Sargassum Inundations in a Social Ecological Context

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From the communities of the Bahamas, the Yucatán, the Virgin Islands, and my global village, I appreciate my innovative, revolutionary, and resilient friends and chosen family- may we continue to study the undersides of palm fronds and brilliant blue water.

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Abbreviations

HABs	hazardous algae blooms
SST	sea surface temperature
GASB	Great Atlantic sargassum Belt
GOM	Gulf of Mexico
Tg	teragram

Definitions

Sargassum spp. –referring to more than one species of the genus *Sargassum*

sargassum – common name (lower case, not italics), a non-taxonomic descriptor, can be used singularly or plural, referring to the mix of pelagic sargassum species/ morphotypes

inundation – the arrival of large amounts of pelagic sargassum overwhelming shorelines and bays where it beaches or is trapped

teragram- 10^9 kg, 1 million metric tons, approximate mass of the steel Golden Gate Bridge

Terminology in this paper is based on the recommendations of the "Proposal for standardization of terms of research on pelagic *Sargassum* species" suggested by Brigitta I. van Tussenbroek on behalf of Hazel Oxenford, Ligia Collado Vides, Shelly-Ann Cox, and Anne Brearly, shared with the sargnet@fiu.edu email list community, received June 6, 2022.

ABSTRACT OF THE THESIS

Sargassum Inundations in a Social Ecological System Context

Pelagic sargassum seaweeds have experienced explosive spatial and temporal range expansion throughout the Atlantic Basin in the last decade. Beyond the thriving ecosystem of the Sargasso Sea, the recent proliferation of sargassum now includes the entire region between the equator and 40° North, effectively doubling the previous range. This new patch of macroalgae stretches zonally from West Africa to the Caribbean and is detrimental when it washes ashore and decomposes, polluting air, land, and sea. Sargassum inundations negatively impact coastal ecosystems, local communities, human health, and economies on both sides of the Atlantic.

A Social Ecological Systems (SES) approach to sargassum inundations will help illustrate this complex environmental situation while acknowledging humankind's role in the system. SES thinking builds a framework that incorporates causes, results, and feedback loops, creating a method to expand upon current modes of thinking and information sharing.

Anthropogenic climate change may be driving the dispersal of sargassum, and eutrophication is fertilizing the sargassum patches. Impacted communities must quickly adapt and develop mitigation procedures. Disposal techniques have proven expensive and environmentally harmful. Creating a market for this new biomass will incentivize the creation of effective harvesting techniques. Proposals to intentionally sink sargassum as a method of carbon sequestration or to create a biofuel may be both lucrative and globally beneficial strategies.

INTRODUCTION

The iconic white sand beaches of the Caribbean may be a thing of the past. Large amounts of seaweed have increasingly been washing up and covering the beaches, turning the once-clear water brown, and smothering shallow coral reefs (Johns et al., 2020). These seaweed inundations are happening on both sides of the Atlantic Ocean, limiting access to nearshore fisheries off West Africa and devastating the tourist-based economies of the Caribbean (Chavez et al., 2020; Devault et al., 2021; Johns et al., 2020). The phenomenon linking these two regions is a persistent band of pelagic sargassum seaweed, a floating macroalgae that currently stretches across the Atlantic Ocean. Masses of this seaweed are washing up on Caribbean and West African beaches in events called sargassum inundations, negatively impacting coastal ecosystems, human communities, and local economies.

Explosive seaweed growth is not unique to these regions of the Atlantic Ocean, increases in seaweed growth and harmful algae blooms (HABs) have been reported around the world in the last several decades (Johnson, 2015; Van Dolah et al., 2015; Wells et al., 2015). Pelagic sargassum species currently comprise the largest known algae bloom on the planet. Impacted coastal ecosystems and economies are being harmed by sargassum inundations on both sides of the Atlantic Ocean, identifying the current situation of sargassum proliferation and coastal inundation as an HAB (Lopez et al., 2008). Responses to this HAB situation have been hampered by the large geographical scale and sudden temporal onset of the problem, the native status of the species in question, and the diverse political boundaries and economic conditions of the impacted region (McConney & Oxenford, 2021). Important components of understanding HABs are analyzing the causes of the bloom and its impacts, especially how human actions and communities are both contributing to the problem and being affected by it. Considering projected increases in HABs related to global climate change, eutrophication, and land use changes, streamlining HAB recognition and response will benefit future areas affected by blooms.

Incorporating causal links and establishing feedback loops are important aspects of building a framework for problem analysis. Positive feedback loops have an output that then drives production. For example, warming from climate change causes ecological changes which then produce methane, like melting permafrost or rotting sargassum inundations. Carbon emissions in turn drive climate change, causing increased warming and more methane production.

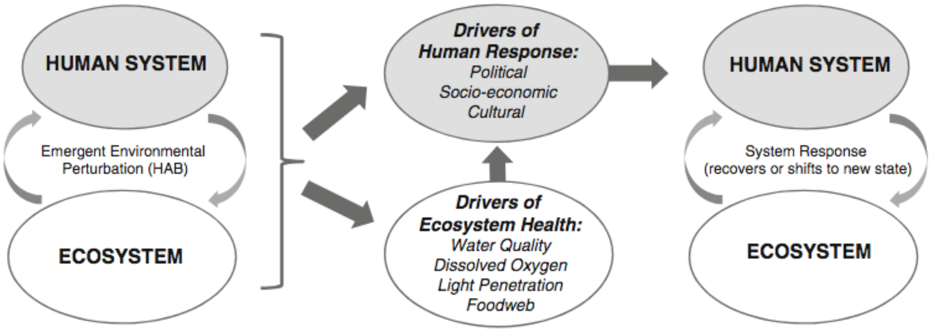


Figure 1. Relationships between Human System and Ecosystem. Reproduced from Van Dolah et al., 2015.

Viewing the phenomenon of sargassum inundations as a result of anthropogenic climate change as well as being the driver of social and economic turbulence illustrates the sargassum cycle of proliferation, inundations, and impacts in the context of human activities. As seen above in Figure 1, the social ecological approach acknowledges that the human world and the natural environment do not exist independently of one another, illuminating the urgency for developing viable solutions that will benefit impacted communities.

Focusing on the recent sargassum phenomenon in the Atlantic Ocean, this thesis primarily reviews the recent literature researching the potential causes of proliferation, the impacts of coastal inundations, community responses, and proposed mitigation and adaptation strategies. Through a review of recent and primary pelagic sargassum literature, I investigate recent sargassum inundations within the framework of a Social Ecological System, incorporating the context of human activities to illustrate the phenomenon.

By viewing this phenomenon as a Social Ecological System (SES), I identify the anthropogenic nature of contributing factors to the sargassum phenomenon in the context of global climate change. Furthermore, I detail current responses and future mitigation proposals, which include innovative carbon sequestration and biofuel projects that may have a global benefit, incentivizing a response.

This introduction includes a description of the sargassum species in question and expands upon SES thinking, especially relating to anthropogenic feedbacks. Descriptions of the historic bounds of the Sargasso Sea, the occurrence of sargassum in the Gulf of Mexico, and then the formation of the new region of sargassum, known as The Great Atlantic Sargassum Belt, set the stage for discussing coastal inundations. These large scale sargassum beaching events negatively impact the ecological, social, and economic wellbeing of the islands and coastal communities bordering the Atlantic.

Reviewing current mitigation and adaptation attempts, I include information about community education and outreach as well as potential valorization programs. In the final sections, I discuss the possibility that the sargassum situation is indicative of regime change and propose directions for new solution-focused work to explore.

With additional sources available constantly, the bulk of the material reviewed was published before May 2022. Using mostly scientific journals, I have also included online sargassum monitoring sources, crowd sourced reporting projects, Facebook discussion groups, conference notes, personal communications, and regional media like small island newspapers. This work has been conducted with the sincere hope that we, as a society of scientists and ocean lovers, can come up with some good solutions that may create a useful product or process from this abundant sargassum biomass, alleviating the unjust burden that this product of climate change has placed upon developing regions in the tropical Atlantic.

***Sargassum* spp.**

Sargassum natans and *Sargassum fluitans* are the only holopelagic varieties of the brown macro algae genus *Sargassum*; they float at the surface for their entire lifecycle and are never attached to a substrate (Fidai et al., 2020). Both *S. natans and S. fluitans* have multiple subspecies, with a reported shift towards *S. natans* VII dominance in some regions while other regions vary in species composition (Dibner et al.; 2021; Fidai et al., 2020; García-Sánchez et al., 2020; Vázquez-Delfín, 2021). Sargassum are often familiarly called seaweed, the common name for macroalgaes, photosynthesizing nonvascular aquatic and marine organisms. For the purpose of this paper both species will be referred to collectively as "*Sargassum* spp." or simply as "sargassum."

Sargassum spp. are not known to reproduce sexually, but instead only by fragmentation, lending an interesting dynamic to metapopulation genetics in species that are not able to locomote, intentionally disperse, or recombine genes (Dibner et al., 2021). Population connectivity is determined wholly by epipelagic zonal transport dynamics in the tropical and subtropical Atlantic Ocean, the endemic range.

Both species in question, *Sargassum natans* and *Sargassum fluitans*, are endemic to the Atlantic Ocean but have expanded their known range and experienced anomalous growth in a novel phenomenon since 2011 (Devault et al., 2021). It is important to note that the presence of sargassum in the Atlantic Ocean has been recorded for hundreds of years, with small patchy amounts occasionally found throughout the tropical and subtropical regions of the Atlantic (Johns et al., 2020; Lapointe et al., 2021).

A new distinct concentrated region formed in 2011 and has produced increasing amounts of biomass that washes onto the beaches of the surrounding continents; this new, farther south, range between Africa and South America is called the Great Atlantic Sargassum Belt (GASB) (Wang et al., 2019). The excessive growth in this new region is understood to be due to anthropogenic changes of nutrient availability in the ocean as well as global climate changes, with the origin event that is hypothesized to have started the GASB also detailed below (Lapointe et al., 2021).

The proliferation of sargassum at sea is then followed by incidences of large floating mats, called wracks, washing into nearshore ecosystems and landing in mangroves and on sandy beaches. These large-scale beaching events, called inundations, are impacting regions on both sides of the Atlantic Basin, harming fragile coastal ecosystems, reducing water quality, and harming human health and communities. Unprecedented sargassum coastal inundations, caused by a proliferation brought on by a combination of shifting nutrient limitations, global climate change, and transport dynamics, are producing cascading ecological disturbances along the shores of West Africa and the Caribbean.

Climate change impacts multiple variables of HABs, as illustrated below in Figure 2, reproduced from Wells et al. (2015); sargassum inundations are categorized as HABs (Butler et al., 1983; Oviatt et al., 2019; van Tussenbroek et al., 2017).

