journey requires much more effort when sargasso masses create an obstacle [70,71]. The most severe negative impacts for the turtles and their habitats are probably caused by the activities of collecting and cleaning-up sargasso from the beach. The beach compaction, caused when cleaning is done with heavy machinery, deters nesting activity and interferes with the emergence of hatchlings from the nest. Vehicle transit may also directly destroy the nests [72].Our own observations in the Parque Nacional Arrecife de Puerto Morelos, are that barriers placed in the sea to confine the sargasso influx, may also trap the newly hatched turtles as they swim to the open sea, especially if the barriers have "underwater skirts" of more than 1 m, and/or a small mesh diameter, as the hatchlings are unable to pass under it.

4.2.2. Nearshore Waters—Sargasso Brown Tides

Close to the shoreline, the decomposition of the algal masses creates Sargasso Brown Tides (SBT), turning the water brown, decreasing light, oxygen levels, and the pH, while increasing the temperature, organic matter and nutrient loads. The SBT can extend >100 m from the coastline. Among the most vulnerable ecosystems affected by SBT are nearshore benthic fauna (including coral colonies) and seagrasses [7,14]. The degree of this impact on the benthos is site dependent, related to geomorphological and hydrodynamic conditions, but follows a similar pattern. Less light in the water column causes a reduction in the photosynthesis of benthonic plants, this decreases oxygen levels, and the accumulation of organic matter causes hypoxia or anoxia [14]. In addition, hypoxia decreases the abundance and diversity of benthic organisms [73,74]. The loss of seagrasses in the nearshore zone has repercussions for coastal protection and the maintenance of water clarity, as seagrasses attenuate the waves, which allows the deposition of fine particles, reducing turbidity. The below-ground rhizomes and roots of the seagrasses also fix sediments; without them the beaches are less stable and more vulnerable to the impacts of storms and hurricanes [35].

The oxygen depletion, anoxia, induced by the SBT, caused fauna mortality during the massive influxes of 2015 and 2018 [7,14]. The fauna affected included fish (at times >100 sardines or snappers), crustaceans, echinoderms, mollusks and polychaetes. Mortality events of similar characteristics were reported by personnel from the National Parks, especially at Mahahual and Xcalak in 2019.

Although the SBT is clearly visible from the beach, extending out to sea for tens of meters, the effects of the SBT can extend right across the reef lagoon, affecting the reef (Figure 1). The input of nutrients and organic material due to the sargasso lixiviates is significant, decreasing the water quality and increasing turbidity, long after the sargasso itself has disappeared from the system [14]. The negative consequences SBT are likely to interact with other threats on ecological communities in the region. For example, since 2018 the communities of reef-building corals throughout the Mexican Caribbean have been hit by an emergent disease, often called Stony Coral Tissue Loss Disease [75]. This disease has affected nearly 30 coral species, with severe population losses (>50%) for maze and brain coral (Meandrinidae and Mussidae families) [75]). The outbreak seems to have spread considerably more rapidly along the Mexican Caribbean, than in Florida or other affected regions. One possible explanation is that the deterioration in water quality due to SBT has contributed to the worsening environmental conditions that have favored this disease [75].

4.2.3. Other Ecosystems

The floating rafts of sargasso are habitats for epibionts, such as diatoms, protists, filamentous algae, invertebrates. They provide refuge from predation and offer breeding sites for larger invertebrates [76–78], fishes and reptiles [79,80]. Over 100 species of fishes, four species of sea turtles, over 145 invertebrate species and 658 bacterial and archaeal families, distributed across 350 orders and 57 phyla, have been associated with the pelagic sargasso [81]. In the Mexican Caribbean, studies conducted in 2018 and 2019 found 87 taxa of motile invertebrates and 11 species of fish associated with sargasso mats, with nine of these species presenting new records for this coast [82,83]. The drifting mats of sargasso may also serve as a vector for many non-native species [82]. Sargasso also affects the food webs; Cabanillas et al. [84] found that sea urchins had changed their diet from reef algae to sargasso, which may have significant impacts on the overall balance of the trophic structure in these ecosystems. Another potential impact may be the accumulation of metals, imported by sargasso into the system. Of special concern is arsenic [85]; however, further studies are needed to verify these data.

