SARGASSUM WHITE PAPER

Addressing the influxes of the holopelagic *Sargassum* spp. in the equatorial and subtropical Atlantic:

Recent scientific insights in their dynamics

IOC Manuals and Guides 96

GESAMP
Group of Experts on the Scientific Aspects of Marine Environmental Protection

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Executive summary

For over a decade, countries and territories in the Gulf of Mexico, South Florida, Wider Caribbean and West Africa have experienced an unprecedented Transatlantic Triple Threat, the influxes of holopelagic *Sargassum* spp., resulting in significant social, economic and environmental impacts. These impacts have caused challenges to already strained climate-sensitive socio-economic and environmental sectors. Emerging impacts recently reported in the energy and water sectors further highlight the need for adaptive management strategies to address this triple threat.

The magnitude and complexity of the *Sargassum* issue has inspired scientists to investigate many aspects associated with this phenomenon, including the source and causes of bloom events. There has been considerable debate about the root cause(s) of unprecedented *Sargassum* spp. influx events, but it is generally agreed that the post-2011 *Sargassum* phenomenon in the tropical Atlantic can be considered a 'wicked problem'. A wicked problem can be defined as a social or cultural problem that is difficult or impossible to solve because of its complex and interconnected nature (Rittel and Webber, 1973). *Sargassum* influxes are influenced by a complex interplay of both natural and anthropogenic factors, and the social dynamics associated with response planning and management are subject to real-world constraints which hinder (risk-free) attempts to find a solution.

After more than ten years, there are still many unanswered questions and research gaps that need to be addressed to further inform decision-making and support policy development. An effective science–policy interface supported by a strong *Sargassum* scientific community will be key in promoting improved response planning and exploration of sustainable valorization initiatives to mitigate impacts and/or offset management costs.

This White Paper aims to present the current fundamental scientific understanding of the holopelagic *Sargassum* spp. population dynamics and transport, highlight research gaps and provide insight to the main players in the *Sargassum* scientific community. It outlines a clear and focused review of the state of knowledge and current understanding of the spatial and temporal variations in and the factors (both biotic and abiotic) underlying influxes of holopelagic *Sargassum* spp. into the Gulf of Mexico, South Florida, the Wider Caribbean Region and West Africa. Although focused on this area, the document can help addressing similar problems in other regions of the planet.

Main findings suggest that research on the estimation and spatial distribution of holopelagic *Sargassum* spp. and understanding the spatial distribution of bloom events have received a significant amount of investment of human and financial resources needed to produce operational remote sensing products that support ocean-scale early warning systems. However, other research areas need to be prioritized to develop more precise forecasts that promote collaboration at the science–policy interface. Validation studies including ground-truthing exercises are needed to better understand the occurrence of high biomass of *Sargassum* that impacts beaches and how that relates to oceanic scale estimates.

Less attention and financial resources have been invested in studies that investigate the linkages between the physical, biogeochemical and biological factors that influence growth and mortality. These studies are required to better understand the mechanisms underlying *Sargassum* population dynamics, and can improve the accuracy of forecasts and possible mitigation efforts.

Key research gaps were identified in areas related to atmospheric interference on remote sensing products and fine scale and subsurface detection to support holopelagic *Sargassum* spp. monitoring. The need to better understand nutrient sources driving *Sargassum* blooms was also highlighted. Another area of importance included the need for experimental exercises to understand how different physical conditions and oceanic and atmospheric factors affect the proliferation and transport of Sargassum under different climate change and nutrient scenarios. This, in combination with local and traditional knowledge, can help to further understand bloom development and dispersion.

The paper ends with recommendations for future research that will advance the understanding of the phenomenon, and the funding strategies and sustainable financing mechanisms needed to shore up important contributions to knowledge.

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List of abbreviations

AFAI	Alternative Floating Algae Index
AI	Artificial intelligence
AMM	Atlantic Meridional Mode
CENA	Central Equatorial North Atlantic
CERMES	Centre for Resource Management and Environmental Studies
CS	Caribbean Sea
CTNA	Central Tropical North Atlantic
CWA	Central West Atlantic
ENSO	El Niño-Southern Oscillation
ETA	Equatorial Tropical Atlantic
FAI	Floating Algae Index
GASB	Great Atlantic Sargassum Belt
GC	Guiana Current
GESAMP	Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection
GOM	Gulf of Mexico
IOC-UNESCO	Intergovernmental Oceanographic Commission of UNESCO
ITCZ	Inter-Tropical Convergence Zone
KI	Key informants
MODIS	Moderate resolution imaging spectroradiometer
MSI	Multispectral instrument
NAO	North Atlantic Oscillation
NASH	North Atlantic Subtropical High
NBC	North Brazil Current
NBCR	North Brazil Current Rings
NECC	North Equatorial Counter Current
NERR	North Equatorial Recirculation Region
NIR	Near infrared radiation
OLI	Operational land imager

SargNet	The Sargassum Network
SCOR	Scientific Committee on Oceanic Research
SEC	South Equatorial Current
SNA	Social network analysis
SST	Sea surface temperature
StOR	State of the Ocean Report
UNEP	United Nations Environment Programme
UNEP-CEP	United Nations Environment Programme – Caribbean Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UWI	University of the West Indies
VIIRS	Visible infrared imaging radiometer suite
WCR	Wider Caribbean Region
WTNA	West Tropical North Atlantic
WV-2	WorldView-II

Glossary

Term	**Definition**
Beaching	Synonymous with stranding but applies to only sandy shores rather than rocky shores or hard surface shore protection
Golden tide	Fresh healthy mats of holopelagic *Sargassum* floating out at sea
Holopelagic	Refers to an organism that remains pelagic during its whole life and never attaches to the seafloor
Influx	Arrival of holopelagic *Sargassum* into a broad area (e.g. the Caribbean Sea, Mexico's EEZ, etc.)
Inundation	Arrival of large amounts of *Sargassum* overwhelming shorelines and bays where it beaches or is trapped
Mat	Densely packed raft with irregular round or teardrop shape measuring from a few to hundreds of metres across
Morphotype	Classification grouping sargassum specimens with common morphological characteristics; the morphotypes are not recognized as official taxonomic groups
Pelagic *Sargassum*	Common name referring to the mix of floating holopelagic *Sargassum* species
Raft	Aggregation of floating holopelagic *Sargassum* species (as opposed to scattered thalli), generally classified into two different forms – mats and windrows
Sargassum bloom	Refers to the proliferation and expansion of the holopelagic *Sargassum* species population
Sargassum brown tide	Plume of brown, poor-quality water that occurs when sargassum dwells in the nearshore and starts to degrade, releasing pigments and fragments of fine brown particles. This term is different from 'brown phytoplankton blooms or brown tides'.
Sociograms	A visual model or graphic representation that displays all the personal connections within a group. It plots the structure of interpersonal relations in a group situation
Wicked problem	A social or cultural problem that is difficult or impossible to solve because of its complex and interconnected nature
Windrow	Raft of holopelagic *Sargassum*, generally arranged in a long line from a half to several metres in width
Wrack	Seaweed or seagrass distributed along the shoreline (can be any quantity)

1. Background

For more than a decade, countries and territories in the Gulf of Mexico, South Florida, the Wider Caribbean Region (WCR) and West Africa have experienced an unprecedented proliferation of holopelagic *Sargassum* species (hereafter *Sargassum*) in the Tropical Atlantic, with repeated inundations of shorelines. This phenomenon has been described as a *Sargassum* invasion (Johnson et al., 2012), golden tide (Smetacek and Zingone, 2013), *Sargassum* bloom (Wang and Hu, 2017), the Great Atlantic *Sargassum* Belt (Wang et al., 2019) and the *Sargassum* crisis (Oxenford et al., 2021). *Sargassum* influxes have caused significant social, economic and environmental impacts, resulting in challenges to already strained climate-sensitive socio-economic sectors (UNEP-CEP, 2021). Multisectoral impacts of *Sargassum* inundations are well documented (Solarin et al., 2014; van Tussenbroek et al., 2017; Resière et al., 2018; Oxenford et al., 2019; Chávez et al., 2020), demonstrating the magnitude of the crisis and the need for adaptive management strategies to address this 'Triple Threat'.

There has been considerable debate about the root cause(s) of these anomalous *Sargassum* influx events in the northern Tropical Atlantic (e.g. Franks et al., 2016; Djakouré et al., 2017; Oviatt et al., 2019; Johns et al., 2020). However, it is generally agreed that the *Sargassum* phenomenon is influenced by a complex interplay of both natural and anthropogenic factors. Considerable work has also focused on examining drivers of variation in the now annual blooms in the Tropical Atlantic (Brooks et al., 2018; Wang et al., 2019; Jouanno et al., 2021*a*; Skliris et al., 2022; Marsh et al., 2023). UNEP-CEP (2021) outlines that understanding the interannual and seasonal drivers of *Sargassum* influxes in the Tropical Atlantic is critical to any future effort to mitigate the impacts of the blooms, as well as efforts to accurately predict influxes to support adaptive response planning and effective management measures.

The causal pathway outlined in the 2021 UNEP-CEP *Sargassum* White Paper highlights the fact that there remains much that is uncertain or unknown about the details of processes and mechanisms relating to the transport of *Sargassum* to a new consolidation region, the proliferation in the new region and separation and transport to the Wider Caribbean and West Africa.

Scientists, journalists and policy-makers were taken by surprise in 2011 with the first mass *Sargassum* inundations in the southern Caribbean and West Africa, and found themselves scrambling for answers. It initiated a rapid increase in scientific research in an attempt to describe and explain the phenomenon. Thereafter, multisectoral impacts were quickly acknowledged and the scientific community and countries began sharing lessons in how to cope. Increased scientific knowledge, improved technology and data and information-sharing led to the development of forecasts using remote sensing products and data-driven solutions to help inform decision-making. Innovators began exploring opportunities and the multiplicity of potential uses for *Sargassum* (Addico and deGraft-Johnson, 2016; Desrochers et al., 2022). Startups and established companies began exploring potential *Sargassum* products and proceeding with efforts to develop and commercialize a variety of products and services. The Sargassum research development timeline is represented in Figure 1.

These valorization efforts have been touted as innovative blue growth initiatives, highlighting blue economy sector links which led to the integration of *Sargassum* management into blue economy frameworks (UNEP-CEP, 2021). Although several initial communication products were created to dispel myths and raise public awareness, it was not until 2020 that comprehensive science communication initiatives were officially launched (Oxenford, 2021). Moonshot ideas[1] grew in popularity in 2022, including the development of an electric aquadrone for *Sargassum* harvesting and the integration of digital technologies along the *Sargassum* value chain (Cox, 2022). Some data collection and analysis to support decision-making is now being powered by artificial intelligence (AI) and deep machine learning (e.g. Arellano-Verdejo et al., 2019; Shin et al., 2021; Podlejski et al., 2022; Hu et al., 2023; Lazcano-Hernández et al., 2023), offering insights into effective strategies for response planning.

Sargassum research has suggested numerous hypotheses, yet there are a host of unanswered questions that are pressing and require immediate attention. Addressing these gaps is crucial not only to advance scientific understanding, but also to provide the necessary insights for decision-making and the formulation of policies in the coming decade. Transformational adaptation measures including valorization pathways need to be grounded in the best available science to ensure sustainable *Sargassum* management and value chains.

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[1]) 'Moonshot ideas' refers to ambitious, exploratory and groundbreaking goals or projects which typically aim to address significant global challenges, advance technology and bring about transformative change.