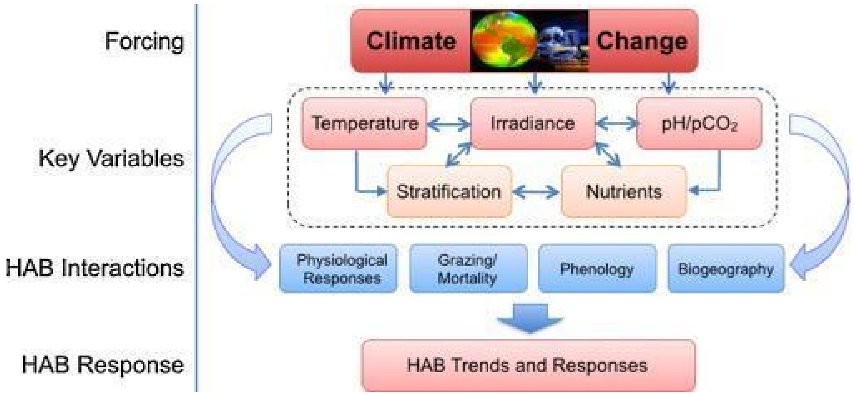


Figure 2. Climate Change Relationship to Hazardous Algae Blooms. Reproduced from Wells et al., 2015.

The human component of this sargassum situation is part of a positive feedback loop: anthropogenic climate changes such as global warming and changing storm patterns as well as nutrient enrichment are implicated in causing sargassum proliferation which results in human communities being burdened with the negative impacts of inundations hitting coastal areas. More carbon emissions are produced by burning fossil fuels to clean beaches using large machinery and incinerating piles of disposed sargassum, and carbon emissions are a recognized driver of global climate change (IPCC, 2021). This human element of an ecological problem needs to be assessed to plan management, mitigation, and adaptation strategies in the years to come.

Social Ecological Systems

A Social Ecological System (SES) perspective addresses complex environmental problems while acknowledging humankind's role in the system. Finding the connections between human actions (or inactions), as well as abiotic and biotic changes illustrates the interconnectedness of our human condition in the context of the world around us.

An SES approach is the basis for sustainability science's functional approach to managing complex relationships between humans and the nature in which we live (DeVries, 2013). Uses of SES thinking include illustrating a feedback loop that incorporates causes and effects, creating a method to expand upon current modes of thinking and information sharing, built upon the premise that human behavior and systems are malleable and that intentional change is possible (McGinnis & Ostrom, 2014).

The Resilience Alliance, a research organization that focuses on resilience in SES systems, defines SES thinking as "An integrated system of ecosystems and human society with reciprocal feedback and interdependence, the concept emphasizes the 'humans-in-nature' perspective" (*The Resilience Alliance*, 2022). Early work by Berkes and Folke (1998) defined social ecological systems as "complex, integrated systems in which humans are part of nature," illustrating the important difference between a human-in- nature vs a human-with- nature approach in Figure 3, below.

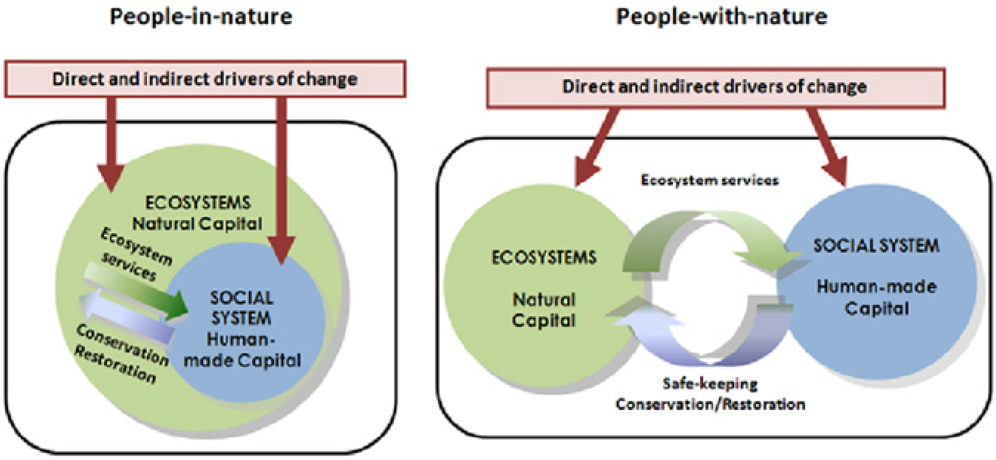


Figure 3. People in nature vs People with nature. Reproduced from Berkes and Folke (1998).

Sargassum proliferation may be due to or exacerbated by anthropogenic climate change and ocean eutrophication, creating a causal link in the sargassum lifecycle. As sargassum washes ashore, it is linked again to human activity through mitigation, adaptation, clean up, and valorization efforts. An SES approach will help identify the linkages and interdependence between the social and environmental changes and has proven to be a useful tool for modern environmental research (Pertelow, 2018).

An SES approach to the recent sargassum research illustrates the interconnectedness of humans, the oceans, our coastal environments, and sargassum inundations. Not a simple relationship of causation, but a complex system with multiple feedback loops existing in a range of spatial and temporal scales. The goal of this problem driven approach is to better manage societal needs in regarding environmental issues and loss of ecosystem services (DeVries, 2013). It is my attempt in this work to use SES thinking to illustrate the roles humans have in the current sargassum bloom in the Atlantic in the hopes that this will better guide management decisions.

CHAPTER 1

Background

For hundreds of years, pelagic sargassum have been concentrated in an oceanic region known as the Sargasso Sea, a subtropical gyre in the Atlantic Ocean rotating clockwise between 20 and 40 degrees North latitude off the coast of North America and bounded by the Gulf Stream, North Atlantic Current, Canaries Current, and the North Equatorial Current (Butler et al., 1983; Coston-Cements et al., 1991; Menzel & Ryther, 1959; Ryther, 1956). Historically, storms have occasionally separated mats of sargassum from the Sargasso Sea. Wracks of sargassum would then circulate around the Atlantic, eventually washing up seasonally on the beaches of Bermuda and more rarely in the Caribbean and Gulf of Mexico, setting a baseline of occasional historic sargassum occurrences outside of the Sargasso Sea (Butler et al., 1983; Coston-Clements et al., 1991; Fidai et al., 2020).

As location is an essential element to this situation, I include historical studies of sargassum and elaborate on the ecological services provided by sargassum historically in the Sargasso Sea and the Gulf of Mexico. The Atlantic basin contains and borders diverse regional communities and ecosystems; I will also include regional generalizations that will help highlight the urgency of the current sargassum situation.

Historical Studies

Early studies investigated the photosynthetic productivity of *Sargassum* spp. and focused on which required nutrient sources associated with sargassum would be limiting factors to the growth and lifecycle (Lapointe et al., 2014; Menzel & Ryther, 1959; Ryther, 1956). Ryther (1956) determined that despite having abundant macroalgal biomass, the Sargasso Sea was a biological desert low in nutrients and with limited productivity, coining the phrase "Ryther's Paradox." Further study by Menzel & Ryther (1959) identified the oligotrophic (low in nutrient concentrations) Sargasso Sea as dependent on nutrient pulses, like upwelling and convective mixing of stratified ocean layers, and determined it to be an N limited system at the time, approximately 60 years ago. However, sargassum found in neritic waters (on the continental shelf) with higher nutrient availability show increased growth rates and productivity than sargassum found in the oceanic and lower nutrient waters of the mid-Atlantic basin (Lapointe, 1995; Lapointe et al., 2014).

A recent historical perspective of comparative sargassum associated faunal and epibiont surveys found an overall decrease in diversity contrasting with the increase in sargassum geographic range and biomass (Butler et al., 1983; Huffard et al., 2014). The increase in sargassum biomass concurrent with the decline in herbivores and assemblage diversity may indicate some release from grazing control, although most hypotheses reviewed indicate that current growth is more probably due to a release from nutrient limitation due to external sources (Chavez et al., 2020; Johns et al., 2020; Lapointe et al., 2014).

The historical sargassum regime differs from the current situation now in several important aspects: the amount of biomass at sea, the amount landing on beaches, the frequency of these landings, and the location(s) of oceanic biomass (Huffard et al., 2014). Historical ("historical" in this sense means prior to 2011) amounts of sargassum in the Sargasso Sea provided vital and beneficial ecosystem services when floating in the middle of the Atlantic Ocean, which is a direct contrast to the loss of ecosystem functions when larger amounts of sargassum are generated and transported to coastal regions (Butler et al., 1983; Louime et al., 2014).

Ecosystem Services Provided by Sargassum

Ecosystem services encompass provisioning, regulating, supporting, and cultural functions that an ecosystem provides. Pelagic sargassum historically contributed to ecosystem functions through all of these services, contrasting the current loss of ecosystem functions due to sargassum inundations. To be clear, this summary is how sargassum, mostly concentrated in the Sargasso Sea, was considered beneficial historically (and relatively recently), prior to 2011.

The remote nature of the sargassum in the Sargasso Sea should not belie its historic provisioning importance. Mats of sargassum provide habitat and a nursery for a wide range of fauna including numerous fishes, sea turtles, the unusual catadromous European Glass Eels, and many invertebrates, including the autochthonous Sargasso Shrimp (Coston-Clements et al., 1991; Cresci, 2021). Fishermen have been known to fish under sargassum mats, especially for dorado (mahi-mahi in the Pacific, or dolphin fish), who shelter in the shades of the mats.

Regulating ecosystem functions include gas exchange at the ocean surface, with photosynthesis capturing CO_2 and oxygenating surface water (Paraguay-Delgado et al., 2020). Supporting ecosystem functions include nutrient cycling, with sargassum able to capture available nutrients at the surface of the ocean while providing forage for herbivores and habitat for fauna, occasionally washing ashore to import nutrients into nearshore environments (Ryther, 1956). Export of nutrients to the ocean floor is another aspect of sargassum nutrient cycling (Baker et al, 2018). The Sargasso Sea has captured the imaginations of sailors and the interest of scientists for hundreds of years, contributing to the richness of our cultural heritage (Hayward et al., 1982).

Sargasso Sea

Historically the Sargasso Sea has been somewhat contained in a North Atlantic gyre, a golden floating forest of pelagic sargassum is a patch of photosynthetic productivity in the temperate North Atlantic Ocean (Coston-Cements et al., 1991). Floating sargassum mats have historically been associated with diverse faunal assemblages- schools of fish traveling underneath and feeding on invertebrates within the mats- with intensive nutrient recycling between sargassum mats and their associated faunal assemblages (Butler et al., 1983; Lapointe et al., 2014). A recent decline in faunal diversity associated with sargassum mats indicates a shift toward a predator dominated assemblage and an associated decline in herbivores; this trophic shift coupled with a reduction in epibiont coverage may indicate a younger age of the mats themselves (Butler et al., 1983; Huffard et al., 2014).

Gulf of Mexico

Mats of sargassum have seasonally accumulated in the Gulf of Mexico (GOM) in large amounts since the early 2000s, but there have been episodes of sargassum earlier in the region historically. Webster and Linton (2013) detail the occurrence of *Sargassum* spp. in the GOM since the 1860s and found an interesting pattern to historical inundations. Using newspaper and magazine reports, they found that every 30 to 35 years there would be an 8- or 9-year period of persistent GOM sargassum landings on Texas shores. However, the last 20 years have not fit this historic pattern, sargassum has varied annually but been consistently present (Fidai et al., 2020: Hill et al., 2015).

Regional Economies, Ecology, and Culture

Sargassum impacts regions far beyond the bounds of the Sargasso Sea. By acting as a nursery for fish and marine animals, these mats of seaweed have supported fisheries throughout the Atlantic Basin. From the coasts of Europe down to west Africa, and up the coasts of the Americas, fishing communities have benefited from a functioning ocean ecosystem, of which the Sargasso Sea has been a vital component. While large fleets of fishing boats have historically hailed from Spain, Portugal, and North America, small artisanal and subsistence fisheries dot the coastline of Africa and South America. Recently, sargassum has been implicated in driving away tourists and producing empty fishing nets on both side of the Atlantic (Adewale et al., 2022; Bartlett & Elmer, 2021; Capron, 2015; "*Seaweed smothers beaches in Sierra Leone*," 2022; Solarin et al., 2014).

