Brown Tides: Assessing the Past, Present, & Future State of Sargassum in Aruba Through a Mixed Methods Approach

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ABSTRACT:

In the last decade, Caribbean shores have been inundated with a floating seaweed known as Sargassum. In large amounts, Sargassum threatens biodiversity by suffocating nearshore ecosystems and decreases tourism levels due to its nauseating smell, putting small island environments and economies at risk. With little to no research conducted on the monitoring and cleanup opportunities of Sargassum in Aruba, I aimed to fill that gap with this thesis by identifying susceptible influx areas and potential impacts. In collecting both quantitative data using geographic information systems (GIS) and Sargassum specific monitoring software, as well as qualitative data through interviews, my research has explored the potential social, economic, and environmental consequences or opportunities that Aruba may face. I used this data to further visualize the spatial distribution and impacts of Sargassum such that my research findings could be applied within the larger Caribbean context.

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1. INTRODUCTION

Pelagic Sargassum is an understudied yet wildly important species of floating brown macroalgae native to the Sargasso Sea in the western Atlantic. There are over 60 species of Sargassum, two of which evolved to be holopelagic. Rather than attaching to a rock substrate on the seafloor, the *S. Natans VIII* and *S. Fluitans III* species are unique in that they stay afloat by means of small air bladders known as pneumatocysts, spending their lifetime drifting about the ocean gyre that is the Sargasso (Franks et al., 2016; Johns et al., 2020).

FIGURE 1: PELAGIC SARGASSUM IN LAC BAY, BONAIRE (OWN PHOTO).

Bound by the strong Gulf stream to the west, the Azores current to the north, the weaker Canary current to the east, and the Antilles current in the south, the Sargasso Sea is loosely defined by an elliptic zone in the western Atlantic influenced by various oceanographic features (Laffoley et al., 2011). This area is characterized by calm winds and cyclonic eddies which drive nutrient upwelling from the deep while pushing Sargassum into the gyre. It is here that the Sargassum has been known to multiply and consolidate into various sized clusters, forming so-called *windrows* or circular mats with long proceeding tails that can stretch for kilometers parallel to the direction of the wind (Ody et al., 2019) (Figure 2).

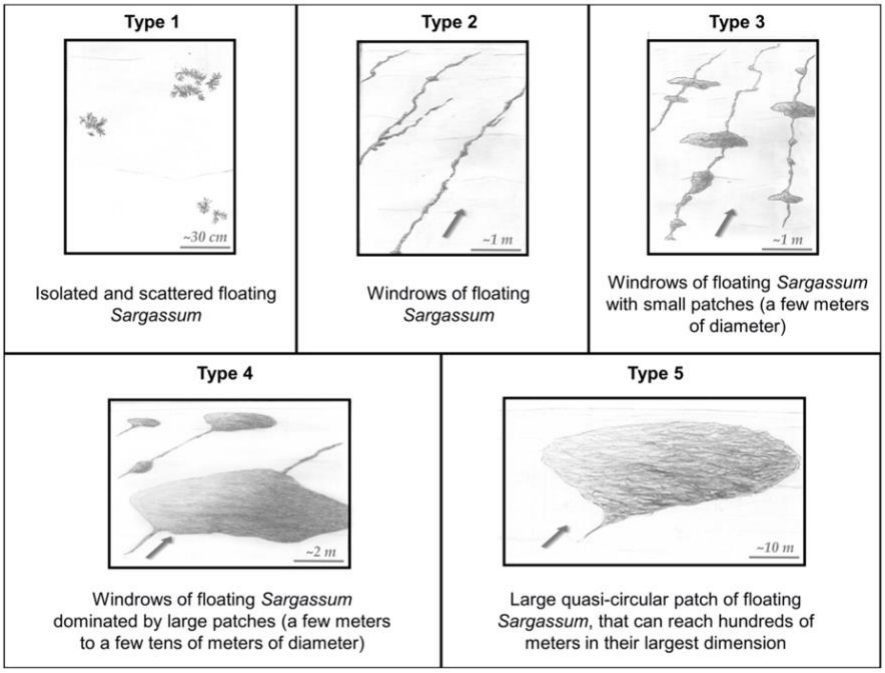

FIGURE 2: OVERVIEW OF WINDROW TYPES (ODY ET AL., 2019, PG. 5).

Windrows provide a unique offshore ecosystem that supports a variety of wildlife, including many endemic species (Ody et al., 2019). More than 145 invertebrate species, 127 species of fish, and many bird species have been associated with Sargassum, each making use of the floating biomass as a shelter, breeding ground, and feeding area (Laffoley et al., 2011). At the end of its lifecycle, Sargassum is eventually dragged below the ocean surface through Langmuir circulation flows where shallow vortices are formed by strong and sustained winds. Once dragged to a critical depth of around 135 meters, the hydrostatic pressure implodes the pneumatocysts that keep the Sargassum afloat, rendering it negatively buoyant (Gray et al., 2021). As a result, the Sargassum will continue to sink and part of the biomass will become available to the benthic community while the rest becomes incorporated into the deep-sea food chain. In fact, Sargassum has been found to deliver around 10% of the overall energy input of the food web in the Atlantic (Laffoley et al., 2011). The majority, however, contributes to Sargassum acting as a critical global carbon sink. The carbon stored in its biomass is taken out of the short-term carbon cycle as the Sargassum is transported to the benthic region where it will all eventually be incorporated into the benthic sediment (Gouvêa et al., 2020). To a lesser extent, Sargassum also acts as a carbon sink by producing calcite which locks away carbon by turning it into a solid form (Delgado et al., 2020). According to climate data and machine learning algorithms, it is estimated that Sargassum from the Sargasso Sea alone sequesters around 7.5 Pg C annually, comparable to that of other global blue carbon stocks such as mangroves, seagrass beds, and tidal marshes (Gouvêa et al., 2020).

Major concentrations of Sargassum have long been thought to be limited to the Sargasso Sea. However, the 21st century has seen a rapid change in Sargassum growth dynamics with unprecedented amounts recorded throughout the Caribbean and West Africa. Studies conducted prior to 2011 to track the movement of Sargassum in the Atlantic estimated that an average of one million tons of the biomass could be found in the Atlantic per year, with no evidence of Sargassum on the African coast (Laffoley et al., 2011). In 2018, this estimate was found to be closer to 20 million tons (Lindeman et al., 2021). While scientists are not certain of the cause behind this shift, more recent studies conducted using satellite imagery and geotagged drift buoys indicate that the origins of recent influxes can instead be traced to the equatorial Atlantic in the North Equatorial Recirculation Region (NERR), as shown in Figure 3 (Ardron et al., 2011; Franks et al., 2016). The research conducted by Franks et al. in 2011 was followed up in 2016 with additional evidence that a new circulation flow and breeding ground for Sargassum had formed between the West African and Eastern South American coasts, as depicted in Figure 3.

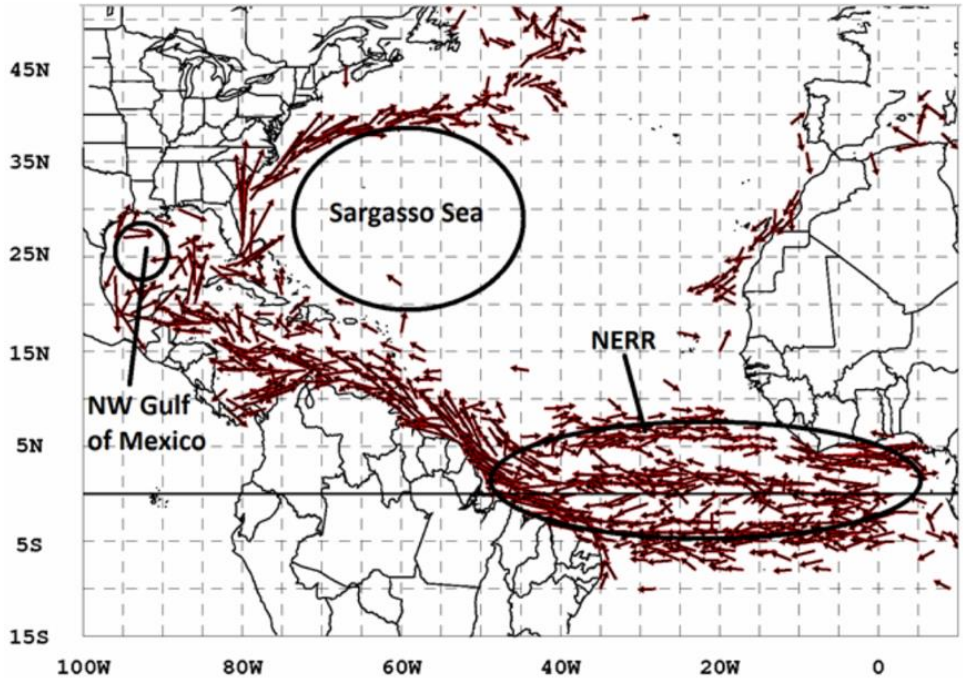

FIGURE 3: MAY OF THE SARGASSO SEA AND NERR (FRANKS ET AL., 2016, PG. 7).

This new consolidation region in the NERR has had an enormous impact on both the amounts of Sargassum in circulation and its impacts on the Caribbean. This is largely because of the warmer waters and large differences in nutrient availability which has had a dramatic effect on Sargassum's reproductive fragmentation rate. Higher nutrient waters allow Sargassum to double in biomass every 11 days, nearly 5 times faster when compared to lower nutrient waters that are more reflective of the Sargasso Sea (Franks et al., 2016). Although little data exists regarding the precise nutrient differences

between the Sargasso Sea and the NERR, studies indicate that excess nutrients like iron and phosphate blown in from the Sahara Desert mixed with excess runoff from the African and South American coasts are the main drivers behind the explosion of Sargassum growth in the Caribbean (Lindeman et al., 2021). This runoff is likely a result of sustained deforestation, subsequent erosion, and improper waste treatment from both the Congo River and Amazon basin (Ody et al., 2019). After Sargassum spends time circulating and fragmenting in the neritic waters, large amounts are transported north to the Southern Lesser Antilles via the North Brazil Current and towards the Eastern Caribbean via the North Equatorial Current (Franks et al., 2016). From there, it will make its way through the Greater Antilles, up the Central American coast, around the Gulf of Mexico, and eventually past Florida into the Sargasso Sea (Putman et al., 2018). During this journey, much of the floating Sargassum will end up on Caribbean shorelines. While Caribbean islands have always experienced small amounts of Sargassum washing up on beaches, the recent emergence of the NERR has led to alarming influxes which have effectively turned this native Atlantic species into an invasive threat. One commonly cited estimate reported 10,000 tons of Sargassum washing up on beaches per day during the 2015 Caribbean inundation with accumulations up to 3 meters thick in heavily hit areas (Cox et al., 2019; J. Milledge & Harvey, 2016).

FIGURE 4: 2018 SARGASSUM INUNDATION IN CURAÇAO (DCNA, 2019, PG 1).

Surprisingly, such an established system that offers a multitude of valuable ecosystem services offshore has turned into a widespread coastal problem. Since 2011, its proliferation in growth has indeed turned Sargassum into an environmental and economic disaster, having even been described as “the single greatest threat” in the Caribbean by the UWI Vice-Chancellor Sir Hilary Beckles (Cox et al., 2019; J. J. Milledge et al., 2020, PG. 1). While it may seem that more Sargassum would lead to larger

offshore ecosystems and more carbon sequestration, its growth has instead induced many social, environmental, and economical concerns.

1.1 Environmental Impacts of Sargassum

Upon reaching shore, Sargassum will accumulate and begin decomposing within 48 hours, creating similar problems to that of widespread algal blooms (Desrochers et al., 2020). For example, it will block light from penetrating to the seafloor where photosynthetic organisms rely on natural sunlight for their functioning. It will also accumulate and create anoxic environments, using all the available oxygen in the water which suffocates underwater flora and fauna. Eutrophication will follow as high levels of nitrates and phosphates are introduced into the nearshore systems. These aspects become especially troublesome when Sargassum inundates vulnerable ecosystems such as mangroves, seagrass beds, and coral reefs, which are abundant across Caribbean coastlines. For example, coastal Sargassum buildup can affect oxygen levels up to half a kilometer from shore and less than 20% of species in these systems can survive a prolonged state of hypoxia (Lindeman et al., 2021; Rodríguez-Martínez et al., 2019). This lack of oxygen stuns mangrove and seagrass productivity for the season and kills the polyps that give corals life, which leads to rapid coral bleaching (Johnson et al., 2021).

Beaches are also heavily disrupted, both from the natural and anthropogenic impacts associated with Sargassum beaching. While small amounts of Sargassum are good for nearshore fertilization and sand stabilization which both prevent erosion, large amounts of decomposing Sargassum have been shown to create a sandy sludge and deliver toxic concentrations of inorganic arsenic to the beaches, which is harmful to all surrounding biodiversity. In a 2014 study conducted in Martinique, Devault et al. tracked and analyzed a Sargassum patch of 34,000m^3 for arsenic content when it reached the shore. Their findings showed that this patch delivered over 210kg of highly toxic inorganic arsenic to the exposed shoreline in just a few days (Devault et al., 2021).

Applying these values to other influxes would mean that many islands receive several tons of this toxic metalloid on their coasts and beaches each year. Little data can be found on the bioavailability of arsenic and its impact on the surrounding terrestrial and nearshore environments, but implications may be severe. It has been shown that if sargassum were turned into fertilizer, arsenic concentrations would be around 125 mg/kg which exceeds the European limit by 2.5 times (J. J. Milledge et al., 2020). Many Caribbean shores are also important grounds for turtle nesting sites. When Sargassum piles up on beaches it covers turtle nests and creates an insurmountable barrier for turtle hatchlings to climb, dramatically decreasing their chances of survival. Additionally, when tourist beaches experience large

Sargassum accumulation, intensive removal methods using heavy machinery are often utilized to keep the beaches clean (DCNA, 2019; Gray et al., 2021; Vos et al., 2016). This process is very invasive as the sand trapped within the Sargassum will be removed from the beach and turtle nests may be crushed if not carefully monitored.