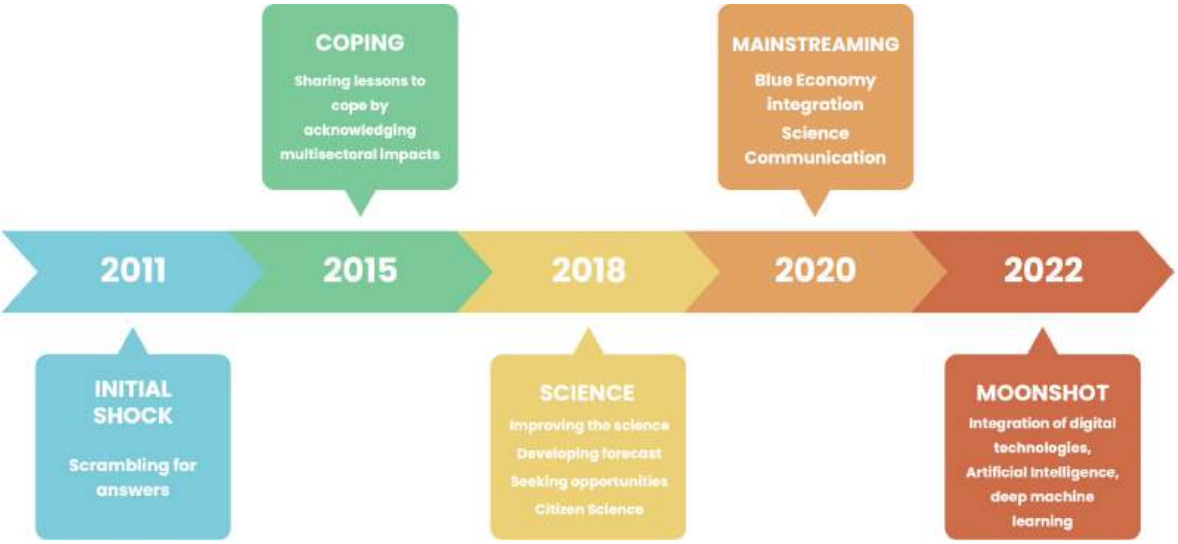

Figure 1. *Sargassum* Research Development Timeline. *Source*: Adapted from Oxenford, 2021.

2. Introduction

This White Paper has been commissioned by the Intergovernmental Oceanographic Commission of UNESCO (IOC-UNESCO) on behalf of the IOC and Scientific Committee on Oceanic Research (SCOR) Scientific Steering Committee for GlobalHAB and the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) correspondence group on *Sargassum*. It is intended to complement the UNEP-CEP 2021 *Sargassum White Paper: Turning the Crisis into an Opportunity*.

The purpose of the White Paper is to present a clear and focused review of the state of knowledge and current understanding of the spatial and temporal variations in, and the factors (both biotic and abiotic) underlying, influxes of *Sargassum* into the Wider Caribbean Region and West Africa. It includes a review of:

- The distributions of *Sargassum* biomass in space and time, including seasonality, inter-annual variability and long-term trends.
- The influence of ocean-scale processes (including atmosphere and ocean circulation events) on the timing and distribution of the *Sargassum* proliferation, including available statistical analyses to test such linkages.
- The identification of subregional scale factors, controlling *Sargassum* population growth, distribution, abundance and mortality, including: physical (temperature, weather patterns, ocean circulation fronts, eddies, gyres), biogeochemical (macro- and micro-nutrient availability) and biological (genetic variability and adaptive strategies).

Overall, the White Paper aims to present the current fundamental scientific understanding of *Sargassum* population dynamics, highlight research gaps and provide insight to the main players in the *Sargassum* scientific community.

The discussion provides a summary of key results and definitive statements on the state of science, elaborates on gaps identified and suggests how they could be addressed. The paper ends with recommendations for future research that will further advance understanding of the phenomenon and the funding strategies and sustainable financing mechanisms needed to ensure successful implementation.

An active area of research is the identification of the cause of *Sargassum* influxes. It is well understood that this phenomenon does not stem from a single or simple cause, but from a combination of factors that are likely linked to broader underlying issues, such as climate change and general ocean eutrophication (UNEP-CEP, 2021). Some scientists have posited that the precise cause of the 2011 event may be impossible to address now that the bloom has become well established, and appears to have become self-sustaining, persisting without the initial drivers.

The root causes are not well enough understood to support the development and implementation of impact mitigation options that target specific factors directly. In this context, these options refer to mitigation of the impacts of *Sargassum* inundations, as distinct from mitigating the impacts of climate change and/or ocean eutrophication. Further research is needed to investigate these causes that are likely to be transboundary. This will require substantial human and financial resources and high levels of social capital, to sustain arrangements such as multi-country research consortiums. Such consortiums are integral in supporting regional governance mechanisms. The development of an effective science–policy interface, supported by a strong *Sargassum* scientific community, is key in promoting response planning, managed mitigation and exploring sustainable valorization initiatives applicable to affected regions of the Tropical and sub-tropical North Atlantic.

Building a foundation for this interface requires a fundamental scientific understanding of *Sargassum* population dynamics through a comprehensive review of the status of research and identification of the knowledge gaps critical to progress in management and mitigation options. This *Sargassum* White Paper seeks to address the need for a comprehensive review of the state of knowledge on *Sargassum* research and propose interventions to address the issue.

3. Methodology

A multi-method approach, which included both primary and secondary data collection, was employed in the development of this White Paper. Data collection and review took place between May–July 2023, using various means including video conferencing and email correspondence. The use of multiple methods and data sources allowed us to obtain information on respondents' perceptions of the gaps in current *Sargassum* research.

3.1 Systematic review of literature

Literature gleaned from the UWI-CERMES Sargassum Reference Repository[2] and other online sources (Google Scholar, JSTOR, Scopus and ScienceDirect) were used to identify relevant peer-reviewed journal articles and appropriate conference proceedings, which provided insight into the specific areas of interest being investigated. Over 650 documents were reviewed:

1. to assess their relevance in uncovering the current understanding of the estimation and spatial distributions in *Sargassum* biomass, including seasonality, interannual variability and long-term trends;
2. to assess current biomass estimates in oceanic and coastal waters using *in situ*, satellite and citizen science studies;
3. to examine the role of major climatologic forcing (including atmospheric regimes, extreme events and ocean circulation) on the timing and distribution of the bloom events, including available statistical analyses to test such linkages; and
4. to provide evidence on the current understanding concerning the physical (sea surface temperature, winds and sea surface, weather patterns, ocean circulation fronts, eddies, gyres), biogeochemical (nutrient availability, salinity) and biological factors (genetic variability and adaptive strategies) controlling *Sargassum* population growth, distribution, abundance and mortality.

A social network analysis was conducted based on the authorship of relevant publications. The method is further discussed and the results presented in Appendix II

3.2 Key informant interviews

The literature review was used to identify researchers, scientists, academics and practitioners with relevant publications within the specific focal areas under investigation in this research. This approach was complemented by strategic engagement with professional networks and affiliations specializing in the specific domains of interest. These included academic institutions, government agencies, private sector agencies and regional and international organizations in the Wider Caribbean and West Africa. This led to the compilation of the names and affiliations of active researchers in the *Sargassum* scientific community (Appendix I) and a social network analysis was conducted. The method and results are further discussed in Appendix II. From this process, 47 key experts were identified and contacted via

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[2]) See *https://www.cavehill.uwi.edu/cermes/research-projects/sargassum/reference-repository.aspx*

email to ascertain their willingness to participate as key informants (KIs) of this research, in which 12 responded favourably. Among these, 10 were *Sargassum* researchers working at universities in the Caribbean, North and South America, Europe and Africa. The remaining two KIs represented an international company, providing satellite monitoring and surveillance services and a research institution dedicated to marine and coastal resources management.

Primary data collection involved KI interviews (n = 12) with *Sargassum* scientists/experts, private sector actors and regional and international agencies in the Wider Caribbean and West Africa. Semi-structured interviews were conducted, since they facilitate a predetermined list of interview questions but still give interviewers the scope to ask further and more in-depth questions as appropriate. A thematic analysis (Braun and Clarke, 2006) was performed to examine themes and patterns in interview transcripts, to support findings from the literature and provide insight into gaps in current *Sargassum* research.

A social network analysis (SNA) (Wasserman and Faust, 1994) was conducted of the *Sargassum* scientific community working variously on: estimation of biomass and spatial distribution of *Sargassum*; linkages between physical factors and bloom events; and physical, biogeochemical and biological drivers.

The first step in the SNA was the identification of key actors (see Appendix I) in the *Sargassum* scientific community (n = 208) before examining the structure of their relationships. The scientific community was identified based on: geographic location, through an investigation of authorship of *Sargassum*-related publications related to the subjects of interest; composition on *Sargassum* project teams; and participation at conferences where *Sargassum* sessions were hosted.

The intended method sought to examine the structure of social relationships in the *Sargassum* science community to uncover the formal and informal connections among individuals. Given the very low response rate (n = 1) to the SNA survey, an attempt was made to investigate and map a knowledge and information exchange network specific to the subjects of interest.

The analysis was conducted by investigating co-authorship on published literature. A relationship was indicated if researchers published together, and an assumption made that the authors would have exchanged knowledge and information related to the specific areas of interest.

Data were analysed and Polinode was used to create a sociogram (visual representation of social links) to plot the structure of interpersonal relationships within the *Sargassum* scientific community.

4. State of knowledge

Research to date on the phenomenon of *Sargassum* influxes has provided some insight into the magnitude and complexity of the phenomenon. However, after more than a decade there remain many unanswered questions and research gaps that need to be addressed, to inform decision-making and support policy development. This section outlines the current state of knowledge on: the biomass estimation and spatial distribution of *Sargassum*; linkages between physical factors and bloom events; and drivers responsible for the continuing proliferation of *Sargassum* in the Tropical Atlantic.

4.1 Spatio-temporal variability of distribution and biomass of holopelagic *Sargassum* spp.

4.1.1 DETECTION OF *SARGASSUM* SPP.

The holopelagic nature of the two *Sargassum* species, *Sargassum fluitans* (Børgesen) Børgesen and *S. natans* (Linnaeus) Gaillon, responsible for the recent massive *Sargassum* bloom events, makes it possible to monitor the abundance and distribution of the drifting masses at the ocean surface with the use of remote sensing, including: optical satellites; cameras mounted on airborne or land-based platforms; and satellite-, airborne- or land-based radar. Floating *Sargassum* can be differentiated from the surrounding seawater due to its high infrared reflectance caused by the chlorophyll-*a* pigment present in photosynthetic organisms (Gower et al., 2006; Gower and King, 2019). Contrasting against the low infrared seawater, *Sargassum* accumulations in the rafts are highly visible to optical sensors on modern satellites (Frazier et al., 2013; Gower et al., 2013; Gower and King, 2019; Adet at al., 2019; Triñanes et al., 2021; Wang, 2018; Wang et al., 2019). Furthermore, the presence of chlorophyll-*a* creates an identifiable biosignature, known as the 'red edge', that allows satellite sensors with suitable spectral bands to discriminate between rafts of holopelagic *Sargassum* spp. and the surrounding environment (Gower et al., 2013). During the transition from red light absorption by chlorophyll-*a* and near infrared radiation (NIR) reflected by leaf tissue, the 'red edge' becomes apparent to imaging instruments at approximately 748 nm (Gower et al., 2013; Triñanes et al., 2021). This enhanced reflectance in the near-infrared spectral bands has been used to detect large pelagic accumulations of *Sargassum* moving from the North Equatorial Recirculation Region (NERR) into the Gulf of Mexico, South of Florida and the WCR (Gower et al., 2013; Gower and King, 2011; Wang et al., 2019).