Contamination of the only aquifer in the Yucatan Peninsula is a serious risk, due to the inadequacies and irregularities in the sargasso disposal processes that have been employed. To date, no properly conditioned disposal sites have been established, with geomembranes to capture the leachates produced by the decomposing sargasso. As the peninsula is a karst region, it is possible that the nutrients and toxic elements of the sargasso, dumped in the jungle, mangroves, beaches and wasteland, infiltrate down into the aquifer, polluting the only available source of fresh water. In addition, as water from the aquifer eventually flows into the sea, through the underground rivers (Figure 1), infiltrated metals, nutrients and other contaminants will eventually affect the marine environment [86,87]. Inland dumping of sargasso may have further impacts on these ecosystems, as yet unknown. In some wetlands bordering the coast, the sargasso accumulates naturally and decomposes. In Xcalac (for location, see Figure 2), for example, mangrove trees lost their leaves when exposed for long periods to SBTs, probably due to anoxia (see Figure S4). It has yet to be established whether these mangroves have died or if they can still recover. Sargasso decomposition on wetlands can also cause the mortality of flora and of fauna attached to their roots; however, as far as we know, this has not yet been studied in Mexico.

4.3. Impacts on Society and on Economic Activities Locally

4.3.1. Socioeconomic Impacts

The accumulations of decomposing sargasso on the beaches and in the near-coastal waters affect the perceptions of tourists, most of them attracted to the region´s white beaches, crystal-clear, turquoise waters and warm temperatures. The unattractive visual impact of decaying sargasso, and the foul odor it produces, has harmed the tourist industry, which is the main driver of the economy in the region. There was a particularly evident decline in the occupancy rates at hotels in Cancun and the Riviera Maya after the 2018 sargasso event (2.87 % in the last year as of April 2019 [88]).

In an attempt to stem further decline in tourism and to avoid a deterioration of coastal ecosystems, the Mexican government invested ~USD 17 million dollars in the removal of 522,226 tons of sargasso in 2018, and ~USD 2.6 million dollars for the removal of 85,000 tons in 2019 [89]. The hotel industry also spent large amounts removing the sargasso from their beach fronts: in 2018, hotels between Cancun and Puerto Morelos spent USD 128,770–USD 284,830 just on wages for personnel to clean-up their beaches and the transport of the sargasso to disposal sites [90]. Some hotels have also acquired very expensive equipment, including (a) machinery, to remove the sargasso from the beach (Figure 10), costing an estimated USD 82,000, (b) barriers, to prevent the sargasso arriving on the beach, with costs ranging from USD 220 to USD 330 per meter, plus installation (USD 40–USD 50 per meter) and anchors (USD 450 in rock and USD 900 in sand per unit) and (c) boats, to transport the collected sargasso, costing from USD 200,000 to USD 1 million dollars. Other expenses include the maintenance of the boats (USD 4500 per month), smaller equipment and material for beach cleaning, reimbursal fees to tourists, and payments to sargasso disposal sites [91]. If tourism in this region continues to decline, it will lead to severe unemployment, which could bring a range of social problems, including an increase in poverty and crime. The situation has worsened since March 2020, due to the COVID-19 pandemic. In addition to tourism, property development, including time-shares, has also become an important source of income here in the last decade, with beach properties being highly valued. The negative impacts to the shoreline due to sargasso arrivals will have impacted property values, although no data are available as yet.

The massive arrivals of sargasso on the coast can also potentially affect human health. The decomposition of large amounts of any biomass, produces gases, such as sulphuric acid and ammonia that, under chronic exposure, can be toxic. Resieree et al. [92] suggested that exposure to these gasses can result in irritation to the upper airways, headache, nausea, confusion, and, in extreme cases, in hypoxic pulmonary, neurological and cardiovascular lesions. Inhabitants of coastal villages in the area have reported that the smell given off by the decomposing sargasso is sometimes noticeable up to several hundred meters inland. Another effect of sulphuric acid is the corrosion of copper cables, electronic equipment and domestic appliances in nearshore dwellings.

Sargasso, and other brown algae, absorbs metals and other elements, some of these being toxic in high concentrations [93,94]. A recent study conducted on the Mexican Caribbean coast found that, in 86% of 63 samples collected, the arsenic concentrations exceeded the European limit for its usage as animal fodder (40 ppm dry weight; Rodríguez-Martínez et al., 2020). Further studies on arsenic speciation, are required to determine whether sargasso should be used as food, or to make pharmaceutical products, in compliance with the guidelines of international institutions and organizations (i.e., Food and Agriculture Organization, FAO; World Health Organization, WHO). Metals can also be found in the leachates of sargasso. Preliminary results on leachate produced in a laboratory indicate the presence of aluminum (0.049–0.0521 mg/L) and boron (3.36–3.83 mg/L) [95].