Furthermore, the thousands of islands throughout the Atlantic and Caribbean have been developed as valuable tourist destinations. The Azores Islands, the Madeira Islands, the Canary Islands, and the Cape Verde Islands represent the diverse "Macaronesia" islands of the Atlantic, all dependent on fishing historically and now benefiting also from international tourism. These are all rocky, volcanic islands, closer culturally to Europe than the Americas, speaking Portuguese and Spanish primarily. The Caribbean Islands are culturally diverse in part due to the history of colonization and trade routes, with languages ranging from coastal Central American Garifuna to French, Dutch, Spanish, and English. Many Caribbean Islands historically relied on local fisheries, but now tourism is a major component of the region's economy.

The Caribbean "brand"- white sand beaches, crystal clear water, and vibrant coral reefs- has relied on a balanced healthy ecosystem. While there are many contributing factors to this balance, sargassum has historically supported fishery stock and greater ocean diversity from a distance, only occasionally directly importing nutrients to coastal communities. Sargassum inundations now compromise water quality and reduce beach aesthetics in places relying on these resources for economic benefits.

Summarizing the background of sargassum studies including life history and geography of sargassum, Figure 4, below, details the regions of sargassum, including the Great Atlantic Sargassum Belt, the new pan-Atlantic region and topic for the next section.

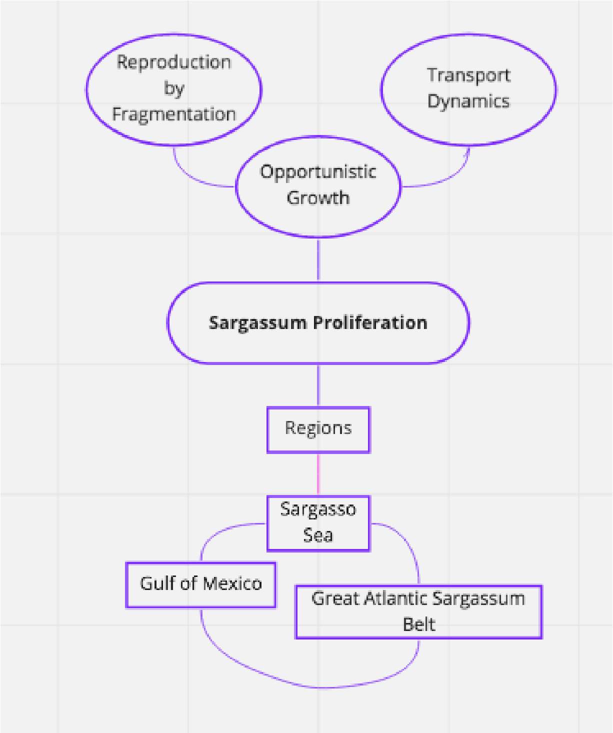


Figure 4. Life History and Regions of Sargassum. Created using Miro.

CHAPTER 2

Great Atlantic Sargassum Belt

The last decade has produced intense blooms of sargassum colonizing a new range between Africa and South America. Satellite imagery originally detected this new swath of sargassum in 2011 and it has persisted since its formation, approximately doubling the estimated biomass and original geographic range of the Sargasso Sea (Fidai et al., 2020). Estimates of annual sargassum biomass historically have been between 2 and 11 Tg (Parr, 1939; Wang et al., 2018). By 2018, the seasonal sargassum biomass was estimated to be 20 Tg (Wang et al., 2019). Pelagic sargassum are now found throughout the area between the equator and 40 degrees North in the Atlantic Ocean - doubling the previously established known range in a region termed the Great Atlantic Sargassum Belt (GASB) (Wang et al., 2019).

The satellite imagery below, in Figure 5, shows the GASB in green tones, indicating biomass quantity in early 2021, stretching westward from the coast of Africa.

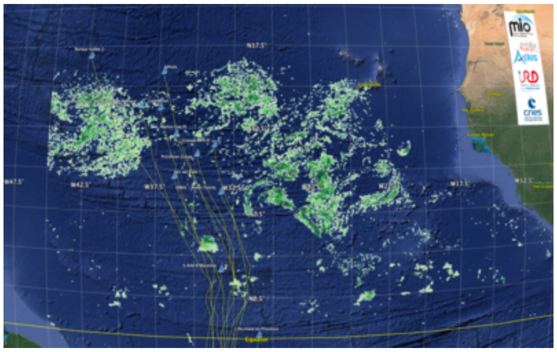


Figure 5. Image of Sargassum mats in Atlantic Ocean. Used with permission from Jacques Descloitres, AERIS/ICARE Data and Service Center

Contrary to the semi-gyre-containment of the Sargasso Sea, the GASB transports pelagic mats in an east to west zonal flow, often as long windrows, eventually landing on Caribbean Islands and the eastern edge of Mexico's Yucatan Peninsula (Coston-Cements et al., 1991; Descloitres & Berline, 2021).

Geographical context defines sargassum's role in the ecosystem. Sargassum location determines whether they are the foundation species in their native range of the Sargasso Sea or categorized as a harmful algae bloom (HAB) when accumulating in shallow waters and on beaches, as experienced on both continental margins of the GASB (Butler et al., 1983; Oviatt et al., 2019; van Tussenbroek et al., 2017). Anthropogenic climate change and eutrophication are implicated in the process of sargassum proliferation and range expansion, tying in both the source and resulting impacts to the social ecological context of the GASB.

Possible Causes

The origin of the GASB can be traced to a series of specific events coinciding with an era when sargassum is released from nutrient limitation. The recent nature of this occurrence has prompted ample research and theories, but simply put: A seed crop of sargassum colonized a new oceanic region which is connected laterally to the whole tropical and temperate ocean, and encountered abundant nutrient resources and no natural predators, allowing nearly uninhibited growth and range expansion.

An anomalous weather occurrence in the winter of 2009/2010 attributed to transporting a significant amount of sargassum from the Sargasso Sea to the eastern Atlantic where it may have encountered nutrient upwelling off the western coast of Africa, causing rapid proliferation of this seed crop (Chavez et al., 2020; Gray et al., 2021; Johns et al., 2020; Wang et al., 2019). The Intertropical Convergence Zone

(ITCZ) then transported windrows of sargassum to the coast of South America. The near shore regions of the GASB by West Africa and South America may be nutrient enriched by rivers and upwelling while Sahara dust deposition has been suggested as a source of nutrients, especially iron, promoting anomalous growth in the mid-Atlantic (Oviatt et al., 2019). Remote sensing showed a new region of sargassum at the mouth of the Amazon in 2011, an origin of sargassum mats that then either inundated the Caribbean or traveled along the equatorial current back to the coast of Africa (Gower et al., 2013).

Global climatic changes contributing to the proliferation of sargassum in the GASB include increases in riverine runoff, land use changes, and increasing ocean temperatures (Doney et al., 2012; Fidai et al., 220; Gray et al, 2021; Oviatt, 2019; Wang et al., 2019). Ocean heat is stored in the upper layer of the ocean and global warming has included a rise in sea surface temperatures, with global ecological effects including an increase in harmful algae blooms (Dahlman & Lindsey, 2021; Garcia-Gomez et al., 2020). Continued work is needed to determine heat tolerances for sargassum, but warmer water may be a contributing factor to range expansion.

The Sargasso Sea has historically had low levels of nutrients available and sargassum have been recorded as having slow growth rates and limited productivity while in this North Atlantic gyre (Butler et al., 1983; Gruber & Keeling, 1999). However, sargassum found in neritic waters with higher nutrient availability show increased growth rates and productivity (Lapointe, 1995). These neritic waters have riverine outflows and continental margin upwellings which provide N, P, and micronutrients necessary for growth (Oviatt et al., 2019). A sargassum whitepaper from

2015 suggested that when cold fronts push sargassum mats into the Bay of Campeche in the GOM, the result is explosive vegetative growth due to high nutrient loads in the bay (Hill et al., 2015).

Globally, land use changes which produce more fertilizer and erosion runoff coupled with increased riverine output have contributed to increasingly large plumes entering the oceans from the mouths of rivers (Oviatt et al., 2019). It has been disputed whether Amazonian flood waters contain a significant nutrient pulse to promote the sargassum growth witnessed since 2010 (Wang and Hu, 2016). More updated analyses and calculations for the Amazon, Xingu, and Tapajos rivers combined during non-flood events found nitrogen concentrations of 15um, enough to support an estimated 30 million tons of sargassum (Oviatt et al., 2019). Determining what environmental factors may be promoting sargassum growth and range expansion is a critical step in determining if this new phenomenon is indicative of a regime shift.

Additionally, the Mixed Layer Depth (MLD) of the open Atlantic Ocean deepens under the ITCZ and contains nutrients accessible for the GASB. Johns et al. (2020) calculated that the MLD supplied nutrients exceeded the availability of riverine sources and could adequately support GASB growth year-round.

Higher N availability in both neritic and oceanic waters is due to external sources of nutrient deposition, such as upwelling, atmospheric deposition from land clearing fires in Africa, Sahara dust, and riverine runoff, suggesting that the GASB is indicative of a greater ocean nutrient enrichment problem (Chavez et al., 2020; Lapointe et al., 2014; Lapointe et al., 2021). Riverine runoff is increasing due to global climate change patterns that include greater precipitation coupled with deforestation and land use changes in Africa and South America (Chavez et al., 2020). Patches of sargassum receive nutrient pulses from flood years in Africa and South America in alternating years on either end of the GASB, a climatic pattern that may contribute to both perpetuation and proliferation (Oviatt et al., 2019). The aspects of anthropogenic climate change contributing to sargassum proliferation are illustrated below in Figure 6.

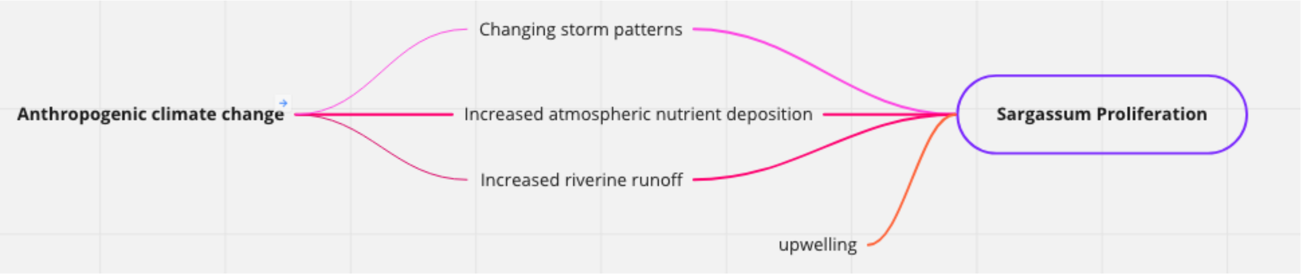


Figure 6. Climate Change Driving Sargassum Proliferation. Image created using Miro.