1.2 Economic Impacts of Sargassum

The Caribbean is one of the most tourism dependent areas in the world and is thus highly susceptible to external factors that may disrupt economic activity. Areas that experience large inundations of Sargassum on important tourism beaches are faced with the difficult task of carrying out cleanup operations. In places like Guadeloupe, Barbados, Punta Cana, or the Yucatan, Sargassum regularly accumulates in such amounts that it cuts off water access to those onshore. Fishermen cannot leave the harbor because their boats are surrounded by layers of Sargassum, tourists cannot swim or enjoy their time on the beach, and nearshore business operations are similarly stunned. The mayor of Quintana Roo estimated that in the 2017-2018 season, Sargassum alone led to a 35% decline in tourism (Gray et al., 2021). In Punta Cana, where tourism contributes around $2 billion to the GDP of the Dominican Republic annually, the 25% decline in tourism seen in 2018 equated to approximately $500 million in losses for just one season (Gray et al., 2021). Cleanup costs are also prohibitively expensive and require specialized machinery that has yet to be developed at scale. A single hotel front in Quintana Roo spends an average of $54,000 per month on Sargassum removal while the US government spends $3.5 million to keep 32 miles of the coastline along Galveston Island in Texas clear of the seaweed (Gray et al., 2021; J. J. Milledge et al., 2020). Several estimates have cited that removing Sargassum inundations from all Caribbean shorelines would require an annual investment of $120 million, which is still far less than the impact that Sargassum has on the cumulative Caribbean economies (Gray et al., 2021; Lindeman et al., 2021). There is therefore a large financial incentive to develop a widespread solution to the Sargassum problem.

1.3 Social impacts of Sargassum

Alongside the multitude of economic impacts, Sargassum accumulation and decomposition also has various social implications. The quality of life for coastal residents and the livelihoods of many who depend on coastal activity suffer throughout the Sargassum influx season. Some islands which take Sargassum off the beach to landfills reported a lack of space in disposal sites and resorted to dumping overflowing amounts on the properties of nearby homeowners (Oxenford et al., 2021). Latest reports have even claimed that Sargassum piles are being burned on the beaches as a last resort (S. Cox,

personal communication, April 21, 2022). Sargassum also has major health implications as it releases hydrogen sulfide during its decomposition process. While tourists are constantly on the move and have a high turnover rate, local residents and cleanup workers who are exposed to this toxic gas on a regular basis have been found to experience higher rates of various respiratory, cardiovascular, and neurological health problems (Saldarriaga-Hernandez et al., 2020). Between January and August of 2018, hydrogen sulfide related health complications totaled to 11,402 cases between the islands of Guadeloupe and Martinique alone (Devault et al., 2021). More immediate than the accompanying health problems is the smell of the hydrogen sulfide released from the decomposing seaweed. At best it has been described as repulsive and is thus one of the largest sources of complaints by locals throughout the Caribbean.

1.4 Current State of Sargassum Monitoring and Addressal

To limit the economic, environmental, and social impacts of Sargassum, several monitoring, cleanup, and disposal methods have been developed with varying levels of success. As much of the damage occurs within 2 days of reaching shore, it is important that Sargassum beaching events can be predicted to best allow for the prompt allocation of adequate cleanup resources. Many islands use various free and paid detection platforms to predict when and where Sargassum may land. Each of these platforms utilize Geographic Information Systems (GIS) as a tool to work with various types of satellite data and visualize the distribution and density of Sargassum across the Caribbean. The Satellite Based Sargassum Watch System (SaWS) from the University of South Florida, the Experimental Weekly Sargassum Inundation Report from the National Oceanic and Atmospheric Association (NOAA), and the Sargassum Outlook Bulletin from the University of the West Indies provide free and open access reports to Sargassum detection every week (Sargassum Information Hub, 2022). Unfortunately, the data from the SaWS require a specialist to interpret while the others only release information from the past week, meaning prediction possibilities are nonexistent. Alternatively, paid software platforms may allow for real time Sargassum detection, monitoring, and even near-future drift prediction models. The SAMtool offered by the French Satellite data company CLS is one such example that is widely used among those who require the most advanced sargassum models.

Each of these systems makes use of datasets from one or more satellite systems. Some of the first Sargassum specific GIS studies used the Medium Resolution Imaging Spectrometer (MERIS) in combination with the Maximum Chlorophyll Index (MCI) to differentiate between Sargassum and water in the ocean until it stopped functioning in 2012 (Gower & King, 2008; Hu et al., 2015; Lasquites et al., 2019; Wang & Hu, 2016). Post 2012, several other studies recommended using the Moderate

Resolution Imaging Spectroradiometer (MODIS) with the alternative floating algae index (AFAI) for slightly better resolution (250m) and more robust image interpretation options (Cuevas et al., 2018; Hu et al., 2015; Wang & Hu, 2016). Others have also validated and recommended the use of the more recent Sentinel 2 satellite platform with its Multi Spectral Imaging (MSI) sensor for detecting Sargassum (Lasquites et al., 2019; Miranda et al., 2018; Tjong, 2020).

The SAMtool uses a combination of six satellite instruments including MODIS-Aqua which measures data on visible and infrared radiation, Sentinel 3A & 3B which measures ocean surface color and topography, Sentinel 2A & 2B measuring vegetation, soil, and water cover, and Landsat-8 measuring various wavelengths for land change (Datastore, 2022). Together, these satellites allow for the SAMtool to locate Sargassum throughout the Caribbean on a daily basis, as well as provide drift forecasts indicating where the patches are likely to be up to 5 days in advance. Unfortunately, not all who are interested in such a complex detection and forecast tool are willing or able to pay the monthly fee of $2400 for access.

Instead, it is also possible to perform a similar task using GIS through powerful open programs like ArcGIS or Google Earth Engine (GEE). In the context of sargassum, these platforms can be easily used to make any number of tailored interpretations and predictions on Sargassum dynamics using the same free and open-source satellites that the SAMTool uses. This is an especially interesting option for islands that receive highly varied amounts of Sargassum throughout the season and thus have less incentive for a 24/7 paid monitoring service.

While there are several options for Sargassum monitoring, the question remains of what to do when the Sargassum arrives. A compilation of Sargassum projects can be found in the Sargassum Uses Guide produced by Anne Desrochers et al. of the center of resource management and environmental studies (CERMES) from the University of the West Indies. From crop production and bioenergy to bioplastics and pharmaceutical products, the Sargassum Use Guide highlights all Sargassum-derived products, local entrepreneur's work, and ongoing research and limitations in the field (Desrochers et al., 2020). Additionally, a novel Sargassum disposal pathway designed by Luke Gray in his MIT master's thesis provides a unique alternative solution to sargassum disposal and value creation. His described process aims to sink Sargassum in the deep ocean to replicate its natural lifecycle. In doing so, it minimizes beach impact as no heavy machinery is needed to transport the Sargassum onshore, cuts landfill dumping costs and arsenic leaching, and eliminates methane and hydrogen sulfide emissions. However, this sinking method involves using pumps costing upwards of 150k USD each which is a major limitation for small island states (Gray et al., 2021).

2. BACKGROUND

Not all parts of the Caribbean have experienced the recent surge of Sargassum equally. From differences in geophysical positioning to the surrounding currents and wind directions, each island may have vastly different experiences with Sargassum inundations. When looking for island-specific Sargassum data and possible addressal strategies, there is a lack of specific knowledge as most research has been conducted over a larger scope of the entire Caribbean region. Focusing on a smaller subset of the Caribbean islands may offer a unique perspective and understanding of Sargassum dynamics and related impacts at a more local scale. Through this research, I will explore this relationship through the lens of Aruba in comparison to nearby Curaçao and Bonaire (hereby referred to as the ABC islands) which make up part of the Lower Dutch Antilles. The ABC islands are a prime example of a cluster of islands that receive highly varied amounts of Sargassum despite their proximity.

Being positioned in succession above Venezuela at the edge of the Guiana Current, Bonaire is the first of the three islands to receive any influx of Sargassum, followed by Curaçao and Aruba, respectively (see Figure 5). This can be attributed to the established currents and trade winds that push Sargassum down this trajectory (Putman et al., 2018).

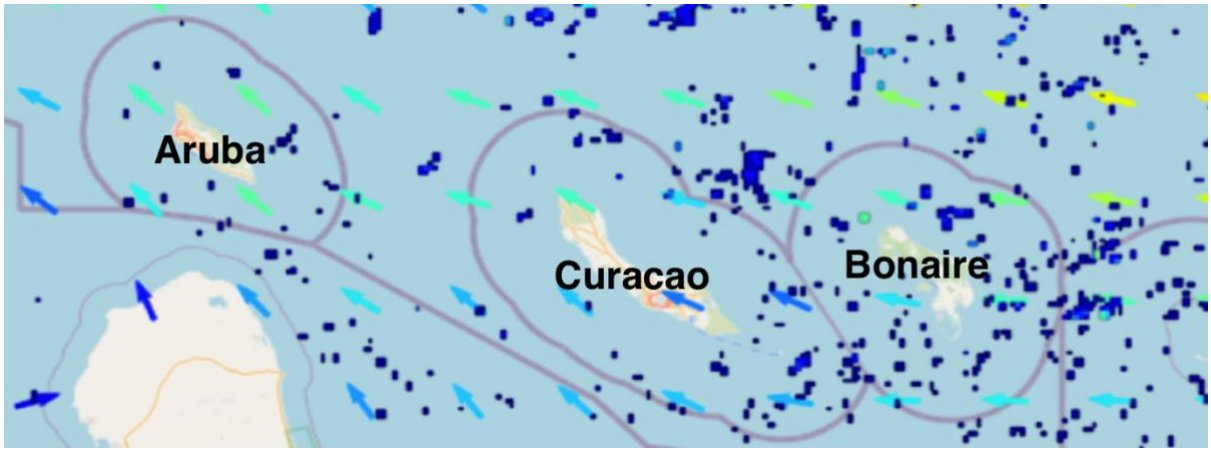

FIGURE 5: POSITIONING OF THE ABC ISLANDS IN RELATION TO THE CURRENT DIRECTION SHOWN WITH ARROWS. STRENGTH INCREASES WITH WARMER COLORS. THE IMAGE WAS TAKEN AS A SCREENSHOT FROM THE SAMTOOL SOFTWARE PROGRAM.

In addition to the various amounts the three islands receive, associated impacts of Sargassum beaching are also felt differently due to the relative locations of both sensitive ecosystems and tourism areas. In March of 2018, Bonaire experienced its largest influx to date which completely covered the entire windward coastline and filled the Lagun, Washikemba, and Lac Bays (DCNA, 2019) (Figure 6). This

killed thousands of fish and resulted in the die-off of critical seagrass patches and several hectares of mangroves. In the same month, Boka Ascencion in Curaçao was so full of Sargassum that water in the bay was barely visible, leading to similar devastating ecological impacts. Contrarily, no abnormal Sargassum influx was recorded on the Aruban coasts during that time (DCNA, 2019).

FIGURE 6: SARGASSUM ACCUMULATION IN LAC BAY, BONAIRE 2018. PICTURE SOURCED FROM HTTPS://BONAIRE.NU/2018/03/09/OPRUIMEN-SARGASSUM-GAAT-FOODIES/.

Nonetheless, Sargassum does still make its way to Aruban shores with reports having been published confirming beaching events (Gibbs & Thijzen, 2018). Talking with the people of Aruba, locals have acknowledged its occasional presence and limited impacts. The marine park management plan completed in 2019 has also identified Sargassum as a threat that needs more research, monitoring, and possible addressal strategies put in place (Parke Marino Aruba et al., 2020).

Fortunately, some research relevant to the potential impacts of Sargassum has already been conducted and will be used within the context of this thesis. Several conservation tools utilizing the power of machine learning and satellite data have mapped out the global distribution of vulnerable ecosystems including coral reefs, seagrasses, and mangroves around the ABC islands. For example, the MANGROVE_FORESTS dataset from the Landsat Satellite maps out global mangrove distribution and can be used to identify and accordingly classify areas with mangrove cover across the ABC islands (Giri et al., 2011). Similarly, the Allen Coral Atlas dataset from the Planet Satellite classifies the world's shallow coastal areas and can be used to visualize both coral reef and seagrass distribution globally (*CoralMapping/AllenCoralAtlas*, 2020). Together, these datasets build a comprehensive picture of the

distribution of critical ecosystems which were used to explain and further predict the environmental impact Sargassum may have on the ABC islands.

Another critical aspect of understanding potential Sargassum impacts looks at where human activity takes place on the islands. While the capital cities of each island are located on the leeward side, Aruba's windward side is especially desolate due to the desert landscape, strong waves, currents, and difficult beach access. Both Bonaire and Curaçao have more visited regions of the windward coast making Sargassum influxes more impactful on human and economic activity.

Besides having different impact areas, islands that receive various amounts of Sargassum also have various cleanup and disposal options. Having an overview of what removal strategies are currently being used, along with information on how sargassum is disposed of or could be utilized, will give valuable insight into limitations and areas of improvement moving forward. These options will be highlighted in the discussion section based on the following publications:

Topic	Literature
Compilation of the current and potential uses of Sargassum	Sargassum Uses Guide: A resource for Caribbean researchers, entrepreneurs and policy makers (Desrochers et al., 2020)
Potential valorization pathways based on the chemical composition of Sargassum	Golden Tides: Problem or Golden Opportunity? The Valorisation of *Sargassum* from Beach Inundations (J. Milledge & Harvey, 2016)
Multi-Method analysis of challenges experienced by Sargassum stakeholders in finding value in the biomass	Challenges of Turning the Sargassum Crisis into Gold: Current Constraints and Implications for the Caribbean (Oxenford et al., 2021)
Potential for Sargassum to be used in biosorption and bioaccumulation	Bioremediation potential of Sargassum sp. biomass to tackle pollution in coastal ecosystems: Circular economy approach (Saldarriaga-Hernandez et al., 2020)
Potential for Sargassum to be used for biogas and fertiliser production using hydrothermal pretreatment and anaerobic digestion technologies	E!ciency of hydrothermal pretreatment on the anaerobic digestion of pelagic Sargassum for biogas and fertiliser recovery (Thompson et al., 2020)
Novel nearshore collection and offshore sinking method to mitigate sargassum derived problems	Caribbean-Wide, Negative Emissions Solution to *Sargassum* spp. Low-Cost Collection Device and Sustainable Disposal Method (Gray et al., 2021)

Table 1: LITERATURE TO BE USED IN DISCUSSION SECTION REGARDING CLEANUP AND DISPOSAL METHODS FOR SARGASSUM.