4.3.2. Beach Removal and Off-Shore Collection of Sargasso

Over the last years, best practices for removal of sargasso from the beach have been established through trial and error. Sargasso masses should preferably be removed from a beach within 72 h of arrival [61]. If it arrives in moderate quantities, removal should be done manually, and light machinery only can be used if this is impossible, and without affecting the beach itself, or the beach and dune fauna and flora (Figure 10). Collected sand should be sieved out and returned to the littoral system (preferably the dune). However, the implementation of these guidelines is still deficient in places, and reinforcement by the authorities is inconsistent.

The collection of Sargasso off-shore is preferable, as once it has arrived at the beach damage has already been inflicted, even if collected within one day of arrival. Barriers are used to prevent the sargasso reaching the beach at several sites, placed 40–50 m off the coast. Initially, barriers used for retaining oil-slicks were used, but these proved insufficient in stopping the sargasso masses, and at present barriers reaching > 30–40 cm above the surface are used. Practices and common sense perceptions based on technical expertise, found that the most effective barriers are those with below-water nets, or skirts, with a mesh size of 2–5 cm to prevent marine fauna from becoming trapped, and extending at least 60 cm below the sea surface [96]. Recent experience has now established that best practice for anchoring systems use the substratum: alcayata anchors for hard rocky substratum and stingray anchors for sand; using mooring blocks should be avoided. The spacing of the anchors depends on local conditions, but should never exceed 20 m.

The location, dimensions and shape of the barriers depends on the oceanographic and geomorphological characteristics of the sites, but the aim is to concentrate the sargasso, thus facilitating its collection. U-shaped barriers are used to contain the sargasso (Figure 13), while V-shaped barriers (inverted triangle with angles of 45°–75°) are used to direct it to specific points along the beach for collection and disposal. The sargasso that accumulates in the U-shape barriers tends to decompose after 24–48 h and sink, so it may be carried under the barrier and towards the beach. To prevent this, the algae must be frequently removed using sargasso-boats. In the Mexican Caribbean the vessels used for this can remove 15–45 ton/h [97]. The sargasso that accumulates on the sides of U-shaped barriers, or on the extremes of the V-shaped ones, must be uploaded onto trucks, either with transportation bands or backhoes; the first is the preferred method, as the algae does not touch the sand. However, even where there are barriers in place, around 30–60% of the algae may still reach the beach. One concern of collecting sargasso in the sea is potential by-capture of associated fauna. However, Monroy-Velazquez et al. [82] found that the sargasso mats that had passed the reef contained mostly the small fauna typically associated with Sargasso, so extraction of this fauna does not affect local populations of the ecosystem. Extraction may even be desirable, because the associated fauna may include non-native species [82].

Preliminary trials to remove sargasso from the open sea by the Navy took place, but more research is needed for successful implementation. Moreover, more knowledge is required on the movement and areas of concentration of the sargasso in the open sea, as well as studies on whether this could be cost-effective and not harmful to the associated fauna.

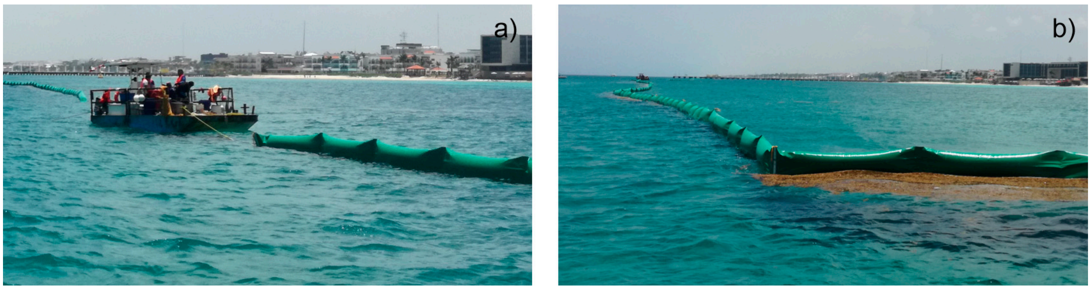

Figure 13. U-shaped barriers to contain sargasso off in Playa del Carmen. (**a**) Frontal view, (**b**) lateral view.