While a range of *Sargassum* forecasts has emerged over the last six years (Marsh et al., 2022), the detection of various non-*Sargassum* features continues to reduce the accuracy of forecasts (Laval et al., 2023; Podlejski et al., 2022). To overcome false positive detection biases, efforts have been made to create *Sargassum*-specific contextual features (Podlejski et al., 2022) and deep learning models specific for *Sargassum* detection (Laval et al., 2023). To date, major strides have been made to detect masses of pelagic *Sargassum*. What initially started off as 'simple' surface area estimates (*Sargassum* coverage) has now been improved upon to include depth of the masses, thus allowing the estimation of *Sargassum* biomass (Hu et al., 2023). Beyond satellite initiatives, efforts to map *Sargassum* distribution include traditional shipboard observations (Goodwin et al., 2022; Schell et al., 2016), airborne devices (i.e. drone, plane) and land-based observations.

4.1.2 SPATIAL AND TEMPORAL VARIABILITY OF *SARGASSUM* DISTRIBUTION

Sargassum Loop (before the 2010–2011 period)

Prior to 2011, *Sargassum* was essentially restricted to the North Atlantic central gyre (Sargasso Sea) with a connection to the Gulf of Mexico via the Gulf Stream (Figure 2) (Gower and King, 2011). However, Addico and deGraft-Johnson (2016) indicate that 'the arrival of the invasive brown seaweed *Sargassum* in the Western Region of Ghana was first reported in 2009'.

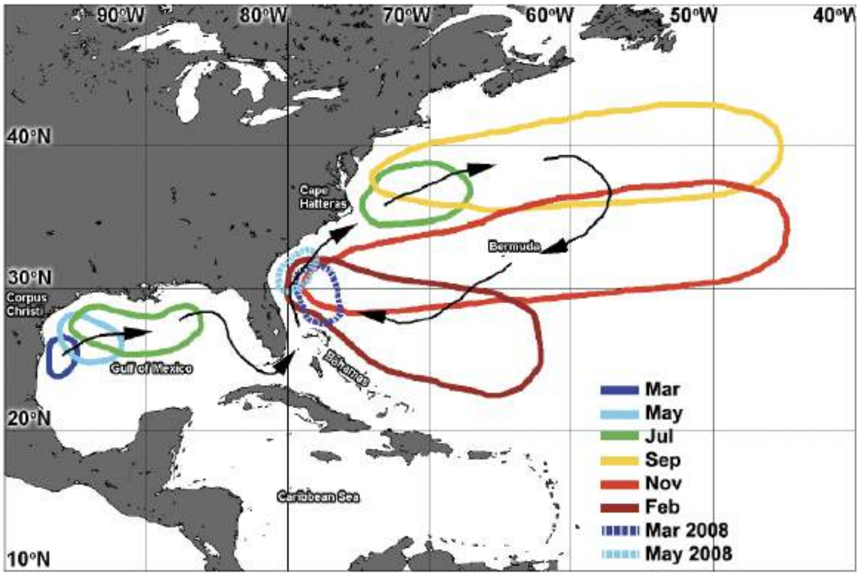


Figure 2. Schematic representation of the annual *Sargassum* pattern in the North Atlantic prior to 2010–2011.
Source: Gower and King (2011). Reprinted by permission of Taylor & Francis Ltd.

In the Sargasso Sea, high pressure atmospheric conditions create wind patterns that drive *Sargassum* south, into the Caribbean, where it is then pushed west by the oceanic and atmospheric currents carrying it into the Gulf of Mexico (Frazier et al., 2014). Once in the Gulf of Mexico, an annual pattern is observed with the transport of *Sargassum* rafts from the Gulf of Mexico via the Loop Current and Gulf Stream (Figure 2). Research efforts by Gower and King (2011) indicate that *Sargassum* is first detected in the northwest Gulf of Mexico during March and grows in this area between March and June. In July, *Sargassum* gradually expands eastward with *Sargassum* appearing in the Atlantic, north and east of Cape Hatteras. Under the influence of the Gulfstream, the eastward expansion of *Sargassum* continues to reach about 45° W in September. Northeast trade winds then move *Sargassum* south and west during autumn and winter months (Gower and King, 2011). The *Sargassum* loop may still occur today, but dispersal has become more diffuse. For instance, on the northern Cuban coast, *Sargassum* still arrives mainly in the winter and is dominated by *S. natans* I, that typically dominates in the Sargasso Sea (Torres-Conde et al., 2023).

Great Atlantic *Sargassum* Belt (after the 2010–2011 period)

Since 2011, *Sargassum* has widely increased its historical distribution range, with large-scale blooms and beaching events reported across the WCR and in West Africa (e.g. Oyesiku and Egunyomi, 2014; Sankare et al., 2017). Satellite data from 2011 indicated *Sargassum* blooms in the equatorial Atlantic (centred at about 7° N, 45° W), an area not previously associated with the high *Sargassum* spp. accumulations (Franks et al., 2012; Gower et al., 2013). This 'new' accumulation region (Figure 3) located in the NERR is loosely bounded by the South Equatorial Current (SEC) and the North Equatorial Counter Current (NECC) (Franks et al., 2016; Gower et al., 2013; Wang et al., 2019).

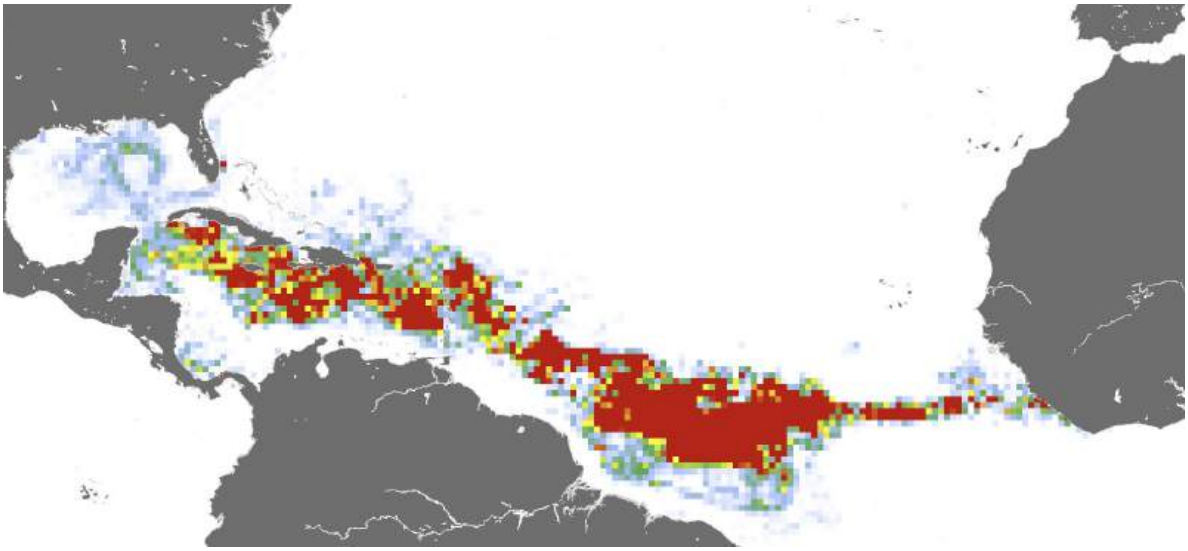
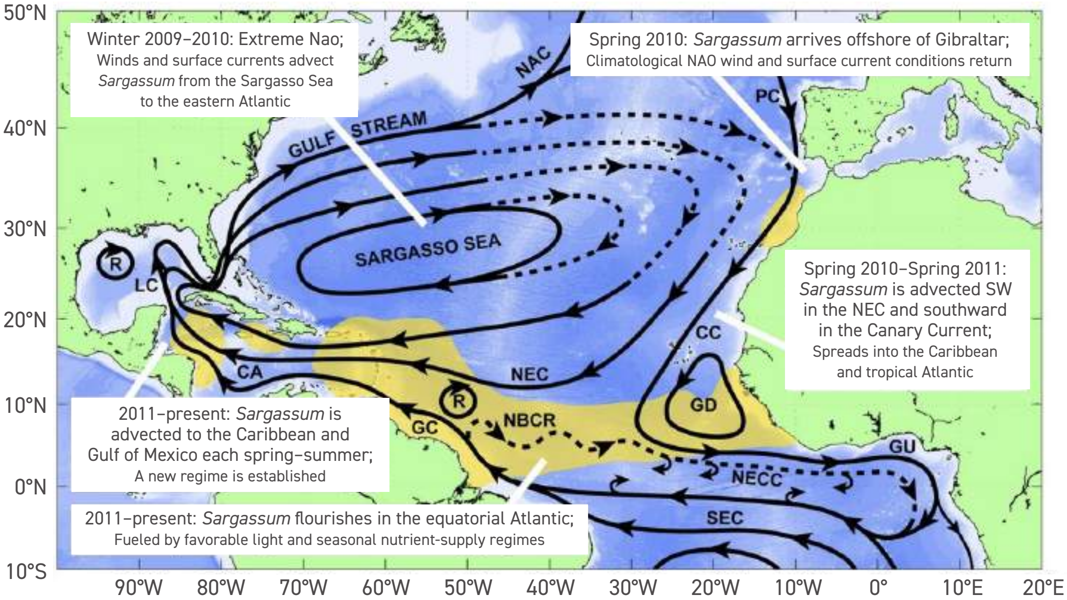


Figure 3. The Great Atlantic *Sargassum* belt (June 2022). Image provided by Dr Chuanmin Hu.

The most plausible explanation for the 2011 *Sargassum* proliferation 'event' has been put forward by Johns et al. (2020), based on variations in the North Atlantic Oscillation (NAO). The NAO is a measure of the sea-level pressure difference between the Azores High and the Icelandic Low (Hurrell and Deser, 2009). Variations in the NAO affect the position of the Jet Stream and hence the location of the wind field and ocean currents over the North Atlantic. During positive (+ve) phases of the NAO, westerly winds shift northwards and trade winds are strengthened. During negative (-ve) phases, westerly winds are located further south and trade winds weaken. The period 2009–2010 was characterized by record -ve phases, compared with the long-term average (1899–present). Johns et al. (2020) hypothesized that this extreme -ve phase allowed the transfer eastwards of *Sargassum* from the Sargasso Sea towards Northwest Africa, before being transported south in the North Equatorial Current (NEC) and Canary Current (Figure 4). The 2011 event and subsequent recurrence of *Sargassum* blooms in the NERR appear to mark a regime shift (Wang et al., 2019). However, it is not clear whether this



Winter 2009–2010: Extreme Nao;
Winds and surface currents advect
Sargassum from the Sargasso Sea
to the eastern Atlantic

Spring 2010: *Sargassum* arrives offshore of Gibraltar;
Climatological NAO wind and surface current conditions return

Spring 2010–Spring 2011:
Sargassum is advected SW
in the NEC and southward
in the Canary Current;
Spreads into the Caribbean
and tropical Atlantic

2011–present: *Sargassum* is
advected to the Caribbean and
Gulf of Mexico each spring–summer;
A new regime is established

2011–present: *Sargassum* flourishes in the equatorial Atlantic;
Fueled by favorable light and seasonal nutrient-supply regimes

Figure 4. Schematic representation of the initiation, or triggering, of the post-2011 Sargassum inundation regime. CA: Caribbean Current, CC: Canary Current, GC: Guiana Current, GD: Guinea Dome, LC: Loop Current, NAC: North Atlantic Current, NBCR: North Brazil Current Rings, NEC: North Equatorial Current, NECC: North Equatorial Counter Current, SEC: South Equatorial Current. *Source*: reproduced from Johns et al. (2020) under a Creative Commons Licence.

represents a permanent change or whether there may be a return to the ‘normal’ pre-2010/11 conditions (Johns et al., 2020). It should be noted that a potential link between variations in the NAO and *Sargassum* inundations was raised previously by Webster and Linton (2013). From 1891 to 2007, they catalogued several periods of inundations of *Sargassum* on the coast of Texas, based on newspaper reports of ‘nuisance’ blooms affecting local businesses and recommended further research on a possible causal link.