With the severity of environmental, economic, and social impacts resonating throughout the Caribbean, more research must be conducted to create a baseline understanding regarding Sargassum dynamics on both the local and Caribbean-wide levels. This thesis will build upon local knowledge from the ABC islands and past Sargassum related research to create this baseline for Aruba. With this understanding, proposals regarding the need for future monitoring, preparation, and cleanup strategies can be discussed.

3. Research Questions

My thesis aims to contribute to the local understanding of Sargassum influxes and to provide a recommendation for an effective addressal strategy to minimize future impacts. To do so, several questions must be answered:

RQ 1 - (How) Can GIS be used to visualize Sargassum accumulation on the ABC coastlines?

RQ 2 - Do Sargassum influxes differ between the ABC islands? If so, how can these differences be explained?

RQ 3 - What are the implications of future beaching scenarios on the Aruban coastal environment and tourism sector?

RQ 4 - What are the current and alternative strategies for addressing Sargassum accumulation in Aruba?

4. Research Methods

Making assumptions on the various impacts of Sargassum can only be useful if its accumulation can be visualized in relation to key economic areas and sensitive ecosystem locations. A combination of qualitative and quantitative research approaches was utilized to gather the necessary data for addressing these research questions. Alongside my independent GIS work, an important aspect of this research lied in the involvement of the community. I acknowledged that Aruban natives have a much better understanding of their island than I as a foreigner ever could, which prompted me to incorporate the information I gathered to better engage with my research questions through a local lens. A very clear and effective way to gather such knowledge is through conducting interviews. Therefore, I started this research process by meeting with various relevant stakeholders including fishermen, managers

from the National Parks of each island, and government officials from several departments in Aruba. GIS work was conducted simultaneously but independently from the interview process, meaning the research questions weren't necessarily answered sequentially, or that parts of the questions were answered at different stages throughout the research period.

Interviewees were chosen using a snowball sampling strategy based on recommendations from previous meetings. Due to the connected nature of people working on a small island, I was able to effectively set up meetings with relevant stakeholders of various backgrounds using this sampling method. In combination with information from ocean current charts and my understanding of relevant literature, these interviews supported my answer to research questions 2, 3, & 4 surrounding differences in Sargassum influxes, implications, and addressal strategies. Engaging with fishermen helped me identify oceanographic trends that lead to differences in Sargassum accumulation and to understand the impacts Sargassum has had on local people (Questions 2 & 3). Talking with park members from ARIKOK, STINAPA, and CARMABI helped with understanding the environmental implications of Sargassum influxes and the state of action from government and volunteer organizations to limit Sargassum impacts (Questions 2, 3 & 4). Finally, talking with government officials clarified if and what kind of protocols are in place to address Sargassum, and gave an indication as to the attitude and urgency the government has towards this problem (Questions 3 & 4). Together, this interview process built upon my understanding of the situation surrounding Sargassum between the various islands and became my main source of community involvement throughout my research period.

Alongside the interviews, I also focused on using GIS to identify sensitive ecosystem locations to gather data on key areas that would be heavily impacted by Sargassum. Of particular interest were the mangrove forests, coral reefs, and seagrass areas of each island, which were gathered from the Landsat Mangrove and Allen Coral Atlas datasets. Identifying these particularly vulnerable areas set the baseline for my answer to research question 3 on Sargassum influx implications.

With these vulnerable locations identified, a comparison with major Sargassum accumulation areas was necessary to assess the severity of influx implications for each of the ABC islands. Based on literature, it was clear that sargassum identification was possible using GIS, but I still had to verify past findings myself before being able to build upon them. I first had to validate that I could indeed use Sentinel imagery to effectively differentiate Sargassum accumulation on the coast. This process directly addressed research question 1 regarding the feasibility of using GIS to map sargassum accumulation. Using the standard RGB bands 4,3,2 from the Sentinel satellite does not deliver effective contrast between Sargassum and its surroundings, calling for the need of a false-color composite. Using the

combination of visible and near-infrared (8), green (3), and blue (2) bands, effective imaging contrast between water and Sargassum could be achieved (Tjong, 2020). The contrast between mangroves and accumulated Sargassum is less distinguishable but still possible using pre-and-post influx images. I started by identifying Sargassum patches in the open ocean and proceeded to focus on 2 bays per island that, through newspaper reports and personal communication with Sietske van der Wal (National Park Manager in Aruba), had been identified to be the most impacted areas. These include Lac Bay and Lagun in Bonaire, Boka Ascencion and Sint Joris Bay in Curaçao, and Boca Prins and Boca Grandi in Aruba as shown in Figure 7 below.

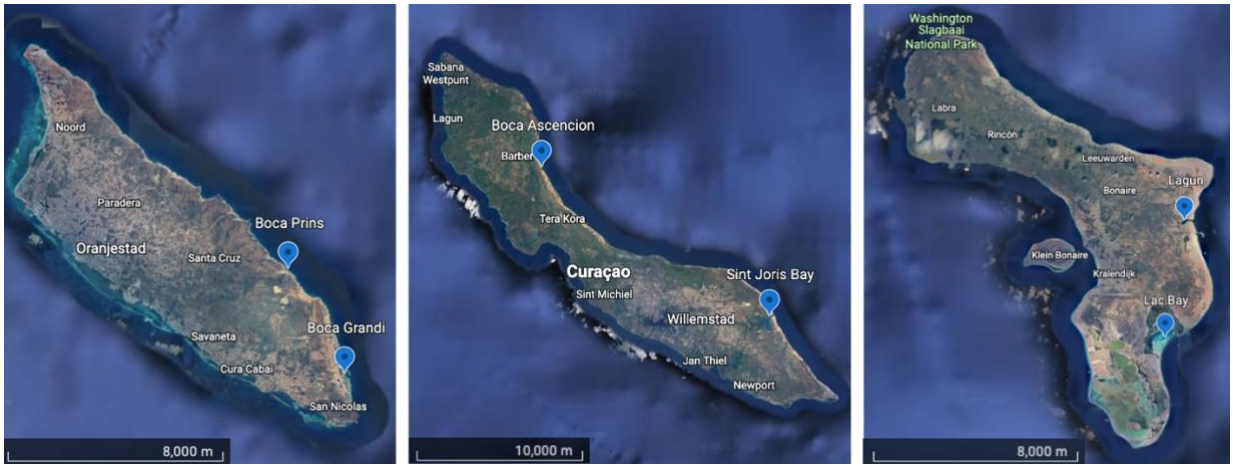

FIGURE 7: LAYOUT OF SELECTED BAYS FOR SATELLITE COMPARISON IN ARUBA (LEFT), CURAÇAO (MIDDLE), AND BONAIRE (RIGHT). CREATED USING A GOOGLE EARTH FEATURE COLLECTION.

If Sargassum was observed in Aruba, it had likely ended up in Bonaire and Curaçao in the preceding days. With the average travel time of five Days between a sargassum influx hitting Bonaire and Aruba, the Bonaire influx dates could be extrapolated by subtracting five days from the known Aruba beaching date (S. van der Wal, personal communication, February 16, 2022). Once I identified a Sargassum influx in Aruba, I first took pictures and then followed up on the ground observation using Sentinel imagery to distinguish the accumulation that occurred at each of the ABC islands. I also flew to Bonaire after the Sargassum influx to see firsthand how the island was impacted and to photograph the effects of the significant influx. Next, I compared the satellite images to that of the SAMtool output from the appropriate dates to verify my findings. With all three methods displaying coinciding information, it was clear that the Sentinel data could be used to correctly identify beached and incoming Sargassum.

After this verification, several four-year time-series animations could be constructed for each of the six areas of interest depicted in Figure 7. If successful, research question 1 regarding the use of

GIS for meaningful sargassum visualization would be verified. Data between January 1st, 2018 and April 20th, 2022 was used since these last 4 years have been some of the most severe. The Sentinel Hub EO browser, an online tool for retrieving Sentinel imagery was used to compile all images within the date range showing less than 20% cloud cover. While the program automatically discarded all images with more than 20% cloud cover, I manually removed the remaining images that were unusable due to unfavorable shadow or cloud cover positioned directly over the coastal areas. A scale between 50 and 200 meters was used depending on the size of the desired region. Boca Prins, the smallest of the 6 locations of interest, called for a resolution of 50 meters while the larger areas including Lac Bay, Lagun, and St Joris needed a scale of at least 200 meters. A speed of three frames per second (fps) was chosen to move through images to keep each animation under one minute in length.

Using both the animations and findings regarding sensitive ecosystem locations, an impact score could be roughly calculated to assess the severity of the state of sargassum for each bay, supporting answers to questions 2 and 3. This impact score is comprised of several quantitative and qualitative values. First, a Sargassum presence percentage was evaluated based on the ratio of frames with Sargassum to those without. Next, an area cover multiplier was added to describe the average size of Sargassum patches. This value was approximated using the map scale against the size of the various influx patches in comparison to the other bays. Finally, a vulnerability factor was included to indicate the extent of ecological and economical importance of each bay. This value was determined through the presence of mangroves, seagrasses, coral reefs, and tourist activities, as identified through the GIS datasets and interview process. Both the area cover and vulnerability factor were evaluated on a 1-4 scale where 1 indicates small Sargassum patches and low vulnerability, while 4 indicates large Sargassum patches and high vulnerability. The overall impact score was quantified as the product of the Sargassum presence percentage with the two 1-4 values.

Finally, research question 4 regarding addressal strategies had to be answered. Various use cases and valorization pathways of Sargassum are described in the literature found in Table 1, but an effective and scalable solution is still lacking. This prompted me to propose an alternative addressal strategy that builds upon Luke Gray's sinking disposal method as a potential solution for various small island states. After working closely with Luke and his team at Sargassum Ocean Sequestration (SOS Carbon) in Punta Cana, I saw the need for a cheaper and lower emissions Sargassum disposal method. I have therefore developed and tested an alternative sinking-by-weight system that eliminates the need for any expensive pumps. During my fieldwork period, I modeled, constructed, and launched a small-scale prototype to assess its feasibility. This pilot was funded by Sink-It, an innovative company looking

to transform the carbon market by developing credible carbon negative projects. A 3-D computer aided design (CAD) model of the prototype was outsourced through a mechanical engineer, materials were gathered via hardware stores, and the pilot was conducted with the help of Jair Rasmein, an Aruban fisherman. If successful, this system could be implemented across many islands at scale, regardless of their Sargassum situation. Recommendations for a sinking location were identified using bathymetry maps and current charts.

5. Results

The results section follows the same logical structure as described in the methods. First, interview results are presented to set the baseline understanding of the sargassum situation among the ABC islands. Next GIS is used to map out the spatial distribution of sensitive ecosystems. Later, GIS is again used to identify sargassum via an initial verification method followed by a practical application through the animations. Finally, results from the pilot showcasing a novel disposal method are shown.

5.1 Interviews

To help answer questions 2, 3, and 4 on influx differences, beaching implications, and addressal strategies, I conducted interviews with local stakeholders from each of the ABC islands including fishermen, national park managers, and government officials (Table 2). Each interview contextualized the state of Sargassum on the respective island where the interviewee was from.

Name	Position	Location	Date
Gisbert Boekhoudt	Director DNM	Aruba	2/14/2022
Sietske van der Wal	Park Manager	Aruba	2/16/2022
Fernando Eduardo	Fisherman	Aruba	2/22/2022
Marlon Croes	Director DOW	Aruba	2/22/2022
Sabine Engel	Marine Biologist	Bonaire	3/18/2022
Sargassum Truck Driver	Government Worker	Bonaire	3/19/2022
Roderick Westrbeek	Fisherman	Bonaire	3/21/2022
Judith Raming	Park Manager	Bonaire	4/22/2022
Jair Britten	Marine Specialist	Aruba	4/27/2022
Erik Houtepen	Park Consultant	Curaçao	4/26/2022

TABLE 2: AN OVERVIEW OF ALL CONDUCTED INTERVIEWS.

Questions 2, 3: Fishermen

The fishermen from Aruba and Bonaire showed very different attitudes towards Sargassum. While the Aruban fisherman stressed that Sargassum had been of no concern, the fisherman from Bonaire stressed it had caused major complications in his work over the last decade.

Fernando Eduardo, a generational Aruban fisherman explained that Sargassum is an afterthought when compared to the impact tourism has had on those from his line of work. He explained that Aruba receives very little Sargassum, nowhere near enough to be a nuisance for fishermen. In fact, he explained that smaller Sargassum patches found offshore are beneficial to fishermen as they attract all types of large fish and are generally very productive areas (F. Eduardo, personal communication, February 22, 2022). Eduardo explained that if Sargassum does wash up on Aruban shores, it is only on the windward coast where fishermen rarely go due to the rough conditions and large waves. Additionally, he mentioned that currents occasionally change direction such that Sargassum may wash up on the leeward side. However, fishermen rarely go out at that time because fish behavior changes along with the current, leading to much lower yields (F. Eduardo, personal communication, February 22, 2022).

Talking with Roderick Westrbeek, a fisherman from Bonaire, it was clear that his feelings towards Sargassum were much different from Fernando's. Roderick and his fishing crew operate on the northern edge of Lac Bay, one of Bonaire's most impacted areas. They use a method of surface trawling in which a large net is dragged behind a boat to catch fish. When Sargassum patches inundate the whole bay, the nets clog with seaweed and removing it wastes time and effort. Sometimes, the Sargassum comes in such amounts that it surrounds their boats, making the exit and entrance from their dock much harder as the motors get caught in the seaweed (R. Westrbeek, personal communication, March 21, 2022). Luckily, Sargassum hasn't stunned their entire fishing operation and is still just seen as a major nuisance that can be dealt with through enough effort.

Questions 2, 3, 4: Marine Park Managers

A similar dichotomy in attitude towards Sargassum could be seen through the park managers I spoke with in Aruba and Curaçao compared to Bonaire. The park managers from Aruba and Curaçao were unphased by the scope of the problem on their islands and explained that there are more pressing issues to focus on. In contrast, the national park and government agencies in Bonaire were heavily invested in Sargassum monitoring, removal, and disposal with a clear central focus on conservation efforts.