4.3.3. Uses and Valorization of Sargasso

Sargasso contains several chemical components, such as alginates, nutrient phenols, and polysaccharides, that mean it could be used in various industries. Due to the costs associated with sargasso contention, removal and transportation, a viable business plan would include the creation of an industrial complex, where different industries use components of the algae sustainably, generating extracts to be used by other industries. Thus, the supply of sargasso, could provide an industrial golden economy [98], based on Porter's diamond of competitiveness and the waste models of the circular economy.

Practical uses of sargasso have been explored in the Caribbean, for example [99–101]:

- Fertilizer (clean and dry sargasso) and compost (contained with equal amounts of water).
- Sodium alginate for food, textile and pharmaceutical products.
- Construction blocks (40% sargasso).
- Manually produced paper.
- Beauty care products.
- Crop and livestock production.
- Bioplastics.

Other the uses of sargasso biomass include biogas production and biosorption.

Biogas

Sargasso can be used to obtain bioenergy via anaerobic digestion. Biogas typically contains 50–70% methane and 50–30% CO_2 and can be used as a source of energy, either directly, or upgraded to biomethane (>97% CH_4, <2.5% CO_2). Sargasso possesses two characteristics that make it ideal for biogas production: high polysaccharides and negligible lignin content. However, the complexity of the polysaccharides, the salinity, sulfur, and polyphenols, and the low carbon to nitrogen ratio (<20/1) are challenges to attaining methane yields close to the theoretical values. Recently, the methane yields achieved with pelagic sargasso species (*S. fluitans* and *S. natans*) were between 0.065 and 0.145 m^3 CH_4/kg volatile solids, representing 17 to 37% of the theoretical yield [102]. These data are illustrative; they may vary since the composition of sargasso changes depending on the species, season, and location.

To fully exploit the potential of sargasso for biogas production, options must include an appropriate pre-treatment step before anaerobic digestion. Alternatively, the sargasso could be used as a feedstock in a biorefinery with biogas recovery. The main objective of pre-treatment is to increase the availability of the organic matter and facilitate its hydrolysis by microorganisms, thus increasing biogas yields. Before applying a pre-treatment method, a characterization of the sargasso (carbohydrates, protein, lipids, sulfur, salinity and polyphenols) is essential. Usually, the pre-treatment of complex organic matter, such as sargasso, requires a customized method that could be physical, chemical, thermal, biological, or a combination of these. All pre-treatment methods have advantages and disadvantages when implemented at full-scale. One of the main challenges is achieving a positive net energy balance, although pre-treatment enhances the biodegradability and biogas yields, it requires high energy inputs [103]. A possible solution to this problem could be the co-digestion of sargasso with a readily biodegradable substrate, for example, the organic part of municipal solid waste. The co-digestion of sargasso with another substrate could help to increase the carbon to nitrogen ratio, dilute salinity, enhancing the anaerobic digestion process overall. This could even help in the continuous production of biogas, when sargasso, which is seasonal, is not readily available.

Biosorption Potential of Sargasso Biomass

Sargasso can also be used for the biosorption of toxic substances, due to characteristics of its cell wall, that endow it with a high metal ion binding capacity [104]. As this alga does not require pre-treatment for biosorption, it is considered a low-cost environmentally friendly biosorbent. The removal of polluting substances using algal biomass has been investigated since 1990 [105] and it is now the most widely used type of biomass. Dead algal mass is reported to be more promising than living algae because it has a high metal ion sorption capacity at a high rate, and the adsorbed heavy metal ions present can easily be removed using de-ionized water or desorption agents [106]. There are several works on the use of many species of sargasso as biosorbents, and in the removal of pollutants, such as metal ions (e.g., Hg, Pb, Cu, Cd, Ni, Zn, Fe, and Cr), organic solvents, and organic dyes [107–115].