Following its establishment, proliferations have subsequently become recurrent. *Sargassum* from the NERR is introduced seasonally into the southeastern Caribbean Sea, transported across the Caribbean into the Gulf of Mexico or Gulf Stream and ultimately back into the north Atlantic gyre (Wang et al., 2019; Johns et al., 2020; Optical Oceanography Laboratory, 2023). This broadscale distribution forms a vast band (5,500 miles in 2018) of *Sargassum*, coined by Wang et al. (2019) as the Great Atlantic *Sargassum* Belt (GASB), that stretches across the Tropical Atlantic from West Africa to the Caribbean, Gulf of Mexico, Gulf Stream and the North Atlantic Gyre. Johns et al. (2020) have described the annual cycle of development, transport and dissipation of the GASB (Figure 5), based on satellite-derived optical data, the relative position of the Inter-Tropical Convergence Zone (ITCZ), nutrient plumes from the Amazon and Orinoco Rivers and upwelling off northwest Africa.

Research conducted by Franks et al. (2016), based on a more than 20-year dataset of drifter tracks, shows that *Sargassum* masses in the NERR consolidate in the eastern (near the Gulf of Guinea) and western regions of the NERR. As *Sargassum* increases in biomass, rafts may be transported to west African coastlines via the NECC or transported to the northeast coast of Brazil via the SEC. Modelled drifter data show that *Sargassum* located along the northeast coast of Brazil and in the western consolidation region of the NERR can be transported to the Caribbean in spring/summer via the North Brazil Current/Guiana Current (NBC/GC) and North Brazil Current Rings (NBCR) respectively. In winter months, drifter transport into the Caribbean occurred via the North Equatorial Current (NEC). Transport routes identified by Franks et al. (2016) align with the formation of the NECC and meridional migration of the Atlantic Intertropical Convergence Zone (ITCZ).

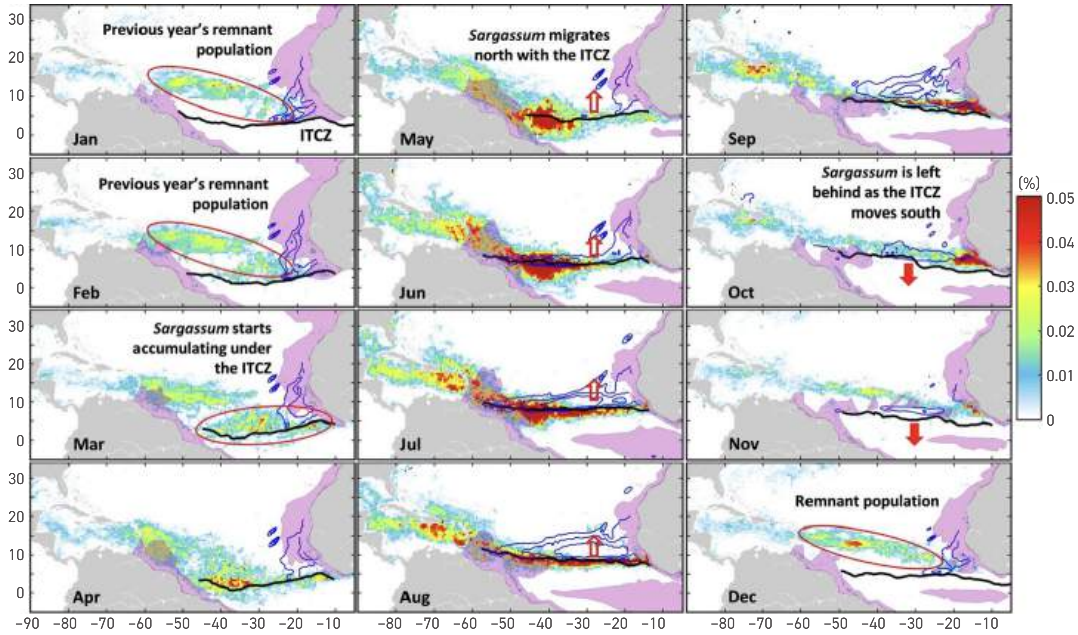


Figure 5. Monthly average distribution of *Sargassum* (2010–2018) showing annual cycle of accumulation, transport and dissipation (colour bar indicates percentage spatial coverage); the black line indicates the position of the Inter-Tropical Convergence Zone (ITCZ) with the red arrows indicating its movement north (open arrows) and south (solid arrows); the blue isolines indicate wind-driven (Ekman) upwelling; the purple areas relate to satellite-derived chlorophyl concentrations > 0.2 mg m^{-3}, indicating plumes from the Amazon and Orinoco Rivers and upwelling off northwest Africa. *Source*: Reproduced from Johns et al. (2020) under a Creative Commons Licence.

The NECC is a major eastward flowing wind-driven current within the Tropical Atlantic that usually forms in spring and strengthens in summer, preventing northward transport of nutrient-rich waters from the equatorial upwelling zone (Skliris et al., 2022) and major westward transport of *Sargassum* during spring/summer. During autumn, the NECC is pushed further north, as the ITCZ starts its upward migration, gradually becoming weaker and ultimately breaking down (Skliris et al., 2022). With the breakdown of the NECC, *Sargassum* is carried westward into the Caribbean. Research by Putman et al. (2018) identified the NBC/GC, NBCR and the NEC as the major currents responsible for the dispersion of *Sargassum* from the Tropical Atlantic into the Caribbean, corroborating the findings of the drifter experiments conducted by Franks et al. (2016). Building on the findings of Putman et al. (2018) and Franks et al. (2016), Beron-Vera et al. (2022) and Alleyne et al. (2023) identified a southerly and northerly *Sargassum* transport pathway located within the Tropical Atlantic. According to their findings, the southern pathway originates close to the equator and follows a convoluted trajectory, first going through the Gulf of Guinea, then across the tropical Atlantic toward the mouth of the Amazon River and finally along the northeast coast of Brazil (Beron-Vera et al., 2022). The second pathway is the faster of the two and it is located further north (9–18° N) (Alleyne et al., 2023). *Sargassum* transported via the northern pathway follows a direct route from the northern coast of west Africa into the Caribbean.

Forecasting efforts by the Optical Oceanography Laboratory (2023) show that large amounts of *Sargassum* in the Equatorial Tropical Atlantic (ETA) are transported to the Central West Atlantic (CWA), where it travels through passages in the island chain of the Lesser Antilles into the Caribbean Sea (CS). *Sargassum* is then transported across the Caribbean Sea by the Caribbean Current that branches further north into the Cayman and Yucatan Currents (Lara-Hernández et al., 2023). Biomass that does not beach along the way is then transported into the Gulf of Mexico following the Loop Current System with distribution patterns similar to that of *Sargassum* from the Sargasso Sea. Transported into the Gulf of Mexico, via the Yucatan Current, *Sargassum* follows the extended or retracted state of the loop current before exiting through the Florida Current into the Gulf Stream (Optical Oceanography Laboratory, 2023). *Sargassum* is also transported from the CWA directly into the North Atlantic via

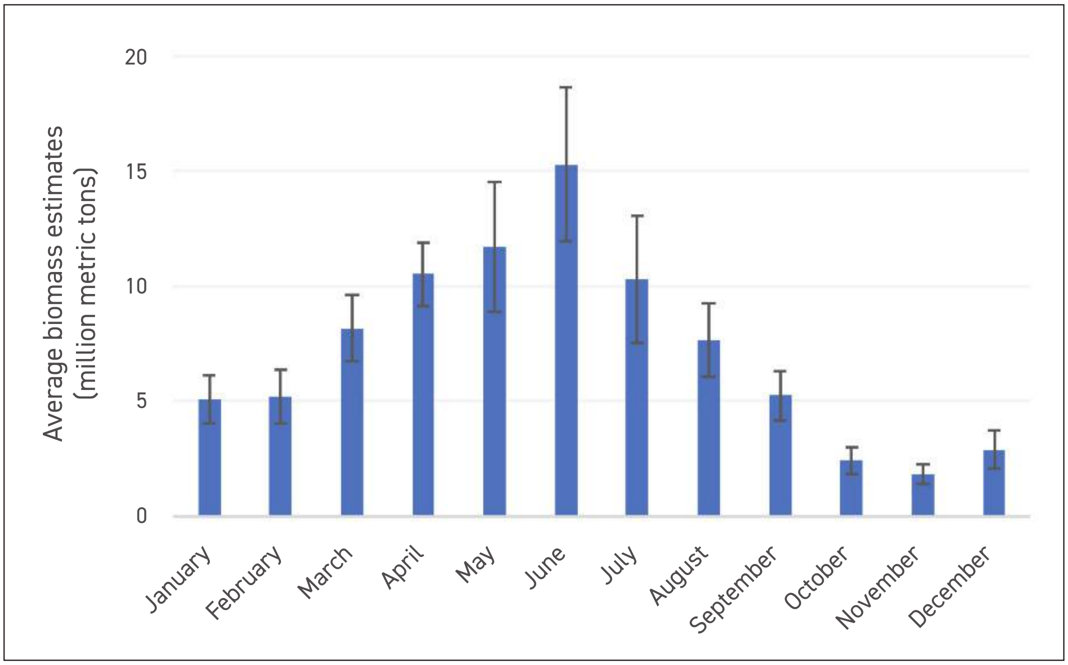


Figure 6. Average monthly biomass estimates of *Sargassum* in the Great Atlantic *Sargassum* Belt (GASB) from January 2018 to October 2023. Quantities sourced from Optical Oceanography Laboratory (2023) (https://optics.marine.usf.edu/projects/saws.html). Error bars represent ± standard error. *Source*: Elaborated by authors.

the Antilles Current (Wang et al., 2019; Current Optical Oceanography Laboratory, 2023). According to Putman et al. (2018), the biomass of *Sargassum* following the various pathways varies seasonally and this has implications for the time it takes *Sargassum* to reach the Caribbean Sea. In addition to the seasonal variation in transport pathways, the intensity of proliferations varies from one year to another based on the remnant population left behind from the previous proliferation year (Berline et al., 2020; Wang et al., 2019). During the winter period, remnant populations accumulate in the eastern Tropical Atlantic and are subsequently transported to the central Atlantic via the NEC (Berline et al., 2020; Wang et al., 2019). If there are large remnant populations, influx events the following year are likely to be of considerable magnitudes (Wang et al., 2019).

Across the region, monthly variations in estimates of the total (oceanic and beached) *Sargassum* biomass have indicated a temporal trend in the abundance of *Sargassum*. Generally, from January to June, there is an increase in the abundance of *Sargassum* followed by a gradual decrease during the autumn/winter months (Figure 6) (Wang et al., 2019; Optical Oceanography Laboratory, 2023).