Sietske van der Wal, a marine park manager from the Aruba National Park Foundation (FPNA) confirmed that Sargassum is not regarded as a critical issue in Aruba due to the minimal amounts that land on the Aruban coast. She explained that while Sargassum does wash up in small quantities in nearly every 'Boca' or inlet on the windward side of the island, the protocols in place call for letting nature take its course (S. van der Wal, personal communication, February 16, 2022). Most often, the sea will drag deposited Sargassum from the beaches back into the water. In cases where it remains on the beach for several days, some workers may be sent to "rake and spread" the Sargassum further back on the beach to "speed up decomposition and ameliorate the beach sediment" (S. van der Wal, personal communication, February 16, 2022). In fact, beach erosion has been identified to be one of the biggest problems on the windward coast, and the limited amounts of Sargassum that Aruba receives may counteract the erosion process (S. van der Wal, personal communication, February 16, 2022). Sietske is also closely connected to the Aruban turtle organization TurtugAruba which deals with protecting Aruba's sea turtles and their nesting sites. She assured me that there is clear communication regarding nesting site locations with the DOW, the organization in Aruba that handles Sargassum cleanup.

Erik Houtepen, the head of consultancy at the Caribbean Research and Management of Biodiversity Foundation (CARMABI) in Curaçao provided the same details as Sietske. Protocols instruct for nature to take its course as Sargassum is not at the forefront of concern due to its limited presence. Nine in ten influxes will be carried back to sea without human intervention. However, Boca Ascencion does receive large amounts several times a year which fills the bay and threatens the seagrasses and turtles that use this bay as an annual nesting location (E. Houtepen, personal communication, April 26, 2022). Leftover oil booms are used in Sint Joris Bay to direct any Sargassum into two pockets on the north side where sargassum will accumulate and decompose naturally (E. Houtepen, personal communication, April 26, 2022).

Sabine Engel, a marine biologist involved with Bonaire's Mangrove Maniacs and STINAPA, and Judith Raming, STINAPA's marine park manager, have had a much more direct relationship with Sargassum over the years. Unlike Aruba and Curaçao, Bonaire annually gets inundated with overwhelming amounts of Sargassum which has a profound effect on the neighboring ecosystems and wildlife (J. Raming, personal communication, April 22, 2022). Most prominently, the protected area of Lac Bay is directly in line with the wind and current directions, making it particularly prone to influxes. Sabine cited that it's home to over 280 hectares of mangroves and is a very important seagrass area that attracts all types of fauna (S. Engel, personal communication, March 18, 2022). Sargassum is a direct threat to these sensitive ecosystems, piling up in amounts that at times, can reach 2 meters in

depth. This leads to large hypoxic areas that kill all surrounding flora and fauna including seagrasses, mangroves, and various types of fish and crab species (S. Engel, personal communication, March 18, 2022). All this matter decomposes and releases large amounts of methane and hydrogen sulfide, to the extent that workers and volunteers must occasionally stop removal operations due to the toxic concentrations of this nauseating gas. Unfortunately, animals are not limited by safety protocols. Many species including Bonaire's flamingo feed on the decaying fauna and get profoundly sick from ingesting excessive amounts of sulfur (S. Engel, personal communication, March 18, 2022). Neither the government nor the volunteers have enough resources and manpower to stop this invasion, but efforts have been made to install floating barriers or 'booms' to strategically direct Sargassum away from ecologically sensitive areas. Foam barriers equipped with a mesh net underneath to stop sargassum from moving underneath the barrier have proved to be successful. Unfortunately, these booms can only be positioned within the bay itself rather than at the entrance which would prevent Sargassum from ever entering. This is because of the strong waves and bathymetry of Bonaire which has very steep nearshore drop-offs, limiting possible anchoring points for the barriers (J. Raming, personal communication, April 22, 2022). Sentinel data and monitoring systems like CLS are checked daily by members from STINAPA, but even the best detection methods can't prepare islands like Bonaire for incoming Sargassum when the influx overpowers the capabilities of prevention and cleanup operations.

As part of my research, I was able to fly from Aruba to Bonaire for several days after it was hit by a large Sargassum influx. Thanks to Sabine, I was able to see first-hand the impacts of Sargassum pileups and cleanup operations. It became clear just how toxic Sargassum could become upon reaching the coast, especially when inundating seagrass beds and mangrove systems. While at Punta Calbas within Lac Bay, I discussed with a government commissioned Sargassum truck driver what specific heavy machinery is used to clean various areas. From custom excavator buckets to landfill dumping costs, it became clear that conducting a Sargassum cleanup is not only a toxic task but also an expensive one. The driver mentioned that after the last influx, 10-15 truckloads were being taken from this location every day for the 23 days the cleanup operations lasted. From a receipt I was shown, an average cost per dump would equal to around $120 at $9 per ton of waste and 12,500 kg per truckload (Sargassum Truck Driver, personal communication, March 19, 2022).

FIGURE 8: TRUCK LOADING SARGASSUM PILE TO BE TAKEN TO THE LANDFILL (OWN PHOTO).

Questions 3, 4: Government Members

Another important perspective comes from the government officials and policymakers relevant to Sargassum work. Both directors were aware of the Sargassum problem and had implemented satisfactory protocols to deal with the limited amounts Aruba experienced.

Gisbert Boekhoudt, director of the Directie Natuur en Milieu (DNM) in Aruba was especially helpful in relaying information on the severity of the state of Sargassum and the procedures in place for its cleanup and disposal. Gisbert made it clear that Sargassum in Aruba was seen as a "concern but not a threat". Compared to Bonaire which receives a regular substantial influx requiring cleanup, Aruba is only severely impacted an average of once a year (G. Boekhoudt, personal communication, February 14, 2022). Confirming what Sietske explained, Gisbert clarified that Sargassum sometimes washes up on the windward shores, but cleanup would only ever be organized along the tourist beaches on the leeward coast. If Sargassum approaches from this side, the real danger lies within people's panic as many mistake the patch for an oil spill. Hotel managers promptly request aid in removal to prevent any negative responses from the tourists. When I asked Gisbert about his thoughts on Aruba making use of a Sargassum-specific satellite detection software, I was informed that the CLS SAMtool was used over a trial period several years ago. However, it was underutilized due to the spread of information via social media. Indeed, since Bonaire is always the first in line to receive incoming Sargassum, their posts on social media platforms regarding the severity of the influx give the successive islands a heads up (G. Boekhoudt, personal communication, February 14, 2022). While this method is not very accurate, Gisbert explained that it has proved sufficient to make paying for detection software unnecessary.

I also had the pleasure of speaking with Marlon Croes, the director at Public Works Aruba (DOW), who guided me through the Sargassum cleanup and disposal process. When the DOW receives notice about a Sargassum influx, they first send personnel to do a scouting and assessment of the situation followed by an evaluation of precautionary measures (M. Croes, personal communication, February 22, 2022). They decide if the amount should be left alone, cleaned up by hand, or if heavy machinery will be needed. Next, they consult with TurtugAruba regarding any possible interference with nesting sites and, if all is cleared, equipment is gathered and contractors, truck drivers, loaders, and rakers are sent to perform the cleanup. The next part of the process involves the disposal site. Rather than taking the Sargassum to the landfill, Marlon explained that any truckload of Sargassum is taken to an old quarry site where it will be sun-dried and buried with sand to quench the smell (M. Croes, personal communication, February 22, 2022). While this is a straightforward option, it requires several work-intensive steps and has the negative side effects of producing hydrogen sulfide and methane alongside arsenic leaching. Additionally, Marlon stressed that if a more sustainable solution could be found and validated, the DOW would coordinate to implement a better strategy for the next large influx.

5.2 GIS Imagery

GIS was used to map out key impact locations, create Sargassum influx animations, and compare where they overlap to answer research questions 1, 2, and 3.

5.2.1 Identification of Ecosystems Sensitive to Sargassum

Since Sargassum accumulation induces hypoxia in nearshore waters, mangrove, seagrass, and coral reef areas are disproportionally negatively affected. To understand the vulnerability of these ecosystems across the ABC islands, I first visualized their spatial distribution. This is very relevant information for answering question 3 regarding the implications of future Sargassum beaching events because areas with vulnerable ecosystems and high influx rates will face larger impacts.

Mangrove distribution could be easily identified using the LANDSAT_MANGROVE_FORESTS dataset through Google Earth Engine (Figure 9) (Giri et al., 2011). Comparing the three islands, the main mangrove areas in Bonaire and Curaçao are much more exposed to Sargassum being on the windward side of the island, whereas the Aruban mangroves are sheltered on the leeward side of the island (Figure 9). Additionally, the Aruban mangroves are more dispersed across several coastal locations which increases their resilience against any particular Sargassum event.

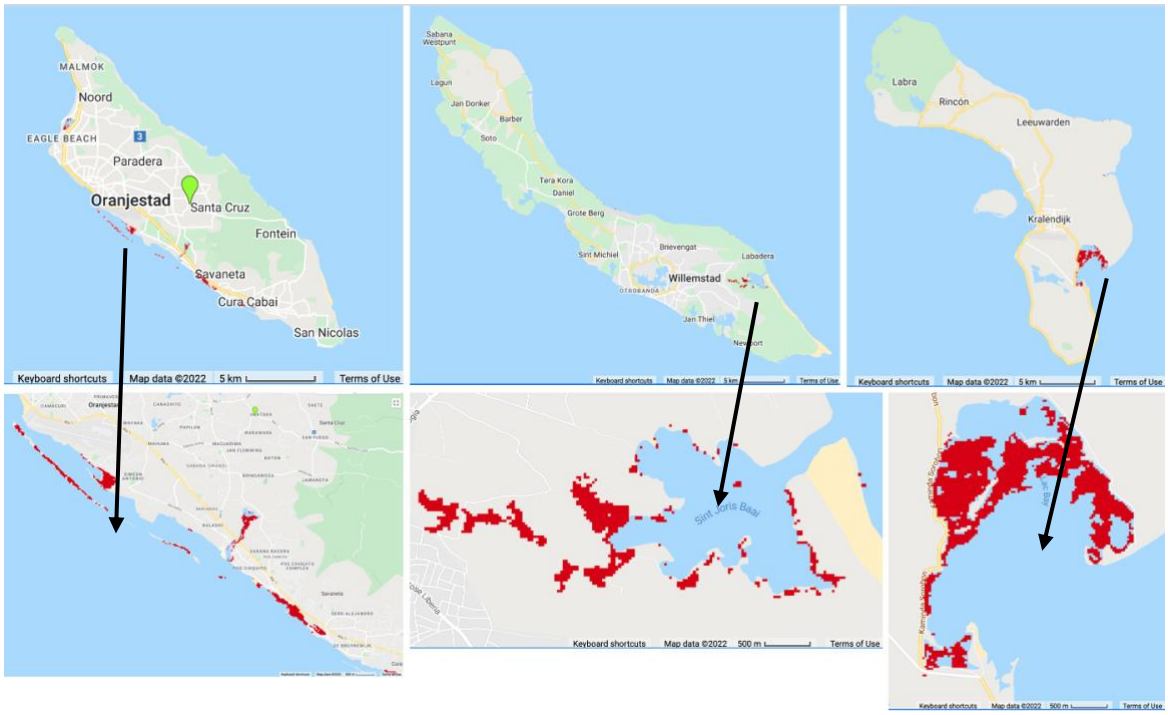

FIGURE 9: MANGROVE DISTRIBUTION IN THE ABC ISLANDS MADE USING THE LANDSAT MANGROVE FORESTS DATASET THROUGH GOOGLE EARTH ENGINE. ISLANDS WERE SET AT A 5KM SCALE, AND KEY AREAS (BELOW) WERE SET AT A 500M SCALE.

Mapping out coral reefs was conducted in a similar manner using the Allen Coral Atlas dataset through Google Earth Engine. A legend for the benthic cover types can be found in Figure 10. Looking at the results displayed below, Aruba appears to have extensive coral reef and some seagrass cover, particularly on the leeward side of the island, but also near the potential influx bays (Figure 11). Curaçao has less coral cover and few seagrass locations. Curaçao's Sint Joris Bay appears to not be classified while Boca Ascencion has some coral reef presence along the inlet of the Bay (Figure 12). Bonaire also has extensive coral reef cover around the whole island and Lagun is comparable to Curaçao's Boca Ascencion in that the Boca itself is primarily rock with reef cover outside the inlet (Figure 13). Bonaire's Lac Bay shows the largest range of benthic covers with large areas of coral reefs and seagrasses alongside sandy and rocky areas (Figure 13).

	Sand - Sand is any soft-bottom area dominated by fine unconsolidated sediments.
	Rubble - Rubble is any habitat featuring loose, rough fragments of broken reef material.
	Rock - Rock is any exposed area of hard bare substrate.
	Seagrass - Seagrass is any habitat where seagrass is the dominant biota.
	Coral/Algae - Coral/Algae is any hard-bottom area supporting living coral and/or algae.

FIGURE 10: ALLEN CORAL ATLAS COLOR LEGEND (*CORALMAPPING/ALLENCORALATLAS*, 2020). LEGEND IS APPLICABLE FOR FIGURES 11,12 &13.