The rate and efficiency of removing polluting substances can be improved by varying the amount of sargasso used, stirring speed, ion concentration, temperature and contact time [116]. On the other hand, modifying the pH can increase its biosorption capacity; pH is usually the most important factor to consider in terms of biosorption since it influences the charge of biomass surface. Sargasso contains high amounts of alginate within its cellular structures, with abundant carboxylic groups capable of capturing cations present in solution. Normally, the biosorption of cationic metals is carried out under acidic conditions related to the (dissociation constant) of carboxylic acids. At pH 5, biomass can reach up to 98% of its pollutant biosorption capacity. However, an increase or decrease in pH can reduce this capacity considerably [117]. A strong acidic environment promotes the protonation of sulfonic and carboxylic groups due to the presence of H^+ ions, which compete with metal ions and thus decrease biosorption [116–118]. In order to increase removal efficiency, mixtures of sargasso and other chemical agents have also been evaluated. Mansor et al. prepared membranes composed of cellulose and sargasso dentifolium and found removal efficiencies of 95.9% and 82.8% for Cd^{2+} and Zn^{2+}, respectively. The use of algae has also been reported for the sorption of heavy radionuclides [119]. It can also recover metal ions, such as gold and silver [120]. Sargasso is also efficient in removing organic dyes (e.g., Methylene blue used in the textile, paper, and cosmetic industries), with removal efficiencies of 95–98%. Sargasso has also been used for the removal of phenol from aqueous solutions [111,121,122]. Filters made with sargasso could be used for the treatment of wastewater and its later domestic, agricultural, or industrial use. In addition, the process of contaminant desorption has been evaluated as a possible reuse of sargasso. All of these sargasso-based filtration systems are scalable, efficient, reusable, inexpensive, and environmentally friendly.

5. Conclusions

The increasing invasion of sargasso onto beaches of the Mexican Caribbean has caused adverse effects on human health and the ecosystems there, as well as on tourism. Even though six years have passed since the massive quantities of sargasso began to arrive, a vicious circle still remains in which the stakeholders, including the government (Federation, State, Municipality), the tourist industry, the private enterprises dedicated to harvest and use of sargasso, academia and society, are coordinating their activities and plans. This has provoked intersectorial conflicts, with no clear leadership for integrating existing experiences and capabilities to solve the problem. Frequently, "lessons learned" are not incorporated when a "new" sargasso crisis emerges, starting over from zero again.

Effective long-term management strategies are needed to deal with the impact of the sargasso brown tides on highly sensitive coastal areas, such as seagrasses, coral reefs, mangroves, and tourist beaches. Improving the reliability and precision of detection and forecasting tools, to give more accurate information on location, time, and expected quantity of sargasso, is key to achieving this. Time series data obtained from satellite images and monitoring of beach cast volumes show there is high spatial and temporal variability in sargasso landings. In the Mexican Caribbean, the coastal area between Tulum and Playa del Carmen, followed by the areas between Puerto Morelos, Cancun and Sian Ka'an, have received most sargasso from 2016–2020. Until date, period the peak year was 2018, when the monthly cover was 4700 ha and the volume of beach cast sargasso in the northern sector was 3.2×10^3 m^3/km. Temporal patterns of the volumes of sargasso detected by the satellite coincided with patterns in biomass of samples collected at a beach in Puerto Morelos. This opens the possibility for the implementation of regional monitoring at specific sites in the open sea to prepare for future sargasso landings, although the volume of sargasso landings is highly variable, depending on wind speed and direction and sea surface currents [123] and coastline geomorphology. Thus, an effective regional early warning system will require several monitoring sites, both on the coast and in the open sea, and a better understanding of the dynamics of the sea surface currents (in neritic and oceanic zones) throughout the year.

The uncertainty in the time and the amount of sargasso arriving each year, and the lack of accurate forecasting models, pose a challenge for adequate management. Disposal of sargasso as a waste should be avoided given the geological conditions of the substrate, and associated underground water flows, as this may allow the leachates generated in decomposition to contaminate the water table and cause irreparable damage to the ecosystems and the water used for human consumption.

Given the high cost of sargasso contention, removal and transportation, it is vital to create industries that use large volumes of it. Sargasso biomass has many properties and advantages; it is a renewable and abundant source, reusable, and biodegradable. However, commercialization of uses means long-term storage of sargasso must be found. Until date, most efforts of valorization area still small-scale or have been only carried out in laboratories and their application in real, larger systems, such as effluents and coastal outfalls, still needs to be evaluated.

The creation of a circular economy, taking advantage of the massive sargasso influx is the best way forward if we are to mitigate damage to the environment and to the local society and economy.

Supplementary Materials: The following are available at http://www.mdpi.com/2073-4441/12/10/2908/s1, Figure S1: Massive sargasso landings in the Mexican Caribbean coast. Figure S2: Superficial evidence of the presence of groundwater flow systems and coastline type in the Yucatan Peninsula. Figure S3: Monitored beach in Puerto Morelos, after Hurricane Michael—October 2018. Figure S4: Loose of mangrove trees leaves when exposed for long periods to SBTs.

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