Within this seasonal pattern, peak *Sargassum* abundance occurs through May, June and July, with the annual minimum *Sargassum* coverage typically observed during October–December (Figure 6) (Optical Oceanography Laboratory, 2023). Significant differences identified from satellite data between spring/summer and autumn/winter months are also reflected in landed quantities (García-Sánchez et al., 2020; Joseph and Goncalves, 2019; Marsh et al., 2023).

4.1.3 INTERANNUAL VARIATION IN BIOMASS

Large *Sargassum* accumulations have been reported in the Atlantic Ocean for centuries (Parr, 1939), particularly in the centre of the North Atlantic gyre (Sargasso Sea) and Gulf of Mexico. However, a rigorous quantitative assessment of their overall biomass is still missing due to technical constraints (Wang, 2018). The first estimates of *Sargassum* biomass (fresh weight) within the North Atlantic date

Table 1. Historical estimates of *Sargassum* biomass (wet weight).

Source	Biomass	Year	Location	Area for recalculation	Biomass recalculated (g/m2)
Parr (1939)	7 million tons	1933	North Atlantic	41.5 M km^2	0.169
	11 million tons	1934	North Atlantic	41.5 M km^2	0.265
	4 million tons	1935	North Atlantic	41.5 M km^2	0.096
Stoner (1983)	74 mg/m^2	1977–1981	Sargasso Sea		0.074
	165 mg/m^2	1977–1981	The Bahamas		0.165
	280 mg/m^2	1977–1981	Gulf Stream		0.28
Gower and King (2008)	1 million tons	2002–2008	Gulf of Mexico	1.6 M km^2	0.625
	1 million tons	2002–2008	North Atlantic	41.5 M km^2	0.024
Siuda (2011)	0.39 g/m^2	1977–2010	North Sargasso Sea		0.39
	0.21 g/m^2	1977–2010	South Sargasso Sea		0.21
Schell et al. (2015)	0.17 g/m^2	1995–2013	South Sargasso Sea		0.17
	0.23 g/m^2	2014–2015	South Sargasso Sea		0.23
	0.25 g/m^2	2011–2012	South Sargasso Sea		0.25
	0.0027 g/m^2	1992–2013	West Trop. North Atlantic		0.0027
	0.07 g/m^2	2011	West Trop. North Atlantic		0.07
	0.84 g/m^2	2014	West Trop. North Atlantic		0.84

Source: Baker et al., 2018.

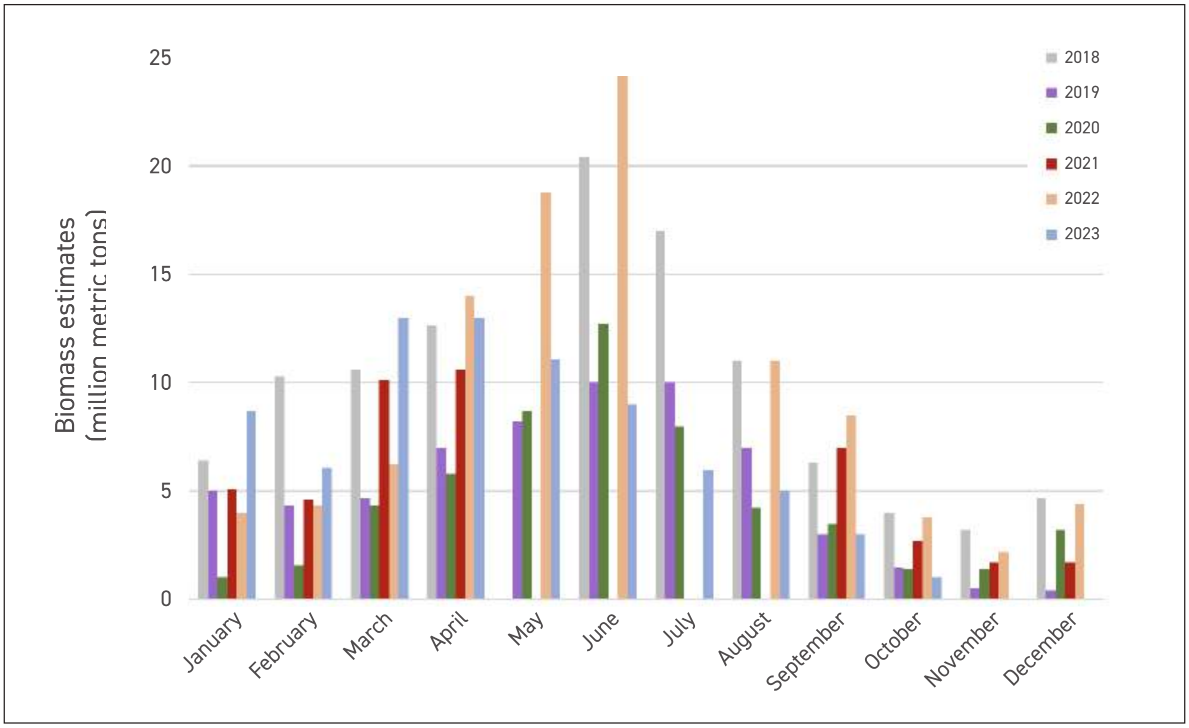


Figure 7. Yearly biomass estimates of the total amount of pelagic *Sargassum* present in the Great Atlantic *Sargassum* Belt (GASB) over the 2018–2023 bloom years. Quantities sourced from Optical Oceanography Laboratory (2023) (https://optics.marine.usf.edu/projects/saws.html). *Source*: Elaborated by authors.

back to 1933, with Parr (1939) reporting a crude estimate of 7 million tons of *Sargassum* in the North Atlantic. Some decades later, Stoner (1983) conducted surveys in the same region from 1977 to 1981, which revealed much lower *Sargassum* biomass compared to studies in the 1930s (Table 1). Later reinterpretations (Butler and Stoner, 1984) show that biomass was significantly lower in only one area near 23° N, 65° W north of Puerto Rico, and suggested that the difference may be due to a seasonal variation (Gower and King, 2011; Huffard et al., 2014). These early biomass estimations were mainly from ship-based samplings using neuston tows, which have difficulties in sampling very dense *Sargassum* rafts. Furthermore, field samplings are likely biased due to their limited spatial and temporal coverage. As such, there have been conflicting conclusions regarding historical *Sargassum* abundance (Wang, 2018).

Since the initial inundation event in 2011, recurrent *Sargassum* proliferations have continued across the Tropical Atlantic; however, considerable variation in biomass quantities has been observed across years (Wang et al., 2019; Optical Oceanography Laboratory, 2023). While some years produced extraordinary amounts of *Sargassum* biomass (e.g. 2015 and 2018), other years (e.g. 2013) had little to no proliferation (UNEP, 2018; Wang et al., 2019) (Figure 7). Biomass estimates of *Sargassum* over the last six years (2018–2023) highlights the substantial variation in *Sargassum* quantities and identifies 2018 and 2022 as major bloom years with approximately 20.4 and 24.2 million metric tons, respectively, recorded during June (Figure 7). The estimated biomass in the GASB at these times greatly exceeded that ever reported in the Sargasso Sea (Table 1).

Annual observations of satellite data reveal that following the first appearance of *Sargassum* rafts in the Tropical Atlantic in April 2011, a gradual increase in biomass was observed until August when massive rafts started to decrease (Wang and Hu, 2016; Wang et al., 2019). Blooms in 2012 closely resembled the distribution patterns observed in 2011, with the exception of slick formations in the early months of 2012 that were presumably left over from 2011 blooms (Wang et al., 2019). Reduced biomass quantities observed in September 2012 and the following months resulted in very few slicks being observed in 2013 (Wang and Hu, 2016). According to Wang et al. (2019), the non-bloom year of 2013 was likely attributed to low remnant populations in 2012 combined with a high sea surface temperature (SST) and limited nutrient availability. While bloom events of 2014 closely reflected those of 2011 and 2012 in the early months, considerable amounts of *Sargassum* were observed during September to December (Wang and Hu, 2016). High quantities of *Sargassum* during the winter period provided a large remnant population, leading to record-breaking blooms in 2015 (Wang and Hu, 2016; Wang et al., 2019). The 'boom and bust' cycle of *Sargassum* resulted in the events of 2015 being followed by three years of lower abundance until 2018, when another record-breaking year was observed (Wang et al., 2019).

In addition to the observed interannual variation, there is a noticeable increase in *Sargassum* biomass since July 2011, when ~2 million metric tons swept through the Caribbean (Wang et al., 2019). Post-2011 blooms have intensified, with record-breaking years observed every three to four years (i.e. 2015, 2018, 2022). Furthermore, large quantities of *Sargassum* have been arriving earlier in the year (Wang et al., 2019; Optical Oceanography Laboratory, 2023) and winter blooms (e.g. December) that were typically negligible, reported record-breaking quantities in 2018, 2020 and 2022 (Figure 7). It is noteworthy that high winter blooms of 2022 resulted in large volumes of *Sargassum* during the early months of 2023; however, an unexpected decrease in biomass was observed over the summer months (Figure 7). Biomass estimates for January and March 2023 surpassed all other years and April reports indicate marginally lower quantities than April 2022 (Figure 7). It should be noted that in the University of South Florida *Sargassum* Outlook Bulletin for March 2023, the low quantity (6.1 million metric tons) of *Sargassum* recorded in February (Figure 7) was attributed to persistent cloud cover in the eastern Atlantic (Optical Oceanography Laboratory, 2023), as cloud cover interferes with satellite-based estimates of *Sargassum* abundance.

4.1.4 VARIATION IN SPECIES/MORPHOTYPE COMPOSITION

Sargassum originating in the Tropical Atlantic is widely recognized as comprising two species and various reported morphotypes (defined by Parr, 1939), three of which are now considered the dominant forms in tropical Atlantic proliferations: these are *Sargassum natans* I, *S. natans* VIII and *S. fluitans* III (Schell et al., 2015). The morphotypes are not true taxonomically accepted classifications and there remains some controversy over the taxonomy and nomenclature (Amaral-Zettler et al., 2017; Godínez-Ortega et al., 2021; González-Nieto et al., 2020; Siuda et al., 2017; Wynne, 2022). The three predominant morphotypes are genetically distinct (Amaral-Zettler et al., 2017; Dibner et al., 2021), with distinctive ecological, biological and chemical traits (Davis et al., 2020; Martin et al., 2021) and physiological tolerances as shown by various growth experiments (Corbin and Oxenford, 2023; Hanisak and Samuel, 1987; Lapointe, 1986; Magañana-Gallegos et al., 2023*a*; Magañana-Gallegos et al., 2023*b*). Historical records identify *Sargassum natans* I as the predominant morphotype in the Sargasso Sea (Parr, 1939; Huffard, 2014; Stoner, 1983, etc.; Table 1). However, in the earlier years, the GASB was dominated by *S. natans* VIII (Schell et al., 2015) and recent reports on morphotype composition have shown a trend of *S. natans* VIII slowly being replaced by *S. fluitans* III (Botelho Machado et al., 2022; García-Sánchez et al., 2020). No sexual recruits have been reported for holopelagic *Sargassum* spp. (Godínez-Ortega et al., 2021), changes in dominance of one morphotype above the others can only occur through differential vegetative growth of the morphotypes, which is likely a gradual process.