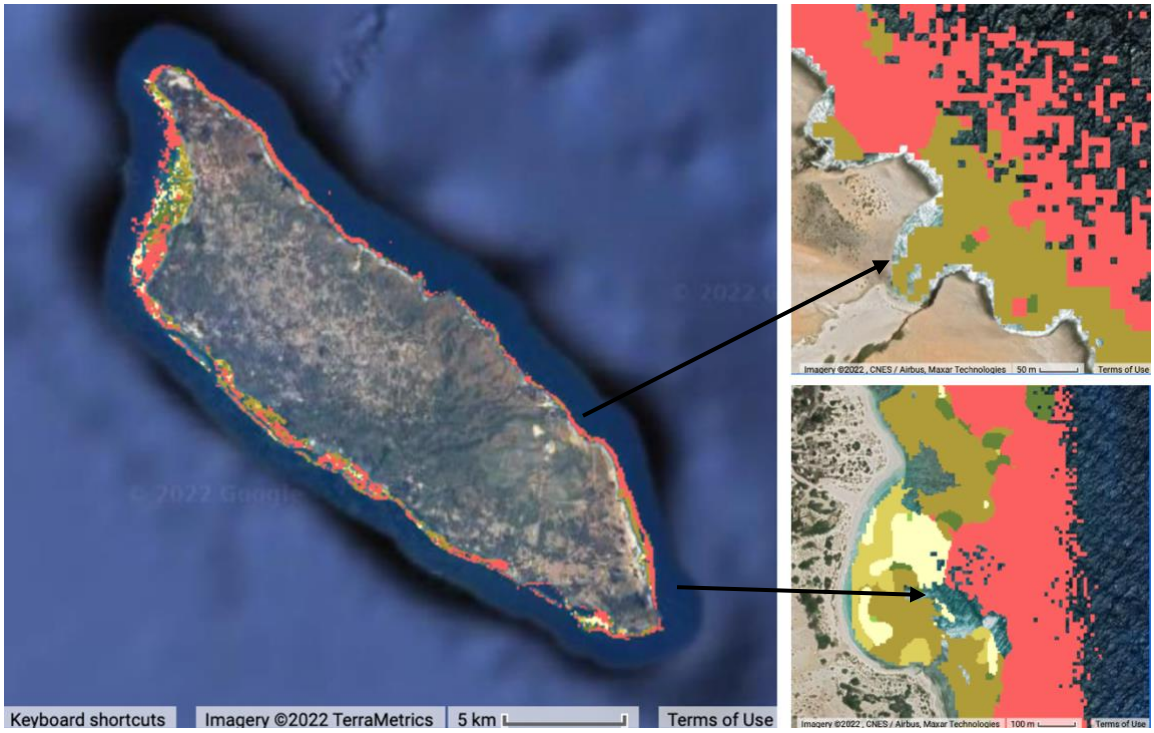

FIGURE 11: BENTHIC CHARACTERIZATION OF COASTAL AREAS IN ARUBA. MADE USING THE ALLEN CORAL ATLAS THROUGH GOOGLE EARTH ENGINE. BOCA PRINS (TOP-RIGHT) AND BOCA GRANDI (BOTTOM-RIGHT).

FIGURE 12: BENTHIC CHARACTERIZATION OF COASTAL AREAS IN CURAÇAO. MADE USING THE ALLEN CORAL ATLAS THROUGH GOOGLE EARTH ENGINE. BOCA ASCENCION (TOP-RIGHT) AND SINT JORIS BAY (BOTTOM-RIGHT).

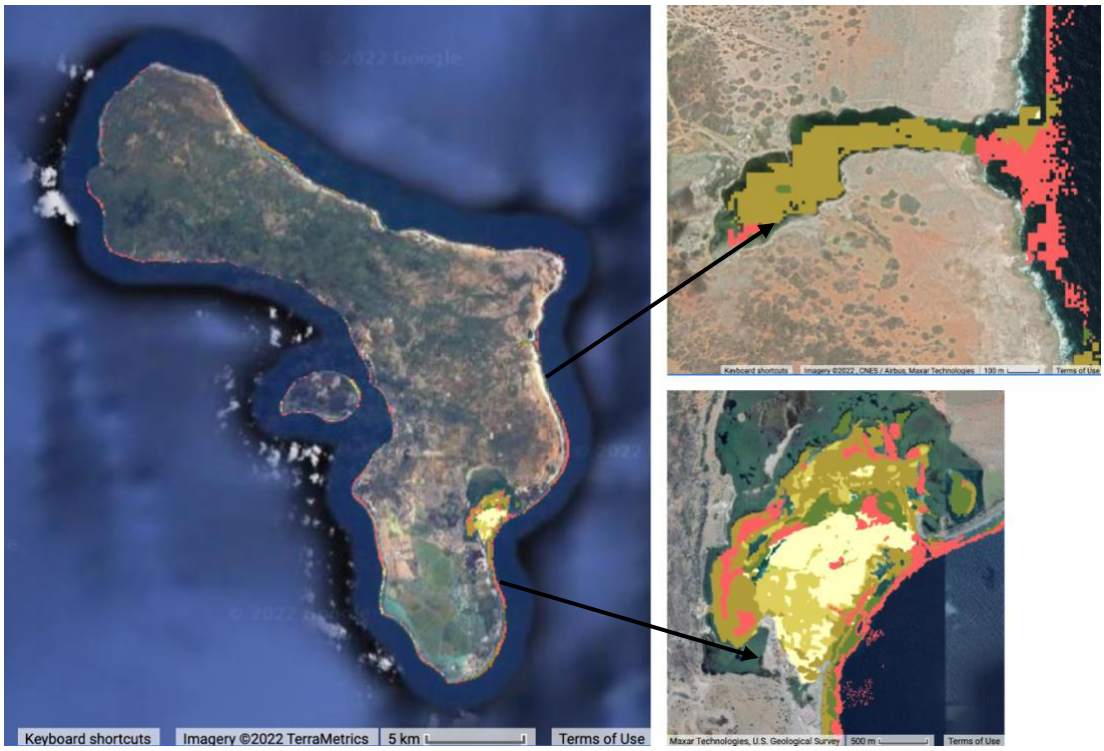

FIGURE 13: BENTHIC CHARACTERIZATION OF COASTAL AREAS IN BONAIRE. MADE USING THE ALLEN CORAL ATLAS THROUGH GOOGLE EARTH ENGINE. LAGUN (TOP-RIGHT) AND LAC BAY (BOTTOM-RIGHT).

5.2.2 IDENTIFICATION OF SARGASSUM

Once the distribution of sensitive ecosystems was clear, Sentinel data could be used to identify where sargassum was landing in comparison. A false-color composite overlay using the 8,3, and 2 bands was used to ensure greater contrast between Sargassum and its surroundings. This was first verified over open water as shown in figure 14 below, and later along the ABC coastlines in the most susceptible bays. With these images differentiating Sargassum, question 1 could be definitively answered.

FIGURE 14: FALSE-COLOR COMPOSITE IMAGE OF OPEN OCEAN SARGASSUM WINDROWS. MADE USING SENTINAL IMAGERY USING GOOGLE EARTH ENGINE.

Next, individual Sentinel images taken from key influx bays were compared to both the CLS software and personal ground truthing images I took in Aruba and Bonaire from the same (or nearest possible) dates (Figures 16 & 17). The date of the images was identified based on in-situ observations when sargassum appeared on the beach in Aruba. I first spotted sargassum on the north shore of Aruba at Boca Grandi on the 24th of February 2022 and again on the 7th of March 2022 (Figure 15). The earliest Sentinel Image I could take to depict this influx on each of the ABC islands was on the 26th of February. No clear Sentinel images could be used to depict the second influx date due to sustained cloud cover and gaps in the dataset. However, ground truthing images were taken for both influx dates as they are independent of the atmospheric conditions (Figure 15). Likewise, the combination of satellite datasets used in the SAMtool increases the resilience of the tool so Sargassum could be detected every day, regardless of unfavorable conditions or missing data from an individual satellite.

FIGURE 15: GROUND TRUTHING IMAGES OF SARGASSUM TAKEN AT BOCA GRANDI, ARUBA. PICTURES WERE TAKEN ON 24/2/2022 (LEFT) AND 7/3/2022 (RIGHT) (OWN PHOTOS).

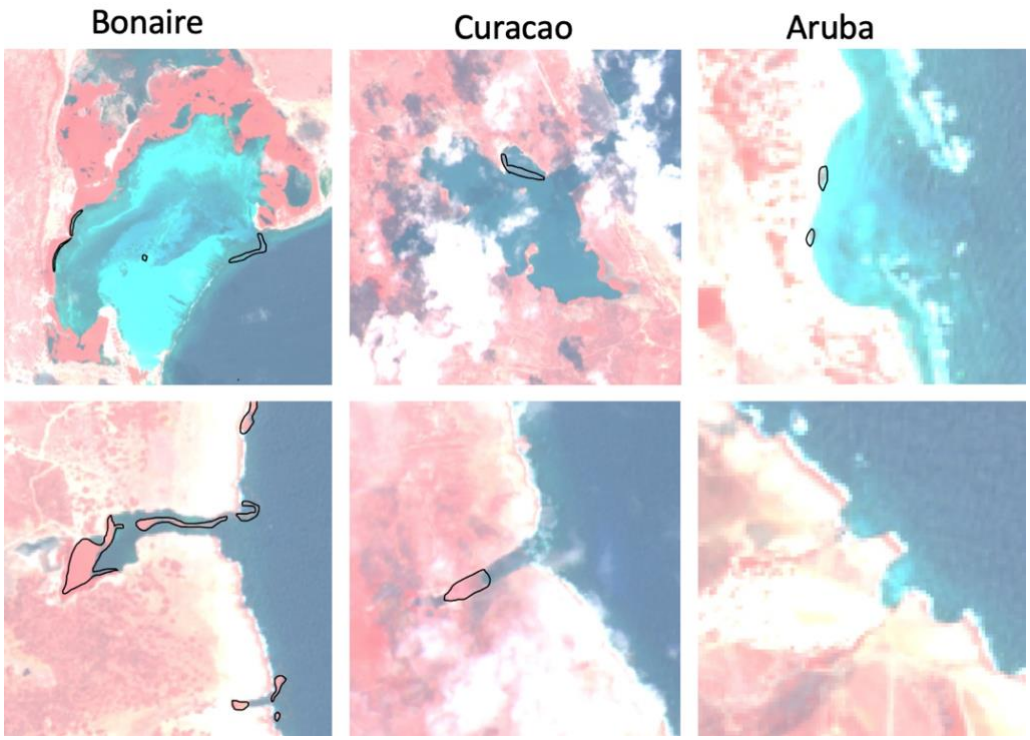

FIGURE 16: 26/2/2022 SARGASSUM IDENTIFICATION IN THE ABC ISLANDS. SARGASSUM IS CIRCLED IN BLACK. LOCATIONS ARE AS FOLLOWS: LAC BAY (TOP LEFT), LAGUN (BOTTOM LEFT), SINT JORIS BAY (TOP MIDDLE), BOCA ASCENCION (BOTTOM MIDDLE), BOCA GRANDI (TOP RIGHT), BOCA PRINS (BOTTOM RIGHT).

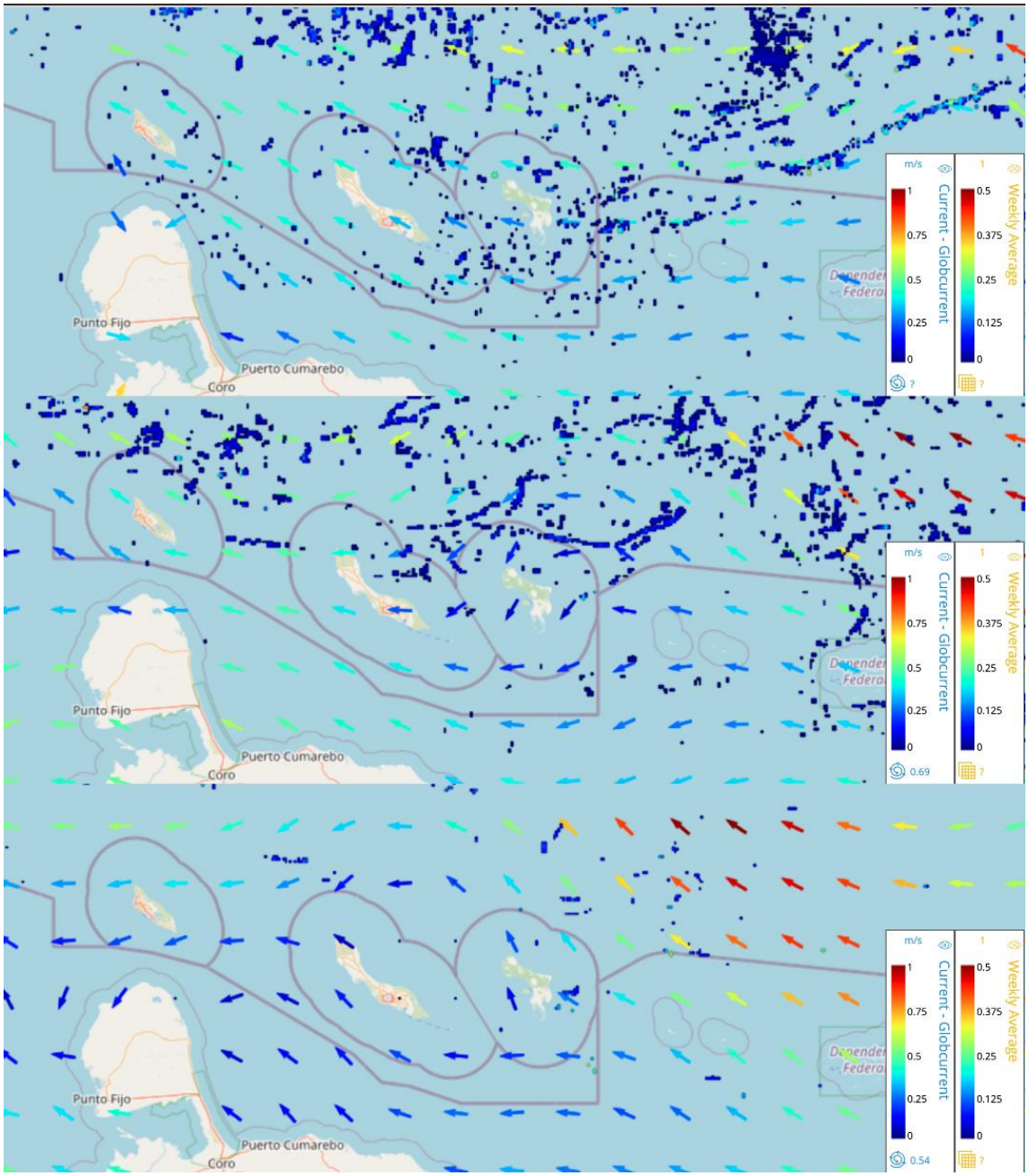

FIGURE 17: SAMTOOL USED TO TRACK SARGASSUM AND COMPARE OCEAN CURRENTS. WARMER COLORS INDICATE STRONGER CURRENTS. IMAGE DATES ARE AS FOLLOWS: TOP 26/2/2022, MIDDLE 7/3/2022, BOTTOM 14/3/2022.