Transport & Perpetuation

The physical dynamics of this Atlantic region perpetuate the transport of sargassum, contributing to a new regime that may be an ecological indicator of Atlantic eutrophication (Lapointe et al., 2021). A generalized illustration of the sargassum loop is seen below, in Figure 7 (López Miranda et al., 2021).

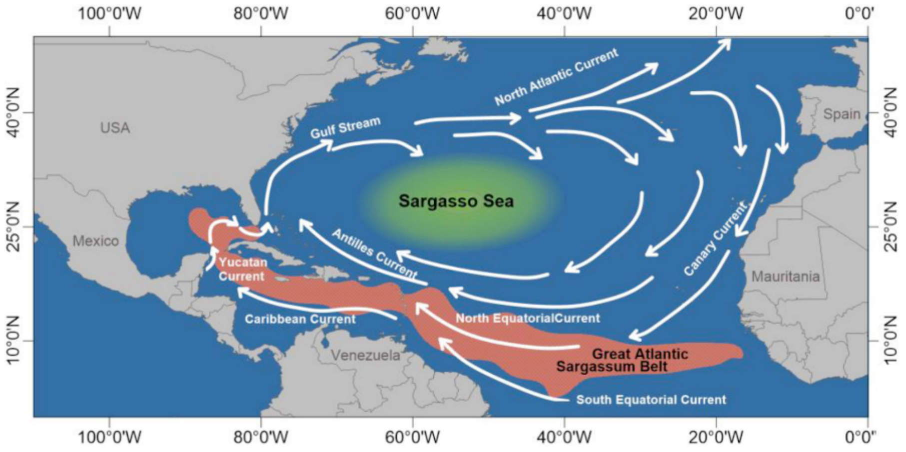


Figure 7. Generalized map of Current Dynamics Affecting Sargassum.
Reproduced from López Miranda et al., 2021, https://doi.org/10.3389/fmars.2021.768470

Wracks of sargassum drift with currents and are blown by the wind, linking regions in a circuitous loop, connecting the Sargasso Sea to the GASB, then Caribbean Sea, followed by the Gulf of Mexico (GOM), Loop Current, and then the Gulf Stream back to the Sargasso Sea (Lapointe et al., 2021; López Miranda et al., 2021).

Horizontal Transport Dynamics

The connectedness of the epipelagic zone of the ocean makes it hard to delineate the biogeographic range of sargassum, moved by winds and waves, unbounded by anything but coastal margins. Understanding the range of sargassum requires understanding the connectivity of the ocean surface as a habitat. Lateral redistribution follows wind and current patterns, which at one point mostly confined sargassum to the Sargasso Sea but now also includes some of the temperate and most of the tropical Atlantic Ocean north of the equator.

Horizontal transport at the surface of the ocean is due to a combination of oceanic currents and windage. A combined approach with six lines of tracking evidence (particle tracking models, wind & current data, drifting buoy trajectories, net tows, & historical hydrography) supported the work of Johns et al. (2020) in tracing the movement of sargassum around the Atlantic Ocean. It should be noted that without currents, floating objects travel at 1-3% of the speed of the wind, indicating that storms and weather events can alter mat destinations (Johns et al., 2020). With both a currently observed and a forecasted increase in frequency and intensity of storms, the potential for increased sargassum fragmentation and transport also increases (IPCC, 2020).

Sargassum dispersal is wholly controlled by ocean dynamics, storms, wind, and, eventually, senescence. Lateral ocean connectivity at the surface follows known patterns which shift seasonally. Early work on the transport dynamics of sargassum investigated the co-occurrence of tar balls, floating petrochemical masses thought to be from early oil spills off the coast of England (Butler & Morris, 1973). Long range transport of sargassum mats across the Atlantic Basin has happened annually since 2011, creating a landscape pattern that has followed a seasonal cycle of summer Caribbean inundations (Oviatt et al., 2019).

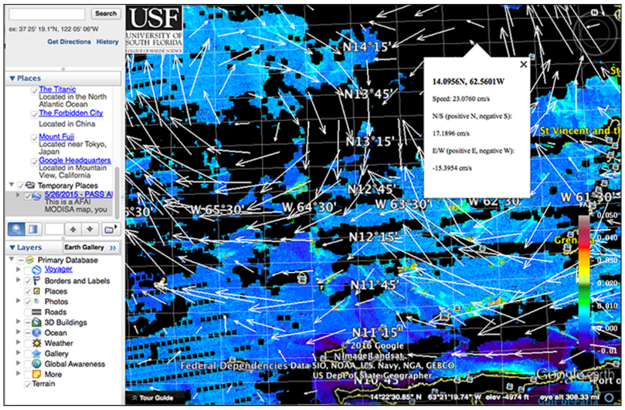
The Intertropical Convergence Zone (ITCZ), the zone where winds from both the north and south converge and blow to the west in a low-pressure region along the equator, transports windrows of sargassum to the coast of South America and the Equatorial Current brings some sargassum back to the coast of West Africa annually to continue the cycle (Chavez et al., 2020). The ITCZ shifts northward in the summer and southward in the winter, shifting the GASB with it (Johns et al., 2020). The southward shift of the ITCZ in September may leave windrows of sargassum behind, which are then advected towards the Caribbean by the North Equatorial Current and Trade Winds and may serve as a seed crop for the following season's GASB (Johns at al., 2020).

However, this theory describes a seasonality which may be outdated as sargassum inundations seem to be shifting toward a perpetual state in 2022, which has yet to be explained. When the zonal winds of the ITCZ are in their most northern latitudes they deposit long windrows of sargassum mats into the Caribbean, some of which cause coastal inundations and some of which continue to join the Sargassum Loop with regional ocean currents (Johns et al., 2020; Lapointe et al., 2014; Oviatt et al., 2019). The GASB region shows a roughly annual cycle of propagation and growth early in the year off West Africa, with westward zonal transport in windrows, arriving in the Caribbean from March until September (Descloitres & Berline, 2021). It has been hypothesized that windage effects may decrease as sargassum ages and loses some buoyancy, as the North Brazil Current System currents transport some sargassum from the Western Atlantic into the Caribbean (Putnam et al., 2018).

The Sargassum Loop consists of a series of currents that connects the GASB to the Caribbean and the Gulf of Mexico, then to the Sargasso Sea, and back to the GASB (Lapointe et al., 2014; Oviatt et al., 2019). The Sargassum Loop System pushes sargassum from the Sargasso Sea with the Azores high pressure system winds and transports mats into the Caribbean Sea, where it is swept by the Caribbean and Yucatan currents into the GOM (Webster and Linton, 2013). Within the Caribbean and GOM, some sargassum is carried into the Florida Current to the Gulf Stream, while some will wind up in westward bound gyres, possibly landing in wracks along the beaches of Mexico and Texas, or sometimes being carried back around to the Gulf Stream and eventually back to the Sargasso Sea (Seas Forecasting, 2021).

Contrasting with this, Brooks et al. (2018) describe the Sargassum Loop as a “dead end” that does not continue on from the Sargasso Sea. This conclusion was made through Lagrangian particle modeling which tracked sargassum in the Atlantic Basin, which was also analyzed in reverse to find causal associations (Brooks et al., 2018). The connectivity of the Amazon River plume to Caribbean sargassum inundations was established, with an eastward equatorial countercurrent transporting a seed patch back to West Africa annually (Brooks et al., 2018). Brooks et al. also suggested that small sargassum patches, not detectable by satellites, serve as additional seed patches for larger mats; when they hit nutrient sources such as upwelling or river plumes, rapid opportunistic growth causes patch expansion. Potential flaws with the modeling of Brooks et al. include mortality and growth rates that were derived from historic grazing and nutrient data, both of which have shifted (Huffard et al., 2014; Lapointe et al., 2014).

Sargassum projections and modeling integrate the images of where mats are and the ocean and weather patterns that will determine their trajectories, as seen below in Figure 8 from the Satellite-based Sargassum Watch System (SaWs) website (Optical Oceanography Laboratory, 2021). Regional connectivity has been undisputedly established through satellite imagery; sargassum is carried between the regions and may be nutrient enriched from multiple sources along the Sargassum Loop.



14.0956N, 62.5601W
Speed: 23.0760 cm/s
N/S (positive N, negative S):
17.1896 cm/s
E/W (positive E, negative W):
-15.3954 cm/s

Figure 8. Satellite- based Sargassum Watch System Ocean Current Integration. Reproduced from https://optics.marine.usf.edu/projects/saws_test.html

Vertical Transport Dynamics

Sargassum are positively buoyant at the surface due to sturdy gas filled air bladders called vesicles that grow along the algal branches, or thalli (Coston-Clements et al., 1991). These bladders compress and lose functionality between 100 and 200 meters deep, rendering the sargassum negatively buoyant (Coston-Clements et al., 1991;

Gray et al., 2021). Senescent sargassum at sea sink to the ocean floor, exporting nutrients to the benthic layer.

Downwelling occurs in convergence zones of oceanic currents; wind driven Langmuir circulation has been documented to sink sargassum by repeatedly pressurizing the gas filled vesicles, and it is assumed that herbivory is also responsible for small amounts of vesicle failure and sargassum sinking (Gray et al., 2021). Understanding the vertical transport dynamics of sargassum mats is essential for modeling future sargassum scenarios; decaying sargassum in the abyssal plain may be an important aspect of oceanic nutrient cycling. There has been research around utilizing sargassum for carbon sequestration by intentionally pumping it to depth, but this proposal will require environmental impact assessments regarding leachate effects and pollutant loads as well as a better understanding of sequestration amounts, temporal scale, and potential side effects (Antonio-Martínez et al., 2020; Devault et al., 2021; Gray et al, 2021; National Academies of Sciences, Engineering, and Medicine, 2022).

Social Ecological Context

Sargassum range expansion appears to have started with a weather anomaly. Anthropogenic climate change is linked to increasing storm frequency, intensity, and weather anomalies (Emanuel, 2020: IPCC, 2021). Sargassum proliferation is perpetuated by anthropogenic climate changes such as changing storm patterns, increased atmospheric and ocean nutrient enrichment, and land use changes that increase riverine runoff. Sargassum proliferation and subsequent inundations are linked to humans in a causal and positive feedback loop. This proliferation drives coastal sargassum inundations which cause ecological, social, and economic impacts in coastal systems and beyond, as detailed in the next section and illustrated below in Figure 9.

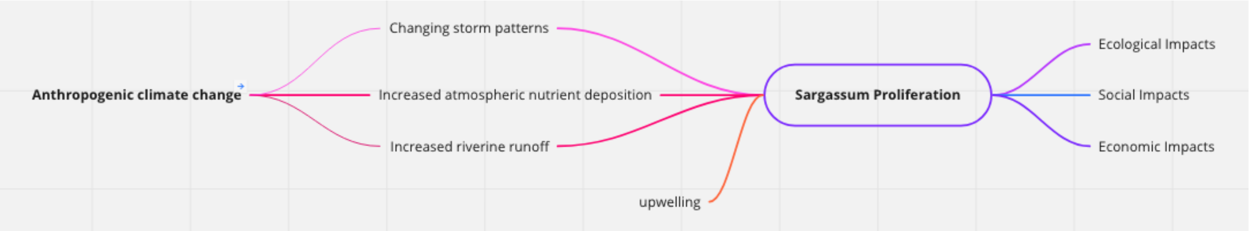


Figure 9. Climate Change Driving Sargassum Proliferation and Impacts. Created using Miro.