There are no early reports on morphotype composition of Tropical Atlantic proliferations (from 2011 until 2014), but from 2014 until 2016, *S. natans* VIII, a previously rare form, was identified as the predominant morphological form (Schell et al., 2015; Garcia-Sánchez et al., 2020), with a noticeable peak in *S. natans* VIII abundance during 2014–2015 (García-Sánchez et al., 2020; Oxenford et al., 2021). High abundances of *S. natans* VIII were particularly noticeable within the Mexican Caribbean during their first major influx event in 2015 (García-Sánchez et al., 2020). Of the three prevalent morphotypes, *S. natans* I was rarely reported during the early bloom events; however, from 2018 onwards a gradual

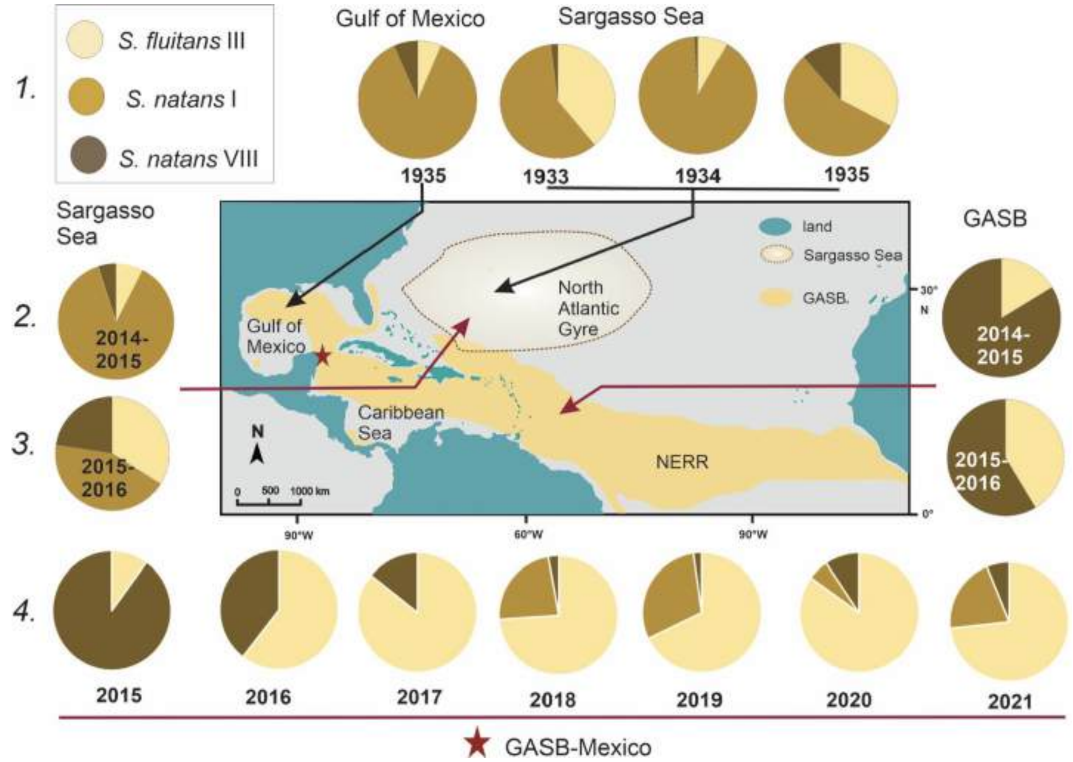


Figure 8. Variations in space and over the years in the relative abundance of the holopelagic *Sargassum* species and their dominant morphotypes. From: 1. Parr (1939), 2. Schell et al. (2015), 3. Martin et al. (2021), 4. García-Sánchez et al. (2020) and unpublished data (Seagrass Lab, UNAM). In Parr (1939), *S. natans* VIII may also include other morphotypes. The data are from several collections in each year, in the open ocean (1, 2 and 3) or from the coast (4). NERR: North Equatorial Recirculation Region; GASB: Great Atlantic Sargassum Belt. Sargassum distribution in Sargasso Sea by Acton et al. (2019) and in the GASB by Putman and Hu (2022). *Source*: Adapted from Conahcyt-FCE (2024).

increase was observed within the Mexican Caribbean, with *S. natans* I accounting for 31% of beached *Sargassum* in 2019 (García-Sánchez et al., 2020). The increase in *S. natans* I was observed with a concurrent reduction of *S. natans* VIII from 41% during 2016 to 3% in 2019 (García-Sánchez et al., 2020; Figure 8). Reports on morphotype composition from Jamaica on 2020 bloom events also identified *S. fluitans* III as the predominant morphotype species and *S. natans* VIII as the least observed form (Botelho Machado et al., 2022).

Reports from the Mexican Caribbean indicate certain trends of seasonal variability in morphotype composition, with *S. natans* VIII being the more predominant species observed during the early *Sargassum* season (García-Sánchez et al., 2020). Torres-Conde et al. (2023) reported that specific composition of beached Sargassum in north Cuba varied between the winter (*S. natans* I-dominated; likely of Sargasso Sea origin) and occasional influxes in the summer (*S. fluitans* III dominated, likely of GASB origin). Recent research by Alleyne et al. (2023) suggests that seasonal variation in morphotype composition is linked to oceanic suborigins, with higher abundances of *S. fluitans* III associated with a southerly transport pathway and increasing quantities of *S. natans* VIII associated with a northerly transport pathway. Moreover, *Sargassum* rafts arriving in Barbados during March to early August were more likely to take the southerly transport pathway, while those arriving between late August to February were likely to take the northern transport pathway (Alleyne et al., 2023). It is therefore plausible that reports on variable morphotype composition within the same year (e.g. 2020) may be attributed to differences in oceanic suborigins, possibly combined with different tolerances to prevailing environmental conditions of each species/morphotype.

4.2 Linkages between physical factors and bloom events

4.2.1 OCEANIC AND COASTAL ESTIMATES OF *SARGASSUM* BIOMASS

To date, remote sensing methodologies (Floating Algae Index (FAI) and Alternative Floating Algae Index (AFAI)), using a variety of optical sensors (MODIS/Terra, MODIS/Aqua, VIIRUS, Landsat 8 OLI, MSI), provide essential information on the relative abundance and distribution of *Sargassum* rafts in oceanic waters (Gower and King, 2011; Gower et al., 2013; Wang and Hu, 2016; Wang et al., 2019). However, there are spatial and temporal limitations associated with these methodologies that make it difficult to provide precise abundance estimates (Arellano-Verdejo et al., 2019; Arellano-Verdejo and Lazcano-Hernández, 2021). For example, data obtained from the MODIS sensor have a spatial resolution between 250 m and 1.2 km; thus, disaggregation of *Sargassum* into rafts <250 m in diameter limits the use of satellite data for *Sargassum* detection. On the other hand, the MSI sensor offers better spatial resolution (10 m, 20 m or 60 m); however, the MSI sensor has a revisit frequency of 10 days, while the MODIS sensor has a revisit frequency of one day (Arellano-Verdejo and Lazcano-Hernández, 2021).

The revisit frequency of the MSI sensor is less than ideal, as *Sargassum* rafts can rapidly change size and aggregation state (Ody et al., 2019), making it harder to track the same raft ten days later. In addition to the aforementioned shortcomings, there are difficulties associated with predicting the amount of *Sargassum* likely to wash ashore due to complex interactions occurring within local settings (Arellano-Verdejo and Lazcano-Hernández, 2021; Triñanes et al., 2021). Within coastal environments, the volume of stranded *Sargassum* depends upon ocean currents, surface winds, waves, tides, coastal morphology and the aggregation state of *Sargassum* (Putman et al., 2020; Triñanes et al., 2021). In the absence of high-resolution coastal datasets that represent local conditions across the region, it has been difficult to predict how much of the estimated oceanic biomass is likely to wash ashore.

Notwithstanding the difficulties associated with shoreline predictions, Marsh et al. (2023) estimated the annual beached area of *Sargassum* for 127 locations across the Caribbean in the year 2020. Forecasting efforts, using historical winds and currents, reveal that beaching events within the Tropical Atlantic predominantly occur along the windward (eastward) coasts of the Lesser and Greater Antilles (Marsh et al., 2023). Moreover, volumes were highest along the Lesser Antilles and the south coast of Hispaniola (Figure 9).

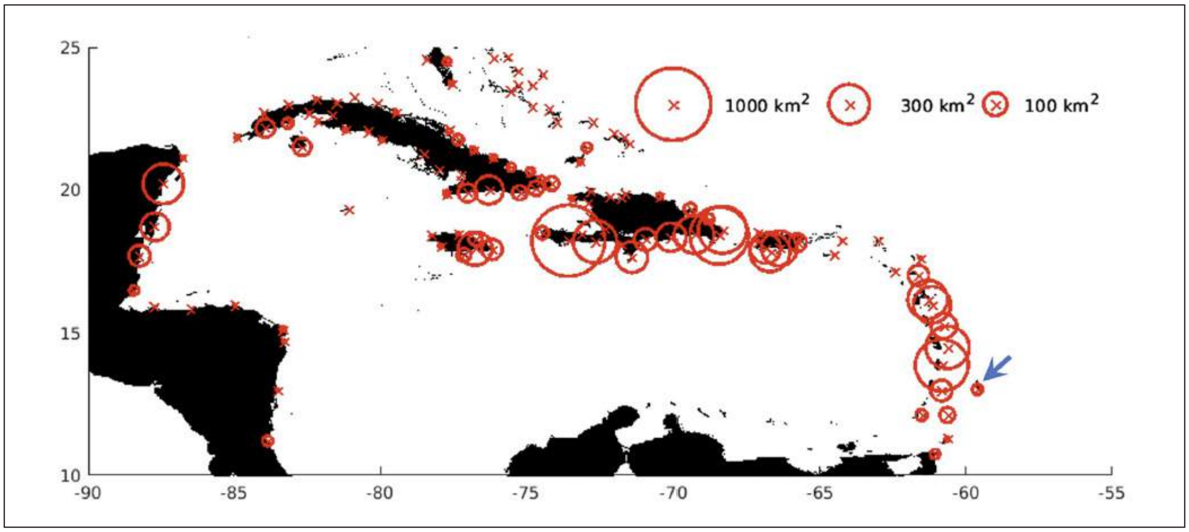


Figure 9. The quantity of *Sargassum* evaluated at 127 coastal and island locations in the Caribbean region, for which associated circle area is proportional to the accumulated amount of beaching *Sargassum* in 2020. *Source*: Reproduced from Marsh et al. (2023) under Creative Commons Licence 4.0.