In examining the area cover of Sargassum in the images, Bonaire clearly received much larger quantities in Lac Bay and Lagun than Aruba did in Boca Prins or Boca Grandi, while Curaçao received moderate amounts in Sint Joris Bay and Boca Ascencion (Figure 16). On the 18th of March 2022, I flew down to Bonaire intending to volunteer with the Sargassum clean up, talk with those who work within the field, and examine how much sargassum was left in the impacted bays three weeks after the initial influx. Even though the patches looked small from an aerial view, in person they stretched for hundreds

of meters and were incredibly dense with the Sargassum compressing over added time and force (Figure 18). Both government and volunteer cleanup efforts lasted 23 days in Bonaire with more Sargassum still to be cleaned up. Among the Sargassum were dead marine life and suffocating mangroves, accompanied by a nauseating smell.

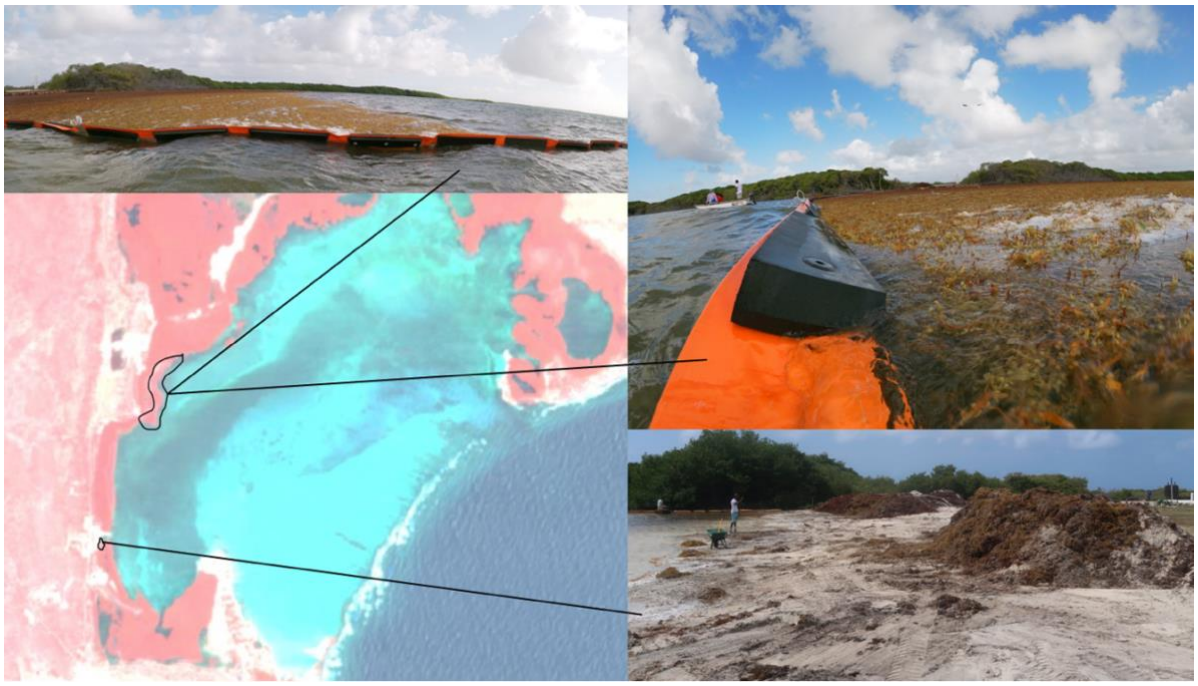

FIGURE 18: SARGASSUM ACCUMULATION IN LAC BAY WITH GROUND-TRUTHING IMAGES 21/3/2022 (OWN PHOTOS).

With this ground confirmation that Sargassum could be correctly distinguished in nearshore areas, it became clear that making the influx animation would be possible by creating a timeseries of every suitable image since January of 2018. Since the scale of the whole island was too big in relation to the total influxes, six individual animations were made: one for each of the key influx bays. Individual frames from each of the animations can be extrapolated to look just like the example shown below in Figure 19. Sargassum can be distinguished as any inconsistent red addition to the coastline. Animations can be accessed through the links, and an impact score was calculated as shown in Table 3.

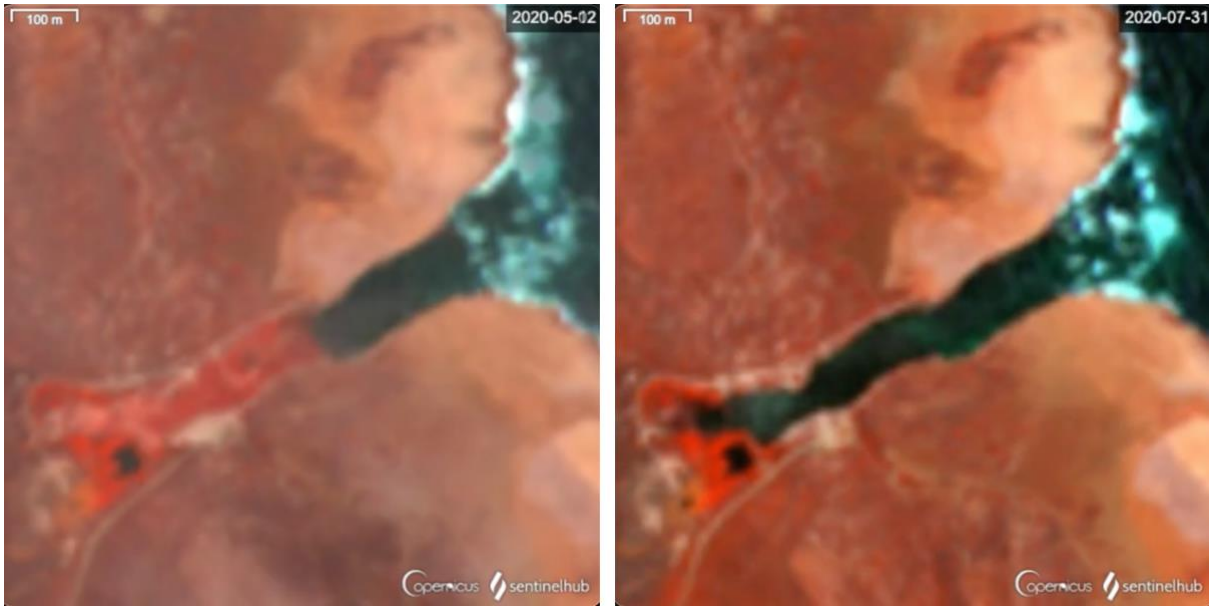

FIGURE 19: EXAMPLE OF ANIMATION FRAMES SHOWING CURAÇAO'S BOCA ASCENCION WITH AND WITHOUT SARGASSUM.

Influx Animations	Sargassum Presence (Jan 2018 – April 2022)	Average Area Cover (A) (1-4)	Vulnerability Factor (V) (1-4)	Impact Score (P x A x V)
Lac Bay, Bonaire	12%	4	4	**1,92**
Lagun, Bonaire	14%	3	3	**1,26**
Sint Joris Bay, Curaçao	10%	2	2	**0,60**
Boca Ascencion, Curaçao	17%	3	3	**1,53**
Boca Grandi, Aruba	8%	1	1	**0,08**
Boca Prins, Aruba	7%	1	2	**0,14**

TABLE 3: LINKS TO INFLUX ANIMATIONS PER BAY. ANIMATIONS MADE USING SENTINEL HUB EO BROWSER AND POSTED ON VIMEO. IN THE (1-4) INDEX, 1 INDICATES THE LOWEST, AND 4 INDICATES THE HIGHEST A AND V VALUES.

These animations and associated impact scores provide the most accurate and holistic evaluation regarding the intensity and impact of sargassum among the most susceptible impact areas of the ABC islands. These values make it clear that both influxes and associated impacts do indeed differ between the ABC islands which is critical for answering questions 2 and 3.

5.3 Disposal Method – Sinking Pilot

The Sargassum problem is in dire need of a solution and islands including Aruba, Bonaire, and Curaçao need a cleanup method that minimizes impacts and costs. Expanding on Luke Gray's proposed offshore sinking strategy, I proposed a low-cost alternative method that utilizes the same sinking principles as the pumping method but instead sinks the Sargassum to depth with a recoverable net and weight system shown in Figure 20.

FIGURE 20: SINK BY WEIGHT 3D CAD MODEL(LEFT) AND PROTOTPYE (RIGHT) (OWN PHOTOS).

As a proof of concept, I gathered the materials needed to perform a pilot. With the help of Jair Britten, a local spearfisherman, farmer, and maritime specialist, we gathered Sargassum from the North shore and tested the sinking method using his boat near Aruba's Spanish Lagoon (Figures 21 & 22).

FIGURE 21: ANCHORING AT THE SINKING PILOT LOCATION WITH JAIR BRITTEN 27/3/2022 (OWN PHOTO).

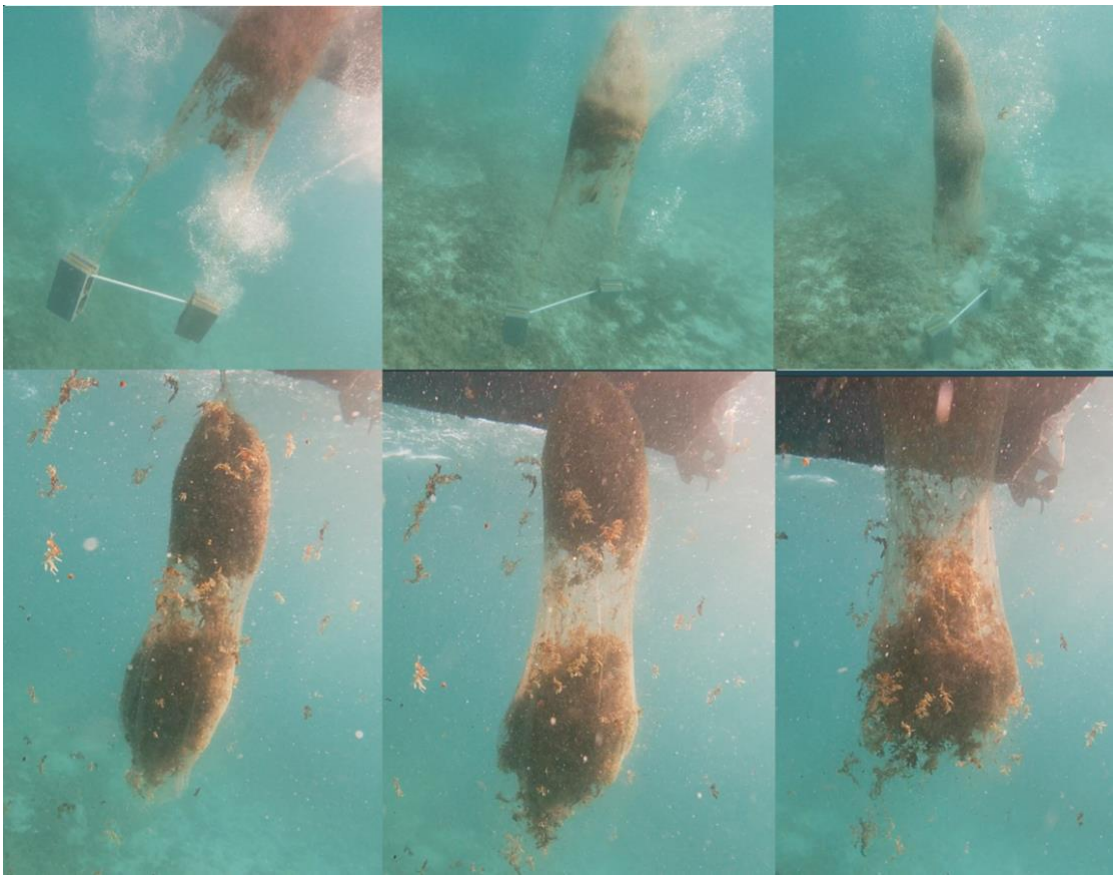

FIGURE 22: SINKING PILOT IMAGES SHOWING NET MECHANISM SINKING AND RETRACTING, LEAVING SARGASSUM BEHIND (OWN PHOTOS).

The pilot proved to be moderately successful. Unfortunately, the hand-stitched part of the net gave way under the weight of the whole system. This meant the mechanism that held the net open no longer functioned as the net was retracted back to the surface, leading to the Sargassum getting stuck, and only half escaping the net. A modified pilot building off these results will be launched in the Dominican Republic in June 2022 with the help of SOS Carbon. Possibilities regarding the application of this disposal method will be evaluated and shared with the DOW in Aruba for future applications.

6. Discussion

A mixed methods approach proved to be a very effective way to gather relevant data and insight into each next step throughout the research period. The information I obtained from the interview process proved to be very valuable for my research. Not only did I verify my literature findings through a local lens, but I also gathered island-specific knowledge and made connections I would have otherwise overlooked. Talking with stakeholders also validated just how much of a research gap there is in the understanding of Sargassum dynamics within the context of individual islands. This reinforced that my research answers add to this local understanding and future addressal framework.

RQ 1: (How and) Can GIS be used to visualize Sargassum accumulation on the ABC coastlines?

As expected, based on previous Sargassum classification studies, GIS can be an effective means for identifying offshore Sargassum patches and estimating the severity of an incoming influx. Currently, each free and open access platform has different limitations with tradeoffs in the spatial or temporal domain including long revisiting time, sensitivity to weather conditions, or poor resolution. Satellites with longer revising times and fewer options for masking cloud cover are susceptible to having larger gaps between useable images in the dataset, making it less useful. Fortunately, the flexibility, accessibility, and ease of use of GIS as a supplementary tool makes it an especially interesting option for small island states, especially when multiple satellites are combined to offer both their benefits. In this thesis, I used GIS in various ways to add to the sphere of knowledge surrounding Sargassum influx locations and potential impacts. Individual Sentinel images were compiled from both offshore and coastal areas of the ABC islands as an identification method for incoming sargassum. These images demonstrated that, by using a false-color composite with the 8, 3, and 2 bands, Sargassum could be effectively differentiated from both water and land. Finally, GIS was used to create multiple animations showing the influx of Sargassum at two key areas of each ABC island over a 4-year period. These

animations ultimately showcased the most useful way I used GIS to visualize sargassum and proved to be valuable for answering research questions 2 and 3.