Without slowing or stopping climate change and ocean eutrophication, sargassum proliferation will continue into the foreseeable future. The proliferation at sea is then swept to shorelines, causing sargassum inundations which are linked to human communities. These inundations

CHAPTER 3

Sargassum Inundations

The dynamic location of the GASB moves sargassum zonally across the Atlantic and deposits it on either side of the Atlantic basin. Sargassum proliferation is followed by currents, regional wind, and storms moving some algal mats towards coastal areas. The topography of coastlines includes bays, beaches, and inlets that can accumulate large amounts of sargassum, piling up in shallow waters and becoming stranded onshore, as seen below in Figure 10. As sargassum mats wash into shallow bays, smothering coral reefs and mangroves, piling up on beaches, and rotting in the hot sun; decomposition can take months to years, releasing methane and hydrogen sulfide gas and creating a habitat for swarming flying insects (Gray et al., 2021).

Figure 10. Sargassum Inundation. Photo from Scenic Views Travel Facebook post, March 22, 2022, in Mexican Yucatan.

When large amounts of sargassum accumulate in nearshore and coastal areas, the resulting inundations have negative ecological and social impacts, potentially leaving lasting ecological effects from eutrophication and aquifer contamination while potentially decimating local economies. The ecological portion of this section will include sections on beach and near shore impacts, organismal impacts, and persistent pollutants while the social portion of this section will include health, and clean-up subsections. The economic section includes diverse communities from both sides of the GASB.

Ecological Impacts

Wracks of sargassum wash up on the shores of West Africa and the Caribbean during “sargassum brown tide” events (Trinanes et al., 2021). Only 11 years after the initial formation of the GASB, sargassum. inundations are implicated in seagrass meadow die offs and sandy beach loss (Rutten et al., 2021; van Tussenbroek et al., 2017). Sargassum inundations import abundant biomass into tropical coastal ecosystems, leading to eutrophication and cascading ecological impacts (Johns et al., 2020). The ecological impacts of these inundations will be organized as beach and nearshore impacts, organismal impacts, persistent pollutants, and a section on the loss of ecosystem services.

Beach and nearshore

Terrestrial abiotic impacts include a loss of sand associated with sargassum inundations due to both beach cleaning and wave erosion (Rutten et al., 2021). Sand accumulates in the biomass that is then removed either mechanically, manually, or by natural processes, reducing the sandy beach area and requiring subsequent beach nourishment (Defeo et al., 2021). As sargassum accumulates at the tide line during inundations, berms of biomass are formed. These berms are then undercut by waves, causing an increase in beach erosion (Rutten et al., 2021). Some developed beaches are being “squeezed” between sargassum berms and hard infrastructure, producing the conundrum of whether cleaning the beach or leaving the sargassum is better to limit beach loss (Defeo et al., 2021; Rutten et al., 2021). In the Yucatán of Mexico, there has been a call for pilot programs to explore ways of controlling beach erosion (Sánchez-Triana et al., 2016).

As sargassum wash into shallow water and onto beaches, productivity declines as the wracks senesce and begin to decompose (Devault et al., 2021). Decomposition releases particulate organic carbon (POC) and dissolved organic carbon (DOC) into the water and beach sediments while hydrogen sulfide gas is released into the air (Powers et al., 2019). Powers et al. attribute sargassum as responsible for large amounts of marine DOCs previously thought to be almost entirely terrestrially sourced. Heat stressed sargassum releases more DOC and POC, while heat increases release rates, such as in shallow bays where large mats senesce (Powers, 2019; van Tussenbroek et al., 2017). Water quality metrics such as turbidity, pH, and dissolved oxygen all decline during inundations; mats of floating sargassum block sunlight and prevent photosynthesis from happening in the darkened water below, negatively impacting seagrass meadows and coral reefs (Bartlett & Elmer, 2021; van Tussenbroek et al., 2017).

Wracks of sargassum import nutrients into coastal systems during inundation events, which can lead to eutrophication of coastal ecosystems if the wracks are not removed either by human effort or wind and wave patterns (Defeo et al., 2021). Thick mats of seaweed smother delicate coral reefs, sea grass beds, and mangrove ecosystems (Bartlett & Elmer, 2021; Oviatt et al., 2018). On land, marine sourced organic material significantly alters coastal ecotone productivity; sargassum has enriched sand dunes, promoting more vegetation in areas where sargassum detritus has been left to decompose (Polis & Hurd, 1996; Williams & Feagin, 2010).

Organismal

Sargassum inundations impact a wide range of coastal faunal, from spawning coral larvae to turtles (Antonio-Martinez et al., 2020; Cabanillas-Teran et al., 2019; Maurer et al., 2015; Rodríguez-Martínez et al., 2019). Lowered dissolved oxygen in the water impacts shallow water organisms, light is blocked from coral reefs below, and mass faunal mortality events have been recorded (Rodriguez-Martinez et al., 2019). A major faunal mortality event in 2018 during a record inundation in the Mexican Yucatán was cataloged to quantify the diversity and abundance of 78 species of fish, turtles, and invertebrates killed (Rodríguez-Martínez et al., 2019). The apparent cause of this mortality event was poor water quality and hypoxia due to sargassum decomposition. Conch yields in the Turks and Caicos have decreased concurrent with sargassum inundations, possibly due to the impacts on the conch's seagrass meadow habitat (Bartlett & Elmer, 2021).

Leachates from decomposing sargassum change the behavior of coral larvae, negatively impacting dispersal, and reduce the presence of native macroalgae, causing cascading trophic effects in shallow reef systems (Antonio-Martínez et al., 2020; Cabanillas-Teran et al., 2019). Antonio-Martinez et al. (2020) surveyed normal coral larval behavior contrasted to larvae in the presence of sargassum leachates and determined a stress reaction that reduces dispersal effectivity. The large-scale implications of this reduced dispersal may have serious consequences for coral; the spawning season is at the seasonal height of regional inundations (Antonio-Martinez et al., 2020). Other regional broadcast spawning organisms should be monitored for leachate impacts to quantify the extent of sargassum disturbances. Sargassum leachates also cause spiny urchins to shift up a trophic level from grazing to facultative omnivory, evident in the isotopic signature of sampled urchins in areas deficient in native algae; sargassum is not consumed even when present in abundance (Cabanillas-Teran et al., 2019). It is not yet clear whether sargassum impacts nesting sea turtles; sea turtle impacts may vary by locality or seasonality of inundations (Maurer et al., 2015; Rodríguez-Martínez et al., 2021).

Persistent Pollutants

Floating at the surface of the ocean, sargassum intercepts other materials less dense than seawater, like plastics, petrochemicals, and plumes of polluted fresh water from riverine run off. Sargassum can contain tar balls and heavy arsenic loads which can then leach into aquifers and groundwater (Butler, Morriss, & Sass, 1973; Devault et al., 2021). Decomposition of sargassum inundations releases harmful toxins, such as arsenic, into the coastal environment, causing some scientists to classify sargassum as macro pollution (Devault et al., 2021; Rodríguez-Martínez et al., 2019).

Loss of Ecosystem Services

In review from a previous section, ecosystem services encompass provisioning, regulating, supporting, and cultural functions that an ecosystem provides. Sargassum inundations can reduce access to fisheries and can cause large scale faunal mortality events, reducing the provisioning ecosystem service (Ramlogan, McConney, &

Oxenford, 2017; Rodriguez-Martinez et al., 2019). Regulating and supporting ecosystem services are reduced as sargassum decomposes in shallow water, lowering water quality and producing harmful gasses (Devault et al., 2021; Resiere et al., 2018). The reduction in cultural functions due to sargassum inundations is due to the closing of beaches and swim areas and the fouling of coastal regions that have historically been white sand and clear water (Defeo et al., 2021). The loss of ecosystem services associated with sargassum inundations leads us into the next section, the social impacts of inundations.

Social Impacts

The socio-ecological impacts of these inundations reverberate on both sides of the Atlantic with poorly understood public health risks, inaccessible fisheries, and declining tourism economies, (Devault et al., 2021; Johns et al., 2020). I will include the health impacts, clean-up efforts, and economic impacts as aspects of this social ecological situation.

Health

Human health impacts include nausea and headaches from the hydrogen sulfide produced while sargassum decomposes on shore (Gray et al., 2021). Reports of the gas causing headaches, dizziness, rashes, eye irritation, and respiratory distress abound throughout the Caribbean, and will continue to increase with the proliferation of sargassum (Crist, 2019; Denoble, 2020). Over 11,000 people experienced respiratory distress related to a sargassum inundation in Guadeloupe and Martinique in 2018, and tourists have been reporting symptoms of low-grade gas exposure when they return home (Resiere et al., 2018). The hydrogen sulfide gas from rotting sargassum has been reported to be strong enough to corrode electronics in buildings close to the beach and increase the rate of corrosion on boats and marine infrastructure in Guadeloupe (Capron, 2015). Decomposing wracks on beaches are a habitat for nuisance biting insects, another potential health concern (Louime et al., 2016). It is such a recent situation that long term health effects are not yet understood.

Clean-up

Cleaning up sargassum while it is fresh reduces risk to workers, and personal protective equipment further reduces potential irritation (Peter, 2020). Safety equipment and clean up protocols vary regionally, as seen in Figure 11., below.

Figure 11. Sargassum Removal with and without Personal Protective Equipment. Photo from MadoMartin→Sargassum Monitoring Facebook post, April 9, 2022

Individual hotels spend as much as $50,000 a month cleaning sargassum off of beaches, and in some areas, the military has been called in to help with removal (Gray et al., 2021).

Disposal techniques have proven expensive and environmentally harmful. Sargassum has been determined to carry a heavy arsenic load; arsenic may be leaching into water sources or bioaccumulating in workers that interact landed mats of sargassum (Devault et al., 2021). The environmental impact of beach cleaning with heavy machinery is an additional negative impact of sargassum, implicated in habitat loss and erosion. Clearing jungle inland to create landfills for removed sargassum perpetuates the problem- leachates from decomposing sargassum trickle into the aquifer, hydrogen sulfide and methane are released as it decomposes, or plumes of black smoke and particulate carbon are released if it is burnt.

Economic

Sargassum inundations have caused economic repercussions affecting sustenance fishermen as well as international tourist destinations. Inaccessible fisheries and coastal fouling have been recorded in Nigerian coastal communities while 30-35% declines in tourism revenues have been estimated in parts of Mexico (Adet et al., 2017; Gray et al., 2021)

The Centre for Excellence for Sargassum Research (CESAR) conference held at Lagos State University in Nigeria detailed the negative impact that sargassum inundations have had on the small-scale fishing industry due to inaccessible fishing grounds and social fabric in coastal towns (Adwele et al., 2022; Foluke et al., 2022).

The once crystal-clear water of the Caribbean turns murky brown as the piles of seaweed rot, releasing dissolved and particulate carbon, harmful leachates, and causing eutrophication of nearshore waters (Treadway, 2019). These are the beaches of the

Caribbean, once known for white sands and crystal-clear water, some of which are now rendered virtually unusable for months of the year. Caribbean hotel occupancy has declined as sargassum inundations have increased, with hotels that are not affected by inundations reporting no change in occupancy (Duan, 2020). Fishing and water recreation industries are impacted because boats can't navigate through the thick mats. Sargassum is impacting small developing countries in the Caribbean, many of which rely on tourism as their primary industry yet are facing loss of the iconic Caribbean brand (Babil & Nadee, 2021).