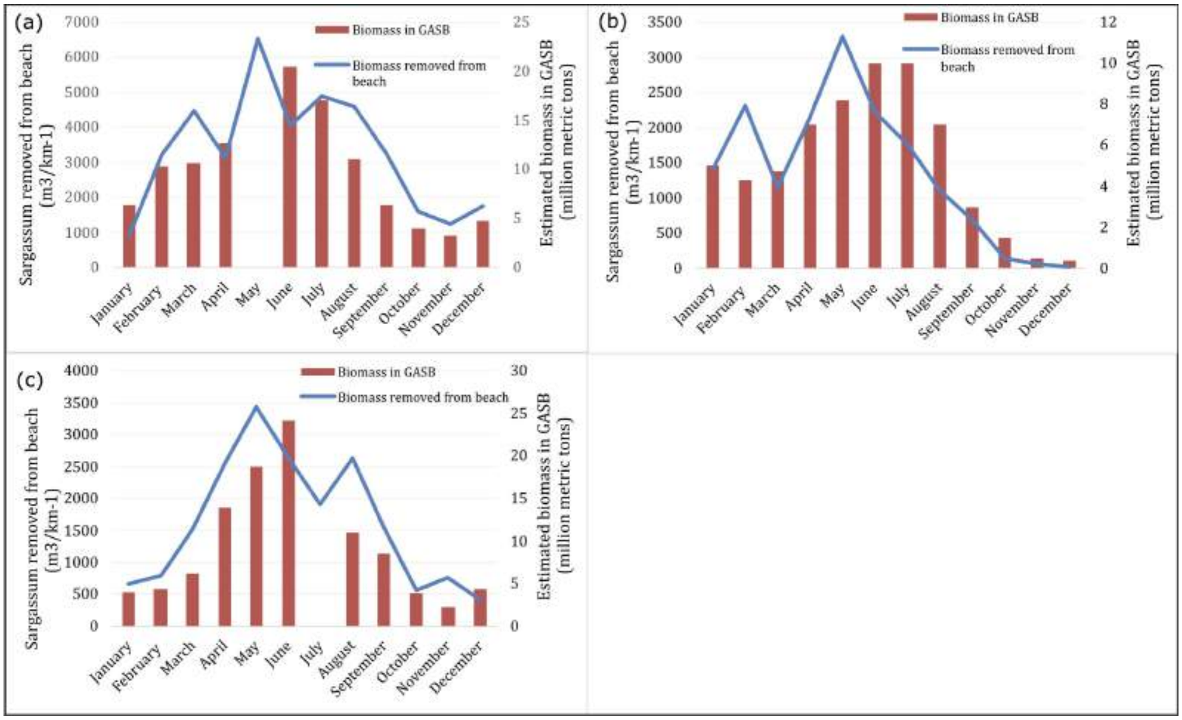


Figure 10. Average monthly *Sargassum* biomass removed from beaches in the Puerto Morelos municipality and estimated *Sargassum* biomass in the Great Atlantic *Sargassum* Belt for 2018 (panel (a)), 2019 (panel (b)) and 2022 (panel (c)). *Source*: Elaborated by authors.

Beyond forecasting efforts, the relationship between oceanic cover estimates and shoreline strandings can be assessed by comparing the volume of *Sargassum* collected from beaches with coastal and oceanic estimates sourced from satellite data. To date, volumes of beached *Sargassum* have been monitored *in situ* at only a few beaches in the region (Marsh et al., 2023); as a result, there is very little information on biomass quantification of beach-cast *Sargassum* since the first mass inundation event in 2011. Addressing this knowledge gap, a study by Rodríguez-Martínez et al. (2023) assessed volumes of beached *Sargassum* removed by 14 hotels in Yucatán Peninsula, Mexican Caribbean, during 2018, 2019, 2021 and 2022. In an effort to understand the relationship between oceanic estimates and beached *Sargassum*, this study compared beached volumes from Puerto Morelos with oceanic estimates of *Sargassum* in the GASB (sourced from the Optical Oceanography Laboratory, 2023) (Figure 10).

During 2018, 2019 and 2022, an increase in *Sargassum* biomass within the GASB generally resulted in an increase in the removal of beached *Sargassum* biomass within the Puerto Morelos municipality ($rs \geqslant 0.77$, $p \leqslant 0.001$). Similarly, Tomenchok et al. (2021) observed a yearly increase in *Sargassum* biomass along beaches in Fort Lauderdale, when there was an increase in *Sargassum* biomass within the Caribbean Sea and Central Atlantic (Figure 11).

While considerable knowledge gaps on coastal estimates of *Sargassum* biomass still remain, recent research (Arellano-Verdejo et al., 2019; Wang and Hu, 2020) aims to address gaps by using computing science paired with remote sensing data. Efforts include the automatic classification of MODIS satellite images, enabling high-generalization classifications of more than 250,000 images with 99.99% accuracy (Arellano-Verdejo et al., 2019; Arellano-Verdejo and Lazcano-Hernández, 2021); the automatic extraction of *Sargassum* features from MSI images (Arellano-Verdejo and Lazcano-Hernández, 2021; Wang and Hu, 2020); and the use of an artificial neural network architecture to classify geospatial dataset values related to the presence or absence of *Sargassum* (Arellano-Verdejo et al., 2019; Arellano-Verdejo and Lazcano-Hernández, 2021). Other approaches involving the use of citizen science

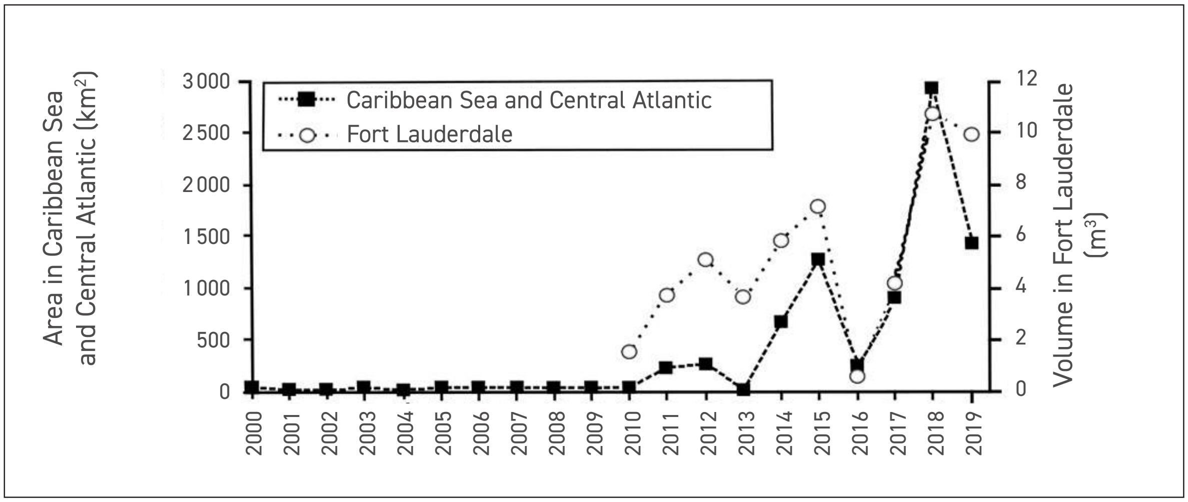


Figure 11. Annual average area of *Sargassum* in the Caribbean Sea and Central Atlantic and annual volume of *Sargassum* in Fort Lauderdale, Florida. *Source:* Tomenchok et al. (2021).

and crowdsourcing are also being utilized for monitoring *Sargassum* in coastal environments (Arellano-Verdejo and Lazcano Hernandez, 2020; Iporac et al., 2022; Putman et al., 2023). For example, Putman et al. (2023) utilized time-stamped, georeferenced photos obtained during a citizen science project to understand the relationship among offshore *Sargassum*, wind and coastal landings. In their research, the inclusion of wind velocities greatly improved the correspondence with coastal observations of *Sargassum* beaching, indicating that it may be a promising avenue for improving regional risk indices. Research by Rutten et al. (2021) applying a processing procedure to images obtained from a coastal camera revealed the interannual variability in the start, duration and intensity of the *Sargassum* arrival season.

4.2.2 THE ROLE OF WINDS AND OCEAN CIRCULATION

While multiple factors influence *Sargassum* blooms, wind and ocean currents have emerged as key drivers influencing nutrient availability, accumulation and distribution of *Sargassum* biomass, as noted by several authors (e.g. Putman et al., 2018; Johns et al., 2020; Marsh et al., 2021; Skliris et al., 2022). A better understanding of how *Sargassum* moves at the ocean surface is necessary to enhance forecasts of when and where *Sargassum* will impact coastlines (Putman et al., 2018; Putman et al., 2020). Over the years, several scientists have contributed to understanding the roles of wind and currents in *Sargassum* distribution, using a combination of tools and technologies (e.g. Putman et al., 2018; Johns et al., 2020; Marsh et al., 2021; Skliris et al., 2022). Some of these include numerical particle-tracking systems, wind and current reanalysis data, drifting buoy trajectories and satellite imagery (Franks et al., 2016; Putman et al., 2018; Berline et al., 2020; Johns et al., 2020). This section explores the interplay of wind patterns and ocean currents on *Sargassum* influxes.

Any part of an object exposed above the surface of the sea will be forced in the same direction as the wind blows (Marsh et al., 2021). Windage, the effect of wind on floating objects, has been used in *Sargassum* models to aid in the understanding of dispersal and beaching patterns of *Sargassum*. Several studies provided compelling evidence (e.g. Putman et al., 2018; Putman et al., 2020; Johns et al., 2020; Jouanno et al., 2021*b*; van Sebille et al., 2021; Marsh et al., 2021) that windage is a critical component in understanding *Sargassum* transport from the open ocean to the nearshore, and hence in the location of beaching. Based on a tracking experiment conducted near the Dominican Republic, Putman et al. (2020) showed that the paths of GPS-tracked *Sargassum* mats were followed more accurately when including windage in model predictions compared to simulations without it. In the absence of the windage component, models neither depicted the overall path of the *Sargassum* mat, nor did they predict the location of the coast that it beached. The importance of wind on *Sargassum* beaching was also demonstrated in a recent study by Putman et al. (2023), where region-wide regression analyses indicated that the amount of *Sargassum* observed on the beach is highly dependent on wind conditions. They also advised that shoreward wind velocities be included in algorithms for *Sargassum* inundation reports.

The Intertropical Convergence Zone (ITCZ) is suggested to be characterized by a significant atmospheric feature that plays a crucial role in driving the GASB. Studies (e.g. Skliris et al., 2022; Johns et al., 2020; Putman et al., 2018) show that the strong convergence of the easterly trade winds, which generate the ITCZ, is a key physical driver controlling the *Sargassum* concentrations in the Tropical North Atlantic. Maximum wind convergence and consequently maximum accumulation of *Sargassum* occurs in the central equatorial North Atlantic and follows the ITCZ seasonal meridional migration (Skliris et al., 2022). Skliris et al. (2022) and Johns et al. (2020) provide clear descriptions of the ITCZ migratory pattern. This migration results in fluctuations in the timing and intensity of *Sargassum* proliferations in different regions. Due to the strength of the converging winds, *Sargassum* aggregates in massive windrows along the ITCZ from March to September (Johns et al., 2020). From March to April, *Sargassum* starts to aggregate along the ITCZ, then from May to September the ITCZ migrates northward, carrying *Sargassum* along with it. According to Putman et al. (2018), the trade winds and the North Equatorial Current advect the *Sargassum* to the west toward the Caribbean. This long-range transport contributes to the global distribution of *Sargassum*.