RQ 2: Do Sargassum influxes differ between the ABC islands? If so, how can these differences be explained?

Through literature, various interviews, satellite image analysis, and in situ observations, it's very clear that Bonaire is most impacted by Sargassum influxes followed by Curaçao and Aruba, respectively. These findings may be explained through the positioning of the islands in succession along the route of the established winds and currents. Indeed, it's clear that Bonaire is at the front line of any southern-based Sargassum trajectory and thus acts as a shield for Curaçao and Aruba, while Curaçao in turn further protects Aruba down the line. This trend is evident from both the initial validation images, as well as in the influx animations which visualize these various influx amounts. These findings were to be expected given the large extent to which sargassum movement is directed by winds and currents. After researching the established trade wind and current directions, much of my fieldwork revolved around gathering proof to substantiate my initial claim using both qualitative and quantitative evidence. While data differentiating between influx events on the windward versus leeward sides of each island weren't gathered, it was more than clear that the sheltering effect made influxes on the leeward side only possible during storm events when conditions shift dramatically. The same sheltering effect can to a lesser extent also explain the differences between influxes among the ABC islands.

Table 3 shows the relative frequency and scale of sargassum influxes for each bay. Between both bays, Bonaire and Curaçao were found to receive Sargassum a similar number of times, but the influxes reaching Bonaire were larger on average. Additionally, while Sargassum in Bonaire is regularly removed, Sargassum in Curaçao is left untouched until nature takes care of it. This means that any larger influx is more likely to appear over multiple frames in the animation, decreasing the true frequency value but increasing the vulnerability of each influx event when compared to Bonaire. Thus, although Boca Ascencion scored higher on the impact scale than Lagun, these values would likely be comparable if similar cleanup efforts were conducted in Curaçao. Both the frequency and scale of Sargassum influxes in Bonaire and Curaçao were much larger than in Aruba. This is reflected both visually and through the impact scores for which Aruba scored significantly lower than Bonaire and Curaçao.

RQ 3: What are the implications of future beaching scenarios on the Aruban coastal environment and tourism sector?

With no literature indicating the severity of sargassum influxes in the past, this question held the most uncertainty when I started my fieldwork. After the first few interviews upon my arrival in Aruba, it became clear that this island has historically experienced minimal Sargassum presence. With the absence of human activity and vulnerable ecosystems on the windward coast, Sargassum is not expected to be of major concern in the coming years. This was clearly backed up by the overall impact scores calculated from the animations, the GIS analysis of sensitive ecosystem distribution, and through interview findings. On the windward side, large waves are likely to take back most of the Sargassum that beaches while strong currents will push out the remainder that sinks to the coral reefs. However, more research regarding the effects of Sargassum decomposition is needed for more concrete conclusions. Thankfully, clear and consistent communication between those involved in Sargassum cleanup and turtle protection organizations indicates little impact on turtle nesting sites. Tourism strictly takes place on the leeward side of the island where Sargassum influxes occur even less frequently compared to the windward side, so minimal impact is expected. The largest effects on tourism may be experienced with individual beaching events over a short temporal scale. However, it is important to note that even though there may not be much Sargassum historically, annual influxes do fluctuate, and currents may periodically overturn leading to a shift in Sargassum dynamics (F. Eduardo, personal communication, February 22, 2022). Because of this, there is always the possibility of a sporadic influx indicating that adequate protocols should exist. Having a local procedure will allow Aruba and other small island states to deal with the influx in the most appropriate and sustainable manner.

RQ 4: What are the current and alternative strategies for addressing Sargassum accumulation in Aruba?

This question can be split into two parts highlighting what *is* being done versus what *could* be done to address current limitations. The Sargassum Uses Guide provides an overview of all current strategies surrounding Sargassum cleanup, use, and disposal. Ultimately, there are limited options that provide a feasible and affordable cleanup method. Sargassum specific cleanup boats exist but have limited capacity and are prohibitively expensive. Floating barriers can guide Sargassum away from high-impact areas including major beaches and sensitive ecosystems, but do not solve any cleanup issues. The use of heavy machinery is in turn a very invasive cleanup method that should only be used as a last resort compared to hand collection. Additionally, the various valorization pathways aiming to create value out of sargassum have yet to deliver a clear solution. Due to the unfavorable chemical composition of the biomass, limited use cases are applicable at scale in a SIS. From fertilizer production and bioenergy conversion to bioplastics and pharmaceutical products, many projects have attempted

to create value out of the biomass with limited success or options to scale (Desrochers et al., 2020). Several papers address the many challenges and limitations such as the unpredictability of supply, intensive processing steps, high costs and regulatory issues that ultimately lead to the failure of many Sargassum centered projects (J. Milledge & Harvey, 2016; Oxenford et al., 2021; Saldarriaga-Hernandez et al., 2020). However, some projects have delivered value and simply require more funding to validate their conversion process. One particular use case surrounding anaerobic digestion for bioenergy applications has been identified to hold more potential than the rest. Anaerobic digestion, especially when combined with a hydrothermal pretreatment step, can capture the methane released by decomposing Sargassum (Desrochers et al., 2020; J. Milledge & Harvey, 2016; Thompson et al., 2020). It requires little pretreatment, is more forgiving with various amounts and conditions, and could be done by individuals in their backyard or on an industrial scale.

Any use case would simultaneously solve the disposal issue once Sargassum is collected from beaches and nearshore areas. However, almost all small island states dump collected sargassum at a disposal site such as a landfill or open pit to decompose. Gray's sinking proposal may hold potential as it creates value in a different way than Sargassum-derived products. Rather than making a physical product, sinking Sargassum contributes to carbon negative climate efforts by avoiding any emissions that would be produced by decomposition or any transformation process (Gray et al., 2021). A carbon negative solution such as this could be eligible for carbon credit approval, which would allow for credits to a sold via various voluntary or regulatory compliance markets.

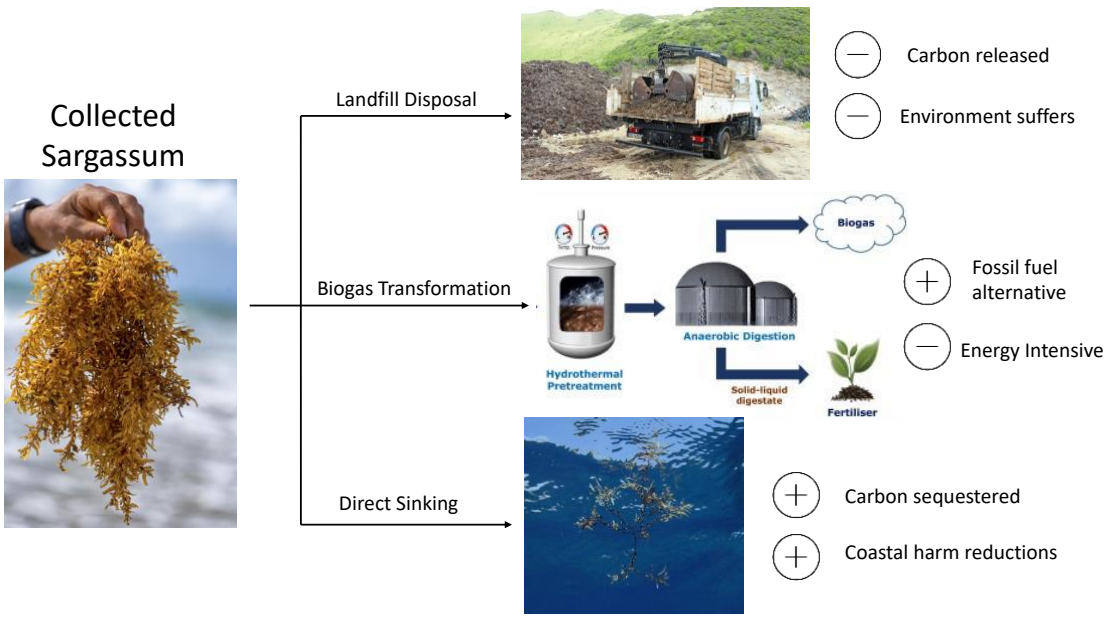

FIGURE 23: VALORIZATION PATHWAYS (OWN DIAGRAM).

6.2 Proposed Future Framework

There are various ways to approach the problem with Sargassum cleanup and disposal, with some options showing clear and extensive added value. Sinking Sargassum will limit the impact heavy machinery use has on beaches, prevent arsenic from leaching into the ground, and will lead to greenhouse gas emission avoidance. With a reallocation of human and physical resources from terrestrial heavy machinery such as bulldozers and dump trucks to a barge and crane system, only an investment in a dedicated sinking net would be necessary to modify the current landfill-based disposal method.

My proposed modification to Luke's barge and pump system to a cheaper and less resource-intensive sink-by-weight system has the potential to be a novel addressable strategy. Unfortunately, the pilot project showcasing the sinking process did not fully work as intended. Due to the weak nature of the net, the prototype broke which resulted in the net closing and only half of the sargassum escaping. Additionally, the Sargassum itself was still buoyant at this shallow depth, which is a critical factor that will be in our favor at scale. Limited time, money, and resources made a full sinking pilot unfeasible, but the results call for a second pilot with better resources and conditions. With the help of Aruba's DOW, this method should be further explored with a repeated pilot. A small barge and 5-10 m^3 net could be used to dispose of a near-future Sargassum influx offshore of the leeward coast. Even if the critical depth is not reached, currents would push the sargassum away from the island so the disposal issue would still be avoided.

Based on ocean currents and depth charts, a proposed sinking location has been identified as shown in Figure 24. The Caribbean has a shallow mixed layer that only extends to around 90m, and the critical depth for the pneumatocysts to implode lies around 135m (Gray et al., 2021). Aside from sinking a sinking pilot run by SOS Carbon in 2019, post-sinking Sargassum tracking has yet to be analyzed so a conservative sinking depth of 250m is assumed to ensure permanence.

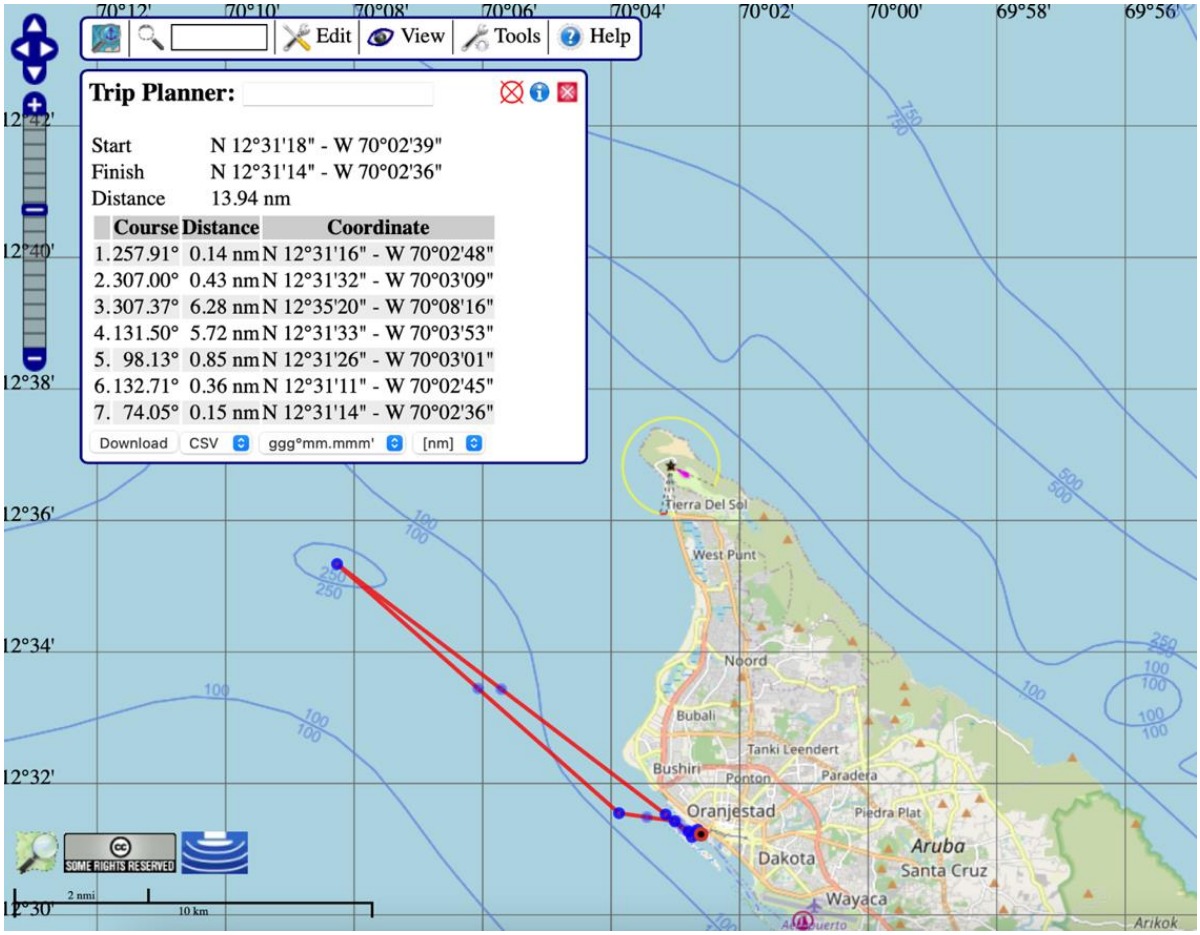

FIGURE 24: PROPOSED SINKING PILOT LOCATION BASED ON BATHYMETRY AND CURRENT DIRECTION. DEPTH AT 250M+ AND ROUND-TRIP DISTANCE OF 25KM. MAP MADE USING OPENSEAMAP.ORG.