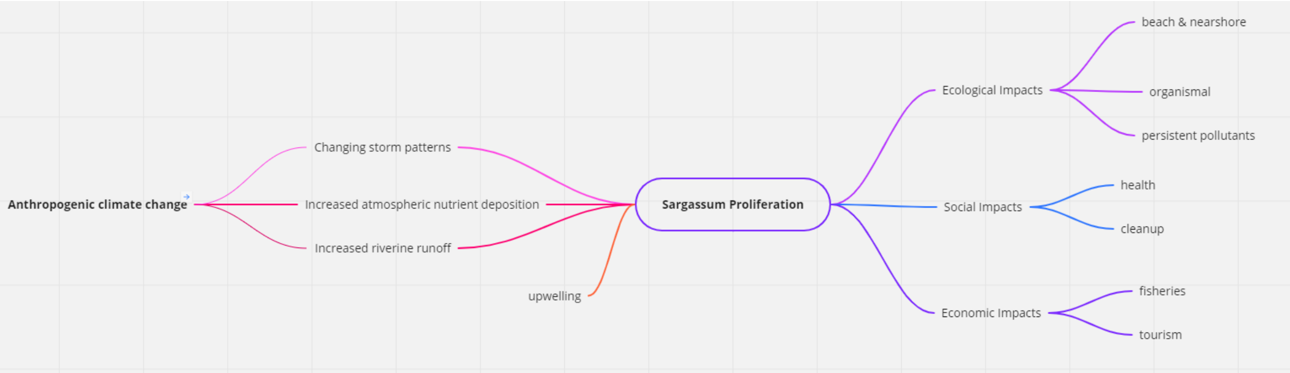


Figure 12. Climate Change Driving Sargassum Proliferation and Impacts Detailed. Created with Miro.

Summarizing the work thus far, Figure 12 uses sargassum proliferation as interchangeable with sargassum inundations. While they are distinct events, they are linked in this illustration for brevity's sake. Proliferation is understood to be an oceanic process, while inundations are understood to be the landing of sargassum mats onshore. It is these inundations that have negative ecological, social, and economic impacts, as detailed above.

CHAPTER 4

Mitigation and Adaptations

Communities around the Atlantic are reacting to the new sargassum inundations impacting their coastal areas. The last eleven years of sargassum inundations have seen innovative adaptations by coastal communities to deter sargassum from landing on their beaches and to clean up, remove, and dispose of sargassum that does make it to the shore. From Ghana to Fort Lauderdale, new adaptation strategies are evolving as different localities work to create best practices that will lessen the environmental, economic, and human health consequences caused by inundations. Additionally, quantifying sargassum at sea using remote sensing, calculating projected trajectories of floating wracks using a combination of satellite and meteorological data, and measuring sargassum related air quality issues are a few of the emerging technologies developing as communities adapt to this new phenomenon.

Sargassum Deterrence

Sargassum deterrence is one area of adaptation that has been attempted in some areas with varying success through the installation of floating booms that divert wracks back into deeper water. These booms are best deployed in calm sea conditions with a consistent directional current and have recently been designed with exclusion devices to lessen disturbances to marine fauna such as sea turtles. Drawbacks to these devices include the possibility that they may increase inundations on beaches downstream, can become dislodged in storm events, and need to be installed with a high level of technical understanding of local marine conditions and at the correct time (*Mahahual Beach Slammed with Sargassum Due to Misplaced Barriers, 2022; Mexican Navy's*

Sargassum Collection Ships on their Way to Cancun and the Riviera Maya, 2022). If booms are installed after sargassum has arrived, it cannot be transported back to sea by waves and currents and is trapped close to shore.

Booms can also fail when excessive sargassum piles up on one side, sinking or becoming entangled in the mats. Collecting sargassum at sea is necessary in conjunction with booms in some areas and may negate the need for booms if done at large enough scale in the future.

Sargassum Collection

New technology continues to emerge in the collection at-sea sector, incentivized by the development of more uses of sargassum. At-sea collection is preferential to collecting it from beaches because it negates the associated loss of sand and erosion issues of beach collection.

At-sea collection devices can skim the water, collecting the sargassum in mesh bags or loading it on to conveyor belts that transport it to waiting barges. The Littoral Collection Module (LCM) designed by a firm called SOS Carbon shows promise in its adaptability to local resources. The LCM can be retrofitted onto local fishing or dive operator boats, providing economic relief in areas that are negatively impacted through loss of fishery or tourism revenues by sargassum inundations (Gray, et al., 2021). Promisingly, a negative carbon footprint for the LCM was calculated using small boats and then sinking the sargassum as a method of intentional carbon sequestration in a pilot program off the Dominican Republic, discussed further in the following section on sargassum valorization (Gray, 2020). An electric aqua drone is being developed by a company named Thalasso for sargassum harvesting at sea with the intent of creating a biofuel industry around sargassum (Cox, et al., 2022). Again, environmental assessments and exclusion devices will need to protect marine fauna.

Once sargassum reaches the beach or shoreline, it starts to rot and mix with sand. Raymond Mossiah, the Chief Tourism Officer of Belize, emphasized that his country's best practices include removing sargassum within 48 hours of beaching (Cox, et al. 2022). Removal from beaches can be done by hand with rakes and pitchforks in areas with enough available labor and small enough inundations to be manageable, as described by Leroy Browne of Barbados (Cox, et al., 2022). At one resort in Saint Maarten, a small tractor designed specifically for beach cleaning, the Cherrington 5500, is used at the water line to avoid compacting sand and potentially harming turtle nests (Cox, et al., 2022). Removed sargassum is piled at the end of the beach so that the sand is not lost to the system; as the seaweed decomposes, the sand washes back into the ocean to be redeposited.

Beaches in Cancun have been using heavy equipment, such as tractors dragging large rakes, to remove sargassum. In 2018, 522,226 tons of sargassum were collected with 2022 projections to be 300 times that amount (*Cancun Hotel Zone Beaches Being Repaired After Mass Erosion*, 2022). In a region built for tourism, sargassum has disrupted an economy that was already threatened by climate change events such as increasing storm intensity and frequency and sea level rise (de Jong, 2022; *Sargassum crisis could wash away tourist income by 30%,* 2022). Removed sargassum is then burned or dumped at inland facilities, reducing sand in the coastal areas. Beach narrowing, also caused by storms and sea level rise, is then combated by beach nourishment, the importation of sand from the ocean floor (*Cancun Hotel Zone Beaches Being Repaired After Mass Erosion*, 2022).

Sargassum Disposal

Disposing of large amounts of marine origin biomass has proved challenging for small islands and coastal communities. Inland landfills require clearing more terrestrial jungle habitat in the Yucatan of Mexico, and leachates contaminate local aquifers. Incinerating sargassum impacts local air quality and is undesirable in tourist or residential areas. Bagging sargassum in plastic garbage bags slows decomposition, but then creates more quantity in landfills. Some resorts relocate sargassum to unused portion of the beach where it will slowly be returned to sea or incorporated in the sand.

Emerging Technologies

When sargassum is not removed onshore, decomposition produces harmful gasses. The French Agency for Food, Environmental and Occupational Health and Safety (ANSES) has specific guidelines around sargassum and hydrogen sulfide exposure and has placed emission sensors in areas with consistent sargassum inundations in Guadeloupe (*Beaching of Sargassum in Guadeloupe,* 2022). With H_2S values between 1 and 5 ppm, susceptible and vulnerable individuals should avoid the area. If values exceed 5 ppm, access is limited to professionals with sensors and safety equipment. Toxic reference values (TRVs) proposed by the US EPA are 1.43 ppb - 2 µg·m-3 for chronic exposure, while the OEHHA range is 7.14 ppb - 10 µg·m-3 (*Sargassum seaweed: limit the exposure of residents and workers to hydrogen sulphide,* 2018). Other parts of the Caribbean do not have clear guidelines, protocols, sensors, or safety equipment, and are receiving sargassum inundations even greater than those in Guadeloupe.

Technological advances made around sargassum forecasting include using satellites, remote sensing, drone technology, and developing a specific algal index, the Alternative Floating Algae Index (AFAI) developed by the University of South Florida (Physical Oceanography Division, 2021). A weekly Sargassum Inundation Report (SIR) is produced by NOAA and the University of South Florida to help inform management decisions (Physical Oceanography Division, 2021). The SIR classifies risk levels of Sargassum Inundations as High, Medium, Low, and no data. The predictions are made using satellite imagery combined with meteorological and ocean current data and are based on where the mats of sargassum at sea will wash ashore. Sargassum presence and abundance can be quantified using remote sensing through a High Resolution Sargassum dataset with sargassum specific indices through NASA's MODIS instrument on both Terra and Aqua satellites (Optical Oceanography Laboratory, 2021).

By using GIS to combine projected sargassum landings, prevailing winds, and quantifiable population data, the number of people potentially in a hazardous zone can be quantified. The Sargassum Inundations Report (SIR) and Satellite based Sargassum Watch System (SaWS) data could be combined with high-definition population datasets to create realistic buffer zones of populations (or hotel zones) that could expect H_2S exposure or the tourist-deterring smell of decomposing sargassum (Optical Oceanography Laboratory, 2021; Physical Oceanography Division - Experimental Weekly Sargassum Inundation Report, 2021; WorldPop/POPGRID, 2022).

Human culture adapts to challenges, and the innovative responses to diverting or collecting influxes of sargassum seaweed continue to improve. The human component of the sargassum situation needs to continue to be assessed to best plan management, mitigation, and adaptation strategies in the years to come, hopefully creating a value stream for this new abundant biomass.

CHAPTER 5

Valorization

Although sargassum inundations initially seem like a negative addition to coastal areas, there may be a way to transform these large amounts of biomass into something of value. Finding that value has been an ongoing challenge on both sides of the Atlantic, as artists, designers, farmers, entrepreneurs, and scientists experiment with new uses for sargassum.

Harvesting sargassum from beaches requires subsequent washing and decontamination to remove sand and detritus; collection at sea reduces the cleaning required, although it still needs to have salt and any collected plastics or garbage removed (López Miranda et al., 2021). The sargassum has then been processed into textiles, soaps, plastics, emulsifiers, construction materials, and agricultural products; an excellent resource for the expanding sargassum industry is the "The Sargassum Uses Guide" (Desrochers et al., 2020).

Other projects have used sargassum as fertilizer and compost, with the creation of fertilizer teas and addition of sargassum to gardens as a soil amendment (Goni, 2022). High levels of arsenic and other heavy metal contamination in the sargassum may contaminate crops grown with these products; levels of contaminants vary by site and season and testing protocols are needed whenever sargassum is used for human food production (Addico & DeGraft-Johnson, 2016; Desrochers et al., 2020; Nielsen et al., 2021). Similarly, using sargassum as animal feed may result in bioaccumulation of heavy metals in the livestock consuming it. The propensity of developing nations to use sargassum as fertilizer on agricultural crops and feed for livestock where contaminant testing is not economically feasible presents added human health risks to the dilemma of sargassum macro pollution (Devault et al., 2021).

There may be a safer market using sargassum for ornamental gardening only, perhaps in resort areas where large amounts of industrial fertilizer are typically used. The Sea Soilution (*sic*) project is developing a more heavily processed sargassum based bio stimulant with lessened contaminants, especially important in areas that have not traditionally been rich agriculturally, like the small rock and sandy islands where sargassum is landing (Goni, 2022; Thigpen, et al., 2022).