6.3 LIMITATIONS

Like several previous studies utilizing GIS for Sargassum identification, my experience using the widely recommended Sentinel platform was far from perfect. It was very difficult to discern Sargassum from the mangroves which made my initial goal of creating an accurate supervised classification model incredibly challenging given my timeframe and lack of previous GIS experience. However, it still proved useful to manually find individual influx dates and examine how well the satellite imagery captured the state of Sargassum at that time. Additionally, sensitivity towards cloud cover, gaps in the Sentinel dataset, and the 5-day revisiting time made obtaining useful images for specific dates very difficult. For a certain month, sometimes I could only load two images per month with useful information for a particular bay. While this is less of a problem for longer timescale applications such as the influx animations, it did prove to be inconvenient for constant monitoring. For this reason, a combination of

Sentinel data with another satellite that has a daily revisiting time should be considered for cases requiring more frequent timeframes.

Other Sargassum-related quantitative tools are also limited. For example, no quantification method exists for estimating the sizes of influxes in tons of Sargassum. Without numerical data, comparisons between monthly and annual Sargassum amounts landing on each island can only be evaluated using image-based estimates as done in this thesis. Basic calculations could be made from landfill information as trucks dispose of Sargassum. However, these values only cover a small percentage of total sargassum influxes and hold large uncertainties as to what this percentage could be. Because of this missing data, more detailed evolving trends may be missed and the sphere of knowledge surrounding modern Sargassum dynamics will be missing a key element until such a quantification method is realized.

There were also some practical limitations specific to my work in Aruba. Conducting the pilot experiment was limited by time and resources. It is common that things do not always go according to plan on the first run, and unfortunately, I only had one try due to my limited fieldwork period in Aruba. Luckily, a second-stage pilot is underway as work will be continued in Punta Cana, Dominican Republic in June of 2022. Regarding work in small island states, there is generally less information available and more difficulties with communication due to unstable WIFI. It is important to know there are often roadblocks that delay the research process.

7. Conclusions and Recommendations

Sargassum has proved to be a major nuisance throughout the Caribbean in the past decade. With the change in Sargassum dynamics being linked to a myriad of global problems including ocean warming and eutrophication, there is little hope for remediation at the source meaning efforts to minimize impact will instead be carried out reactively. Each island will experience the effects of Sargassum inundations in various ways, depending on their positioning in accordance with ocean currents and trade winds that will inevitably push Sargassum onto their shores. The ABC islands provide a great example of how island positioning in combination with sensitive ecosystems and tourist locations affects how severely an island will react to Sargassum. Bonaire, which has extensive mangroves on the windward side and is first in line to receive an influx heading along the South American coast, will face much larger quantities that result in extensive damage without

major cleanup operations. Aruba is much more fortunate being third in line to receive an influx and having it predominantly wash up on the rocky and uninhabited windward side.

These differences in conditions call for tailored monitoring and cleanup efforts. In Bonaire, it is essential to invest in top-of-the-line Sargassum prediction software and expensive floating barriers to guide Sargassum away from sensitive ecosystems. Unfortunately, small island states often do not have adequate resources or capital to pay for software subscriptions, materials, labor, and dumping costs. Nor can they afford to have their sensitive areas destroyed as the ecosystem services and biodiversity maintained by these areas are invaluable. Aruba can mitigate this issue by using social media to monitor if Bonaire or Curaçao had received any influx. If something is detected, park managers, government workers, or other interested parties could utilize the free sentinel platform and create a false-color composite to identify Sargassum patches and give the DNM or DOW a heads up.

An effective addressal strategy suitable for all islands has yet to be created given how recent a phenomenon destructive Sargassum influxes are. While many are working on ways to create value out of this biomass through chemical extraction, biofuel conversion, or as fertilizers, many variables stand in the way and complicate the process. The alternative sink by weight design I tested during my fieldwork period could be considered as an alternative disposal strategy to eliminate several issues associated with land-based disposal. While more research and validation must be done regarding the design and proposed disposal site, this could be a good starting point and at least a partial answer to the ongoing Sargassum problem.

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BIBLIOGRAPHY

Ardron, J., Halpin, P., Roberts, J., Cleary, J., Moffitt, R., & Donnelly, B. (2011). *Where is the Sargasso Sea?* (No. 2; Sargasso Sea Alliance Science Report, p. 24). Duke University Marine Geospatial Ecology Lab & Marine Conservation Institute.

CoralMapping/AllenCoralAtlas: DOI release (v1.0). (2020). [Computer software]. Zenodo. https://doi.org/10.5281/ZENODO.3833242

Cox, S., Oxenford, H. A., & McConney, P. (2019). *Summary report on the review of draft national sargassum plans for four countries in the Eastern Caribbean* (p. 24) [Food and Agriculture Organization of the United Nations]. Centre for Resource Management and Environmental Studies, University of the West Indies, Cave Hill Campus, Barbados.

Cuevas, E., Uribe-Martínez, A., & Liceaga-Correa, M. de los Á. (2018). A satellite remote-sensing multi-index approach to discriminate pelagic *Sargassum* in the waters of the Yucatan Peninsula, Mexico. *International Journal of Remote Sensing*, *39*(11), 3608–3627. https://doi.org/10.1080/01431161.2018.1447162

Datastore. (2022). *SAMTOOL: SARGASSUM DETECTION*. Datastore. https://datastore.cls.fr/products/samtool-sargassum-detection/

DCNA. (2019). *Prevention and clean-up of Sargassum in the Dutch Caribbean* (p. 31). Dutch Caribbean Nature Alliance.

Delgado, F., Carreño-Gallardo, C., Estrada-Guel, I., Zabala-Arceo, A., Martinez-Rodriguez, H. A., & Lardizábal-Gutierrez, D. (2020). Pelagic Sargassum spp. Capture CO2 and produce calcite. *Environmental Science and Pollution Research*, *27*(20), 25794–25800. https://doi.org/10.1007/s11356-020-08969-w

Desrochers, A., Cox, S.-A., Oxenford, H. A., & Brigitta, van T. (2020). *Sargassum Uses Guide: A resource for Caribbean researchers, entrepreneurs and policy makers*. Centre for Resource Management and Environmental Studies.

Devault, D. A., Modestin, E., Cottereau, V., Vedie, F., Stiger-Pouvreau, V., Pierre, R., Coynel, A., & Dolique, F. (2021). The silent spring of Sargassum. *Environmental Science and Pollution Research*, *28*(13), 15580–15583. https://doi.org/10.1007/s11356-020-12216-7

Franks, J. S., Johnson, D. R., & Ko, D. S. (2016). Pelagic Sargassum in the Tropical North Atlantic. *Gulf and Caribbean Research*, *27*(1). https://doi.org/10.18785/gcr.2701.08

Gibbs, R. H. R., & Thijzen, R. (2018). *Rapport Sargassum* (p. 3) [Infrastructuue en Milieu]. Directie Natuur en Milieu.

Giri, C., Ochieng, E., Tieszen, L. L., Zhu, Z., Singh, A., Loveland, T., Masek, J., & Duke, N. (2011). Status and distribution of mangrove forests of the world using earth observation satellite data: Status and distributions of global mangroves. *Global Ecology and Biogeography*, *20*(1), 154–159. https://doi.org/10.1111/j.1466-8238.2010.00584.x

Gouvêa, L. P., Assis, J., Gurgel, C. F. D., Serrão, E. A., Silveira, T. C. L., Santos, R., Duarte, C. M., Peres, L. M. C., Carvalho, V. F., Batista, M., Bastos, E., Sissini, M. N., & Horta, P. A. (2020). Golden carbon of Sargassum forests revealed as an opportunity for climate change mitigation. *Science of The Total Environment*, *729*, 138745. https://doi.org/10.1016/j.scitotenv.2020.138745

Gower, J., & King, S. (2008). *Satellite Images Show the Movement of Floating Sargassum in the Gulf of Mexico and Atlantic Ocean* (p. 13). Fisheries and Ocean Canada, Institute of Ocean Sciences.

Gray, L. A., Bisonó León, A. G., Rojas, F. E., Veroneau, S. S., & Slocum, A. H. (2021). Caribbean-Wide, Negative Emissions Solution to Sargassum spp. Low-Cost Collection Device and Sustainable Disposal Method. *Phycology*, *1*(1), 49–75. https://doi.org/10.3390/phycology1010004

Hu, C., Feng, L., Hardy, R. F., & Hochberg, E. J. (2015). Spectral and spatial requirements of remote measurements of pelagic Sargassum macroalgae. *Remote Sensing of Environment*, *167*, 229–246. https://doi.org/10.1016/j.rse.2015.05.022

Johns, E. M., Lumpkin, R., Putman, N. F., Smith, R. H., Muller-Karger, F. E., T. Rueda-Roa, D., Hu, C., Wang, M., Brooks, M. T., Gramer, L. J., & Werner, F. E. (2020). The establishment of a pelagic Sargassum population in the tropical Atlantic: Biological consequences of a basin-scale long distance dispersal event. *Progress in Oceanography*, *182*, 102269. https://doi.org/10.1016/j.pocean.2020.102269

Johnson, M. D., Scott, J. J., Leray, M., Lucey, N., Bravo, L. M. R., Wied, W. L., & Altieri, A. H. (2021). Rapid ecosystem-scale consequences of acute deoxygenation on a Caribbean coral reef. *Nature Communications*, *12*(1), 4522. https://doi.org/10.1038/s41467-021-24777-3

Laffoley, D., Ardron, J., Roe, H., & Bates, N. R. (2011). *The Protection and Management of the Sargasso Sea The golden floating rainforest of the Atlantic Ocean* (Summary Science and Supporting Evidence Case, p. 48). Sargasso Sea Alliance.

Lasquites, J. J., Blanco, A. C., & Tamondong, A. (2019). MAPPING OF SARGASSUM DISTRIBUTION IN THE EASTERN COAST OF SOUTHERN LEYTE USING SENTINEL 2 SATELLITE IMAGERY. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLII-4/W19*, 289–295. https://doi.org/10.5194/isprs-archives-XLII-4-W19-289-2019

Lindeman, P., Leemans, E., Geers, B., Page, D., Janssen, F., Hendy, I., & Ragazzola, F. (2021). *SARGASSUM CLEANUP END-REPORT FOR THE MIIP018 FEASIBILITY STUDY*. Perpetuus B.V.

Milledge, J., & Harvey, P. (2016). Golden Tides: Problem or Golden Opportunity? The Valorisation of Sargassum from Beach Inundations. *Journal of Marine Science and Engineering*, *4*(3), 60. https://doi.org/10.3390/jmse4030060

Milledge, J. J., Maneein, S., Arribas López, E., & Bartlett, D. (2020). Sargassum Inundations in Turks and Caicos: Methane Potential and Proximate, Ultimate, Lipid, Amino Acid, Metal and Metalloid Analyses. *Energies*, *13*(6), 1523. https://doi.org/10.3390/en13061523

Miranda, E., Mutiara, A. B., Wibowo, W. C., & Ernastuti. (2018). *Classification of Land Cover from Sentinel-2 Imagery Using Supervised Classification Technique (Preliminary study)*. https://ieeexplore.ieee.org/servlet/opac?punumber=8510753

Ody, A., Thibaut, T., Berline, L., Changeux, T., André, J.-M., Chevalier, C., Blanfuné, A., Blanchot, J., Ruitton, S., Stiger-Pouvreau, V., Connan, S., Grelet, J., Aurelle, D., Guéné, M., Bataille, H., Bachelier, C., Guillemain, D., Schmidt, N., Fauvelle, V., … Ménard, F. (2019). From In Situ to satellite observations of pelagic Sargassum distribution and aggregation in the Tropical North Atlantic Ocean. *PLOS ONE*, *14*(9), 29. https://doi.org/10.1371/journal.pone.0222584

Oxenford, H. A., Cox, S.-A., van Tussenbroek, B. I., & Desrochers, A. (2021). Challenges of Turning the Sargassum Crisis into Gold: Current Constraints and Implications for the Caribbean. *Phycology*, *1*(1), 27–48. https://doi.org/10.3390/phycology1010003

Parke Marino Aruba, van der Wal, S., Nunes, G., Silva, N., & de Cuba, R. (2020). *Parke Marino Aruba—Preliminary Management Plan 2019-2021*. Fundacion Parke Nacional Aruba.

Putman, N. F., Goni, G. J., Gramer, L. J., Hu, C., Johns, E. M., Trinanes, J., & Wang, M. (2018). Simulating transport pathways of pelagic Sargassum from the Equatorial Atlantic into the Caribbean Sea. *Progress in Oceanography*, *165*, 205–214. https://doi.org/10.1016/j.pocean.2018.06.009

Rodríguez-Martínez, R. E., Medina-Valmaseda, A. E., Blanchon, P., Monroy-Velázquez, L. V., Almazán-Becerril, A., Delgado-Pech, B., Vásquez-Yeomans, L., Francisco, V., & García-Rivas, M. C. (2019). Faunal mortality associated with massive beaching and decomposition of pelagic Sargassum. *Marine Pollution Bulletin*, *146*, 201–205. https://doi.org/10.1016/j.marpolbul.2019.06.015

Saldarriaga-Hernandez, S., Hernandez-Vargas, G., Iqbal, H. M. N., Barceló, D., & Parra-Saldívar, R. (2020). Bioremediation potential of Sargassum sp. biomass to tackle pollution in coastal ecosystems: Circular economy approach. *Science of The Total Environment*, *715*, 136978. https://doi.org/10.1016/j.scitotenv.2020.136978

Sargassum Information Hub. (2022). *Sargassum Hub*. https://sargassumhub.org/monitoring/

Thompson, T. M., Young, B. R., & Baroutian, S. (2020). Efficiency of hydrothermal pretreatment on the anaerobic digestion of pelagic Sargassum for biogas and fertiliser recovery. *Fuel*, *279*, 118527. https://doi.org/10.1016/j.fuel.2020.118527

Tjong, W. (2020). *Mapping Sargassum on beaches and coastal waters of Bonaire using Sentinel-2 imagery*. Wageningen.

Vos, B., Foursoff, W., Bruin, L. de, & Bruijn, W. (2016). *COASTAL SEAWEED SOLUTIONS*. Delft University of Technology.

Wang, M., & Hu, C. (2016). Mapping and quantifying Sargassum distribution and coverage in the Central West Atlantic using MODIS observations. *Remote Sensing of Environment*, *183*, 350–367. https://doi.org/10.1016/j.rse.2016.04.019