In Puerto Morelos, Mexico, construction projects using sargassum in building blocks include low-income housing, a hotel, and a refugee camp. In the same area, a new product called “Sargacreto” uses sargassum as ~40% of a concrete mix destined for walkways and artificial reefs (Desrochers et al., 2020; *‘Sargacreto’, the new construction material made of sargassum*, 2021).

The development of the carbon offset market has driven kelp farming in more northern areas, but here is a situation where the sargassum grows naturally and doesn’t need to be farmed. For carbon offsets to work, the carbon captured in the biomass needs to then be stored, not released back into the atmosphere with decomposition. By sinking sargassum to the deep ocean floor, the innovative companies SOS Carbon and Seafields claim that decomposition is slowed to about a thousand-year cycle, effectively removing carbon from the atmosphere for the next millennium (Gray, 2020; Gray et al., 2021). If sargassum impacted nations with close access to deep water can develop a carbon market, this could be a financial windfall. Environmental impact assessments will be needed for long term sargassum influxes and storage at depth, but research around sargassum sedimentation indicates that this is a process that has occurred without human intervention, importing nutrients to the sea floor from the surface (Baker et al., 2018). By intentionally facilitating the sinking process, a perpetual sargassum carbon pump from the surface of the ocean to the deep sea could potentially be developed. If we can harness this oceanic process to function as a carbon pump, sequestering it at depth or using it as fuel, this could be a component of the multifaceted portfolio that our global community needs to draw down carbon.

It should be noted that the efficacy of this process has been disputed due to inaccurately high estimated calcifying epibiont coverage on sargassum mats, reducing the net carbon sequestered (Bach et al., 2021; Pestana, 1985). What the dispute fails to recognize is that the young mats of the GASB bound for sinking have much less epibiont coverage, increasing their sequestration potentiality (Paraguay-Delgado et al., 2020).

Additionally, as new sustainable energy sources are sought globally, there is promise of sargassum being developed into a biofuel. The processing of sargassum with waste from a rum distillery creates a biofuel in Barbados that can run properly converted personal vehicles, increasing the island's energy independence. The innovators of this technology, a company called Rum & SarGASsum, tout the benefits of their biofuel as being cheaper and cleaner than traditional petrochemicals as well as keeping the beaches of Barbados clean. More information about this project can be found at https://rumandsargassum.com. The process of refining sargassum through anaerobic digestion is technology accessible to coastal communities, providing an economic benefit to a situation that has had a negative impact since 2011 (Lopresto et al., 2022).

After just over a decade since the onset of sargassum inundations, communities are rallying to create an industry for this new source of biomass. A Techno-Economic Life Cycle Analysis conducted on sargassum concluded that the negative impacts of inundations could be reduced while providing a sustainable economic opportunity for affected regions (Marx et al., 2021).

CHAPTER 6

Collaborations, Education & Public Engagement

The multi-national and pan-Atlantic dimensions of the sargassum phenomenon initially slowed information sharing on either side of the GASB. Communication across industries and information sharing between regions required creating novel interdisciplinary alliances involving diverse stakeholders (McConney & Oxenford, 2021; Oxenford et al., 2021). Sharing knowledge is a challenge, especially when a novel environmental concern occurs in geographically distant locations. The sargassum phenomenon has created new avenues for scientists and experts to come together and work towards solutions and recommendations for best practices. From the global to the hyper-local, the dissemination of information is a vital part of sargassum in a social ecological framework.

Sargassum is being addressed from a global perspective as an emerging HAB by the United Nations Environment Programme (UNEP) and the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) with a recent call for an open science meeting on Sargassum, with more information expected in the Fall of 2022. NOAA CoastWatch (CW) Caribbean Node and AOML hosted an activity entitled "Satellite Monitoring of Pelagic Sargassum" through the 2021-2030 United Nations Decade of Ocean Science for Sustainable Development, and the UNEP 2021 white paper on sargassum, “Turning the Crisis into Opportunity,” also expresses international cooperation and collaboration. The Group on Earth Observation (GEO) Blue Planet 5th Symposium in Ghana this October 2022 will have sections on sargassum, especially around remote sensing and forecasting. Regionally, a meeting of sargassum experts was called in Sierra Leone in 2015 and the Centre for Excellence in Sargassum Research (CESAR) at Lagos University in Nigeria hosted its first conference last year.

Lively debate, information about upcoming events and projects, and calls for papers and current research abound on SARG NET, a list serve hosted by Florida International University. The organization Marine Conservation without Borders has been hosting a monthly sargassum podcast to bring scientists, entrepreneurs, and stakeholders together in a more casual format to share information and projects, as well as hosting virtual meet and greets, allowing students to introduce themselves and ask questions.

Technical manuals, such as “Sargassum Uses Guide” produced by the Food and Agricultural Organization (FAO) of the UN and CERMEs, “Management Best Practices for Influxes of Sargassum in the Caribbean with a focus on clean-up,” and “The Prevention and Clean Up of Sargassum in the Dutch Caribbean” streamline current science and best practices (Desrochers, 2020; Dutch Caribbean Nature Alliance, N.D.; Hinds et al., 2016).

While by no means an exhaustive list, there are new educational and research resources dedicated to learning more about sargassum in the recent context. The Sargassum Loop System has been described and researched through the Sargassum Early Advisory System (SEAS), a Texas A&M Galveston Research Project. Understanding the lateral movement of *Sargassum* mats has been the focus of remote sensing work done by the Optical Oceanography Lab at The University of South Florida, which has developed remote sensing products to estimate biomass and forecast

Sargassum dispersals like the satellite-based Sargassum Watch System (SaWS) and the Sargassum Inundation Report (Optical Oceanography Laboratory, 2021; Physical Oceanography Division, 2021). The French group, Collecte Localisation Satellites, has been developing a cloud based sargassum monitoring and forecasting tool to be used throughout the Caribbean (Sutton, Stum, & Dufau, 2021).

Group sourced and not peer-reviewed sources, like the Facebook Groups Sargasso Seaweed Updates Riviera Maya and Sargassum Monitoring, have abundant user-provided same day photographs for the Yucatan region and archives of dated photos detailing the extent of inundations throughout the Caribbean. The latter is linked to a website, updated daily, with a sargassum map for the region (Sargassum Monitoring, 2021).

Recent courses designed to train stakeholders on sargassum include an Applied Remote Sensing Training Program offered by NASA on Monitoring Aquatic Vegetation with Remote Sensing and a two-part sargassum virtual learning series for tourist industry stakeholders. There is a research focus at the World Maritime University with associated PhD candidates called Closing the Circle: Marine Debris, Sargassum and Marine Spatial Planning in the Eastern Caribbean.

Reaching out to impacted residents in coastal communities has largely been a grassroots movement, with materials designed for school age children and signage on beaches. Marine Conservation without Frontiers has created an informational sargassum booklet in Maya, English and Spanish languages for school children in Belize and Mexico. The sargassum comic book project lead by the Embassy of France in Saint Lucia, the Alliance Française in Saint Lucia with the Embassy of France in the

Dominican Republic, the Alliance Française of Santo Domingo and the Guadeloupean comic book author Jessica Oubile, approaches the situation in an accessible, fun way for children. “Tales of Sargassum Seaweed” by A. L. Dawn French and “Peanut and the Sargassum” by Margot Anderson and Katie McConnachie are two more examples of recent educational Caribbean children’s stories, easily found online (and even Amazon!). Educating children of the ecosystem value and potential hazards of sargassum is a new need being met creatively through approachable media.

Educating tourists varies among resorts, but now the consensus is that admitting that sargassum may affect regional beaches and water access gives visitors an opportunity to find other recreation activities (Cox, 2022). Some hotel websites are offering explanatory blurbs about sargassum, that it is a natural and unpredictable aspect of regional beaches. Facebook groups, from the scientific (“Sargassum Monitoring”) to the tourist base (“Sargazo Sargassum Sargasses Riviera Maya Mexico”) make daily reports available with crowd sources pictures and updates of various beaches’ status. Hotel webcams have become less reliable for real-time imagery, as some hotels may not want to broadcast significant inundations. Surprisingly, although Punta Cana, Dominican Republic, has significant sargassum inundations, some hotels do not have any permanent signage or tourist information about it (personal communication, September 2022). Miami-Dade beaches do have some signs explaining the ecosystem associated with sargassum seaweed, and Florida sargassum protocols are rapidly changing to adjust to recent inundations.

As a significant disruption to coastal tourist economies, sargassum has driven the development of inland recreational activities in some areas. An uptick of tourist interest in Maya archaeological sites and cenotes has shifted tourism away from beaches in Mexico during inundations. It cannot be overstated how unpalatable the smell of rotting sargassum is, and resorts are needing to bolster tourist educational materials so that sargassum inundations can be explained in the greater perspective of climate change. This is an opportunity to drive home the reality of climate change to a wide cross section of tourists and could be used to promote conservation-based initiatives, as well as develop more inland activities.

CHAPTER 7

Next Steps, Trends, and Regime Shift

Next Steps

Further work developing a sargassum SES framework will inform best practices and the policy making process. Continued innovation, research, and development will drive the creation of a sargassum market, improve collection/harvesting technology and provide economic benefits to developing tropical regions. Environmental assessments surrounding proposed carbon sequestration include understanding benthic carbon cycling and potential impacts. By-catch monitoring and prevention is needed for at-sea sargassum collection/harvesting, and improved chemical analysis accessibility is needed for communities using sargassum in agricultural industries.

If sargassum is no longer nutrient limited in its new range, what limiting factors will control its growth? Better understanding of the sargassum life cycle will help determine whether this phenomenon is a periodic occurrence or indicative of a basin wide ecological regime shift. Senescent cues, specific temperature tolerances for subspecies, and a better understanding of trophic structure such as grazing control will better inform forecasts and long-range models. On an ecosystem level, regional broadcast spawning organisms should be monitored for leachate impacts to quantify the extent of sargassum disturbances and track resulting trophic shifts.

An additional question that needs further research is what would be the impacts to the benthic community if large amounts of sargassum are intentionally exported to the ocean floor as a method of carbon sequestration? How can we model this to scale, allowing for a decomposition rate that will take centuries?

Identified as an area needing more research in the National Academies of Science, Engineering, and Medicine's "A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration" (2022), understanding the duration and quantities of algal carbon storage in natural systems is essential for the development of future large scale seaweed farms designed to export carbon to depth. This is already happening in natural cycles, and we urgently need deep sea exploration of extant drifts of sargassum on the ocean floor.

Faunal bycatch surveys need to be conducted in all of the places that sargassum is being collected, but especially patches at sea. As previous decades have seen the demand and development of turtle excluding devices and dolphin safe fishing protocols, the sargassum harvesting industry will also need to determine what can be done to reduce bycatch.

Bountiful work has been done establishing anthropogenic effects in global climate change (Doney et al., 2020; Doney et al., 2021; IPCC, 2021). The link between carbon emissions and climate change is at this point irrefutable, yet the pace of global attempts to draw down emissions are not yet ensuring confidence that we have not already met critical climate tipping points. Our primary aim to slow the onset of catastrophic climate change should be reducing carbon emissions and sequestering as much carbon from the atmosphere as possible. Using a combination of terrestrial, marine, and technological methods for carbon sequestration, coupled with a dramatic reduction in the use of fossil fuels, we still may have a chance at the global goal of the IPCC to limit planetary warming to 2 degrees.

Trends

The first decade of the GASB saw a clear seasonality to sargassum inundations. Although there has been a decade of interannual variation, sargassum was generally found off the coast of Africa through the late winter and early spring, when the winds would pick up and start shifting it westward towards the Caribbean. Sargassum season in the Caribbean has been defined by wracks nearshore and on beaches generally between April and September, with intermittent rafts impacting local communities for days to weeks at a time. Variability of inundation quantities and timing have ranged over the years since 2011, but the trend seems to be increasing amounts over more extended periods of time (Rodríguez-Martínez et al., 2022).

While it is too early to include in a trend, the last winter season, 2021- 2022, seems to have had an unseasonal longer period of sargassum inundations, with some Caribbean reporting sargassum throughout the winter months. The Satellite Based Sargassum Watch System (SaWs) run by the Optical Oceanography Lab of the University of South Florida noted that 2022 has been a record breaking sargassum year and that satellite imagery is currently recording large buildups in the eastern Atlantic, indicative of another bountiful year to come. Please review Appendix 1 for the most recently available sargassum outlook bulletin from SaWs and USF.

The rapid change in sargassum geographical and temporal range and increasing abundance is indicative of ocean eutrophication and may be indicative of a basin-wide regime shift (Lapointe et al., 2021). Reproduction by fragmentation allows for explosive growth with the right conditions; cessation of these conditions is not predicted. The winter of 2021- 2022 was the first year-round sargassum event; previous years only produced Caribbean sargassum inundations from May-October. With this breakdown in seasonality and an increase in actual biomass, the formation of regional adaptation and mitigation plans is imperative.

Regime Shift

The Intergovernmental Panel on Climate Change Sixth Assessment Report asserts that global upper ocean warming and ocean acidification trends are virtually certain (2021). The oceans' ability to absorb carbon from the atmosphere is reduced by acidification, with a third of anthropogenic carbon being sunk in the ocean (Sabine, 2004). Atmospheric carbon has increased to ~413 ppm at the time of this writing, contributing to the warming of both the atmosphere and oceans. Warming global biomes, coupled with land use changes and pollution, are contributing to regime shifts in terrestrial and oceanic ecosystems; global ecosystems are reaching tipping points where historic patterns and understood seasonal dynamics collapse and are structurally replaced with new patterns and dynamics (Dakos et al., 2019; De Vries, 2013; Garcia-Gomez et al., 2020; Johns et al., 2020). The Atlantic Ocean may have already reached the tipping point that now allows a new sargassum regime, potentially disrupting ecosystem services for the foreseeable future (Johns et al., 2020)

As global ecosystems reach tipping points, historic patterns and understood seasonal dynamics collapse and are structurally replaced with new patterns and dynamics (De Vries, 2013; Johns et al., 2020). As we look into the future, what is stopping pelagic sargassum from colonizing other ocean basins? Geography obviously has prevented basin-hopping thus far, but with sargassum in the Caribbean near the Panama Canal, it may be advantageous to monitor the west coast of Central America for sargassum in the decades to come. It is not beyond the realm of possibility for sargassum to be transported in ballast water or attached to ships or equipment and become established outside of the Atlantic.

CONCLUSION

Sargassum seaweed is thriving. Climatic conditions have helped it spread into new ranges while ocean eutrophication has fertilized it. Anthropogenic changes contribute to this new hazardous algae bloom, and this HAB in turn drives change in human societies. The negative effects from sargassum inundations have been recorded thousands of miles apart, decimating fisheries and disrupting tourist economies. As communities on both sides of the Atlantic adapt to sargassum inundations, innovators and entrepreneurs seek to commodify this new bounty of biomass.

The disproportionate ecological, societal, and economic expenses that tropical developing nations endure due to sargassum inundations is a facet of pervasive global environmental injustice. This international situation impacts diverse stakeholders and has been logistically hindered by the complexity of disseminating information across national, cultural, and regional networks. Rapid environmental assessments are needed to support sargassum sequestration and biofuel projects; perhaps these inundations will prove environmentally and economically beneficial with an appropriate technological response. This is an urgent situation requiring immediate research and development to assist impacted communities and hopefully create globally advantageous sargassum value streams.

To reiterate foci of future work needed, we need to asses benthic impacts of sequestration proposals, determine temporal scale and downstream ramifications of said proposals, quantify faunal by-catch in sargassum harvesting processes, and develop appropriate exclusion devices and protocols to lessen by-catch.

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APPENDIX 1

USF
UNIVERSITY OF SOUTH FLORIDA

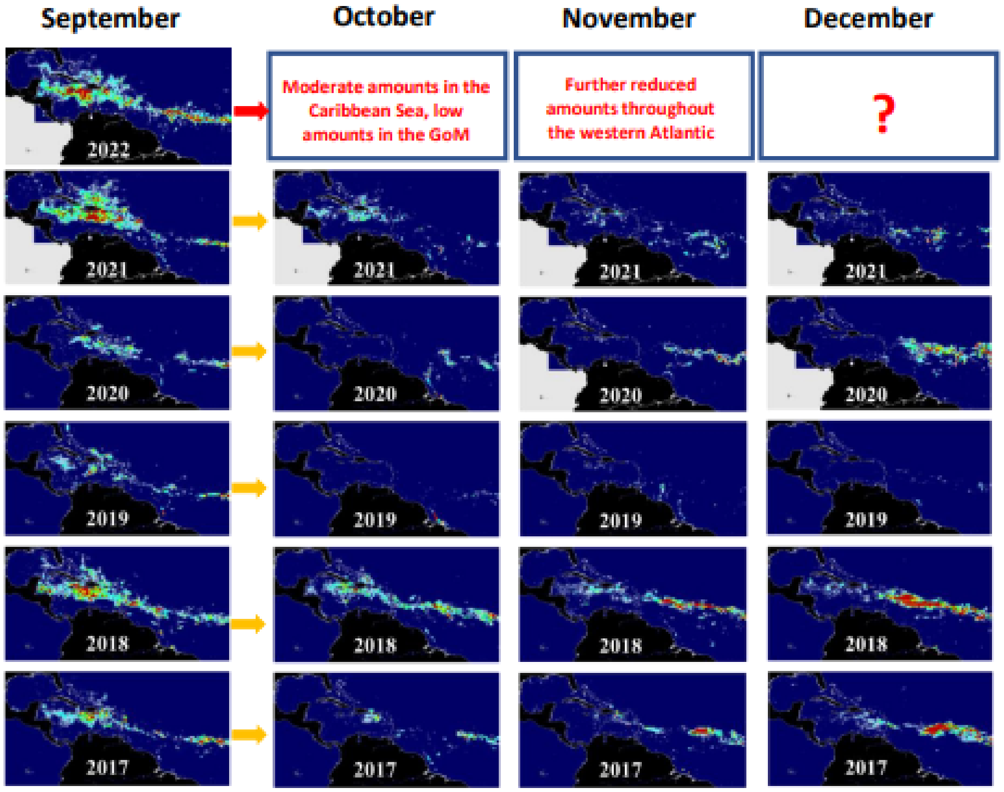
Outlook of 2022 *Sargassum* blooms in the Caribbean Sea and Gulf of Mexico*

October 4th, 2022, by University of South Florida Optical Oceanography Lab
(bbarnes4@usf.edu, yuyuan@usf.edu, huc@usf.edu)

NASA

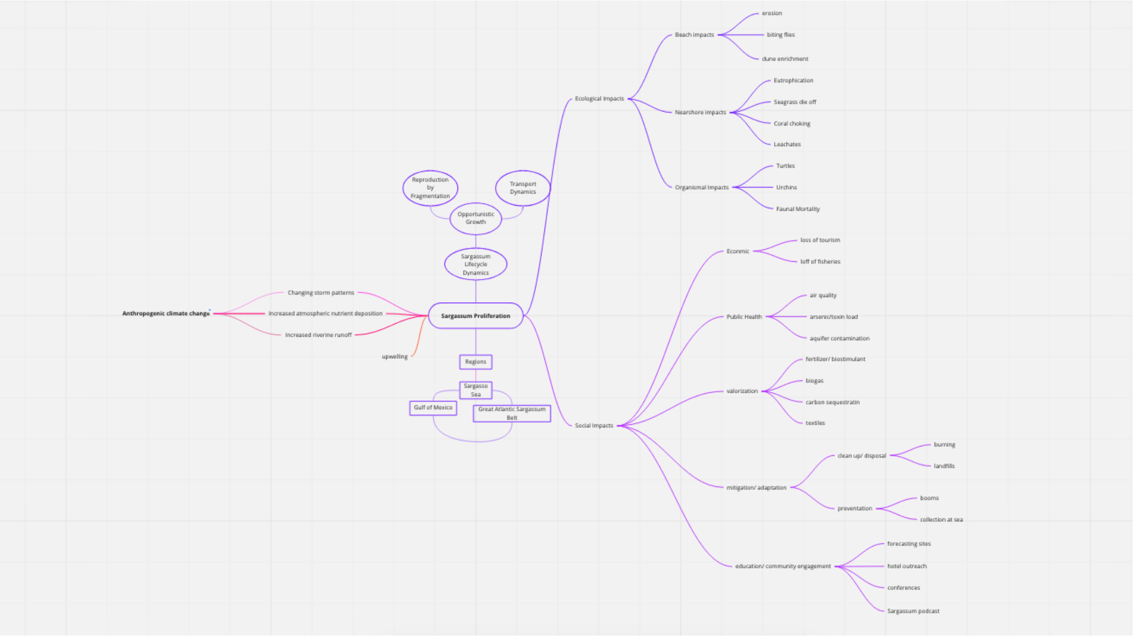
The maps below show *Sargassum* abundance, with warm colors representing higher values. In September 2022, the overall *Sargassum* amount in the central Atlantic Ocean continued to decline from previous months, **but remained at record levels (totaling ~8.5 million tons) compared to previous years** - roughly 20% higher than the previous September record (in 2021). *Sargassum* abundance in both the Caribbean Sea and the Gulf of Mexico decreased roughly 40% from August levels, which was especially apparent near the end of the month. While this decrease was expected, it coincided with substantial hurricane activity (Fiona, Ian), which may have also played a role.

Looking ahead, following previous major bloom years (2018, 2021), the overall *Sargassum* abundance in the western Atlantic, Caribbean Sea, and Gulf of Mexico will likely continue to decrease through November. Of note, however, ***Sargassum* is amassing in the east-central Atlantic (especially just offshore the west coast of Guinea, Sierra Leone, and Liberia) – up 40% from August.** Such a buildup has been observed in the year prior to all previous major blooms. More updates will be provided by the end of October 2022, and more information and near real-time imagery can be found under the *Sargassum* Watch System (SaWS, https://optics.marine.usf.edu/projects/saws.html).



Disclaimer: The information bulletin is meant to provide a general outlook of current bloom condition and future bloom probability for the Caribbean Sea. By no means should it be used for commercial purpose, or used for predicting bloom conditions for a specific location or beach. The authors of this bulletin, as well as USF and NASA, take no responsibility for improper use or interpretation of the bulletin.

APPENDIX 2



Thesis mind map, created in Miro.
Climate change →Sargassum proliferation & inundations → Ecological & social impacts