The ITCZ also plays a crucial role in moving *Sargassum* to nutrient-rich sources from the Amazon River and the equatorial upwelling region, thereby influencing *Sargassum* biomass (Skliris et al., 2022). Skliris et al. (2022) explained that during the spring, the ITCZ is closer to nutrient-rich waters from the Amazon outflow and the equatorial upwelling region, which may be linked to high growth rates in the Central Equatorial North Atlantic. During the summer, the ITCZ moves northward, closer to the Orinoco plume, influencing *Sargassum* biomass in the West Tropical North Atlantic. Easterly

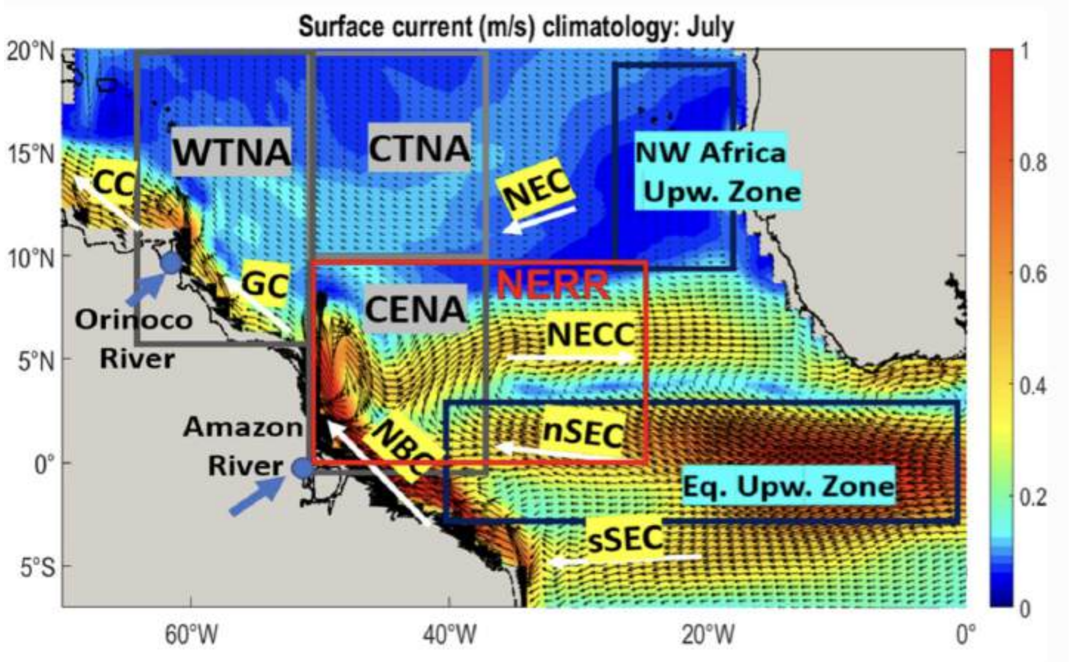


Figure 12. Schematic of the climatological surface currents of the Atlantic Ocean relevant to the transport of *Sargassum* from the Equatorial Atlantic into the Caribbean. CENA – central equatorial North Atlantic, CTNA – central tropical North Atlantic, WTNA – west tropical North Atlantic, NERR – North Equatorial Recirculation Region, NEC – North Equatorial Current, NBC – North Brazil Current, nSEC/sSEC – north/south branch of South Equatorial Current, NECC – North Equatorial Counter Current, GC – Guyana Current. *Source:* Reproduced from Skliris et al. (2022) under a Creative Commons Licence 4.0

trade winds also transport Sahara dust to the tropical North Atlantic. However, the impact of Sahara dust on surface nutrient availability in the western central Atlantic is considered to be less significant than riverine and upwelling nutrient sources (Skliris et al., 2022). However, Jouanno et al. (2021*b*) estimated a 17% and 21% decrease in the annual *Sargassum* distribution based on calculations without river nutrient runoff and without atmospheric nitrogen deposition, respectively.

The North Atlantic Subtropical High (NASH) (i.e. Azores High) is another climatic feature that contributes to the flow of winds in the Caribbean region and influences the dispersion of *Sargassum* (Mendez-Tejeda and Rosado Jiménez, 2019). According to Mendez-Tejeda and Rosado Jiménez (2019), depending on the intensity of the NASH, it can influence the direction and arrival of winds, which in turn impacts marine currents and *Sargassum* dispersion. The tropical Atlantic Ocean is a region of immense complexity and dynamism, where ocean circulation, driven by large-scale winds, plays a crucial role in shaping the dispersion and distribution of *Sargassum* (Putman et al., 2018; Putman et al., 2020; Skliris et al., 2022; Marsh et al., 2021). Understanding ocean circulation patterns is critical in estimating the timing of influxes (Franks et al., 2016).

In the Tropical Atlantic, *Sargassum* circulates in the NERR, a complex area where ocean currents converge and form unique circulation patterns (Franks et al., 2011). The NERR lies between the SEC and the NECC, bounded on the west by the North Brazil Current and the North Brazil Current Retroflection and on the east by the Guinea Current (Franks et al., 2016; Franks and Johnson, 2018). Figure 12 shows a schematic of the major currents which drive circulation patterns within the NERR (Skliris et al., 2022).

Understanding the seasonality of winds and associated ocean circulation patterns helps to improve and refine models to establish a reliable seasonal forecast system of *Sargassum* drift across the region, which is critical in addressing the ongoing challenges of seasonal *Sargassum* influxes.

4.2.3 STATISTICAL ANALYSES USED TO TEST LINKAGES BETWEEN BIOMASS AND SPECIFIC FACTORS

Utilizing appropriate statistical analyses, researchers can gain valuable insights into the roles of various oceanographic and climatological factors influencing *Sargassum* biomass. These analyses can reveal correlations, associations and potential causal relationships between wind and oceanic variables and patterns of *Sargassum* biomass. While most of the research to date on the physical factors controlling bloom events has largely utilized particle tracking and a combination of various modelling approaches to understand the seasonal distribution of *Sargassum* biomass (Brooks et al., 2018; Franks et al., 2016; Marsh et al., 2021; van Sebille et al., 2021; Wang et al., 2019), some studies have also employed statistical analyses to test linkages (Jouanno et al., 2021*b*).

The Spearman correlation (non-parametric) test is used to assess the strength and direction of the monotonic relationship between two continuous or ordinal variables (Ali Abd Al-Hameed, 2022). The use of Spearman correlation analysis was observed in Putman et al. (2018) to determine whether the relative annual variation in transport predictions into the Caribbean were related to relative annual variation in values of *Sargassum* percentage cover in the eastern Caribbean Sea. In other studies, the relationship among winds, currents and *Sargassum* biomass was assessed with the use of regression analysis followed by variance partitioning to determine which of the explanatory variables (winds, currents) best accounted for the observed changes in *Sargassum* biomass (Johns et al., 2020; Putman et al., 2018; Skliris et al., 2022). Investigating the role of winds, Putman et al. (2020) utilized paired t-test analyses to determine the importance of the addition of windage on *Sargassum* distribution. Specifically, pairwise comparisons were used to understand daily separation distances under different windage scenarios and statistical significance was determined with the application of a Bonferroni Correction (Putman et al., 2020). Lara-Hernandez et al. (2023) performed sensitivity analyses to quantify the change in landing percentages on Mexican Caribbean coasts, varying the different modelling factors, among others windage, distribution of sargassum and monthly variability in currents and winds, and they found that the windage factor had the greatest effect on landing estimates.

4.3 Drivers responsible for the continued proliferation of *Sargassum* in the Tropical Atlantic

4.3.1 PHYSICAL FACTORS AND THEIR INFLUENCE ON GROWTH, MORTALITY AND ABUNDANCE

Floating on the ocean surface, *Sargassum* is exposed to and influenced by weather patterns, ocean currents, fronts, eddies, gyres and fluctuating temperatures (Brooks, 2019; Dierssen et al., 2015; Johns et al., 2020, Miron et al., 2020; Ody et al., 2019). These processes are thought to play a role in transport, growth, mortality and the general abundance of *Sargassum*, although it is not precisely known which factor(s) best explain variations in the total quantity of *Sargassum* in the Tropical Atlantic.

It is well established that winds and currents influence the aggregation state of floating *Sargassum* masses (Butler et al.,1983; Ody et al., 2019; Parr, 1939). Commonly observed raft aggregations include isolated and/or scattered clumps, windrows, windrows with small patches (few metres in diameter), windrows with large patches (hundreds of metres in diameter) and large quasi-circular patches that are hundreds of metres in diameter (Ody et al., 2019) (Figure 13). Early studies on *Sargassum* suggest that large rafts are commonly observed under calm sea conditions (Butler et al., 1983; Parr, 1939); however, recent findings by Ody et al. (2019) observed large rafts at both low and high wind speeds (4–11 m s^{-1}) with no significant relationship between raft type and wind speed.

In addition to the horizontal disaggregation of mats on the ocean surface, wind-induced wave mixing can lead to vertical disaggregation of *Sargassum* rafts into the water column under high winds (> 7 m s^{-1}) and rough sea conditions (Brooks, 2019; Ody et al., 2019). Within the water column, *Sargassum* may be exposed to an increased nutrient environment created from recycled nutrients depths beneath

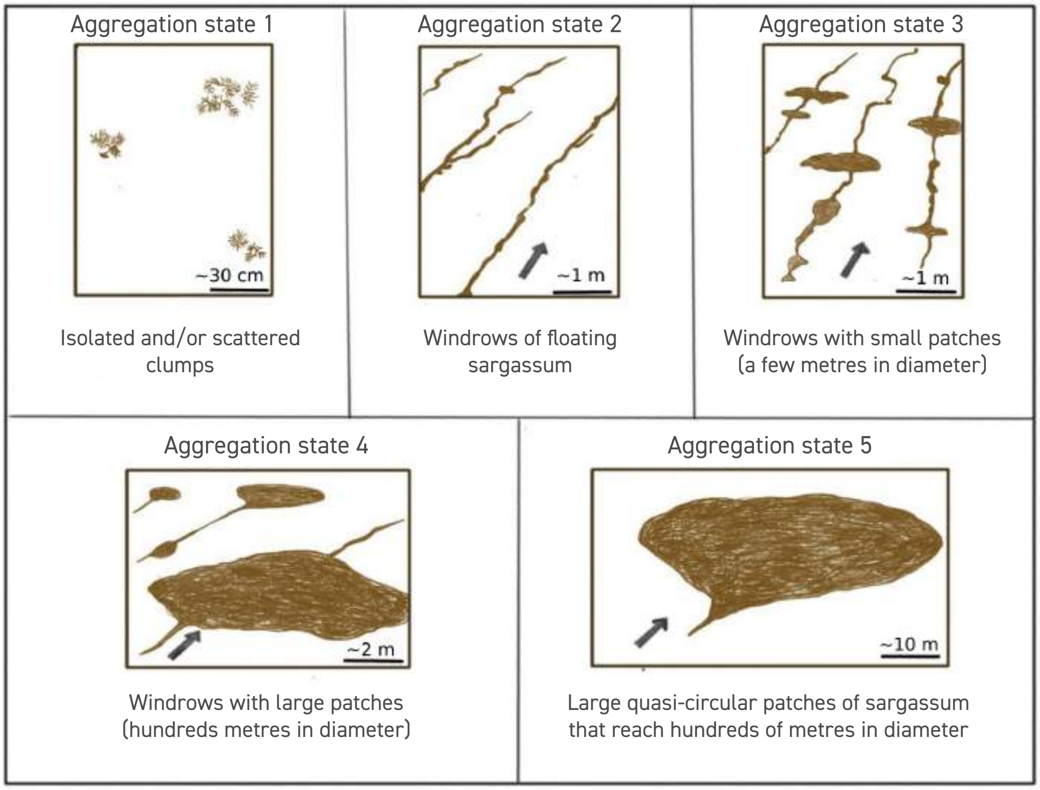


Figure 13. Five aggregation states of *Sargassum* rafts. Wind direction is indicated by arrows. *Source:* Image adapted from Ody et al. (2019) under a Creative Commons Licence.

the surface (Brooks, 2019), potentially resulting in growth and an increased biomass. However, it is also possible that *Sargassum* transported beneath the surface may sink, due to age or epiphyte load of the thalli, thus resulting in a reduced biomass. In this regard, the thallus age of the *Sargassum* plays an important role, whereby 'fresh' young *Sargassum* thalli have a higher probability of returning to the surface when compared to older, partially decaying and often epiphyte-loaded *thalli* with damaged gas-filled pneumatocysts. In addition to the horizontal and vertical displacement of *Sargassum*, it has been hypothesized that hurricanes have the potential to contribute to *Sargassum* growth, as they are capable of mixing nutrient-rich tropical waters from greater depths, and may result in increased nutrient runoff from land (Oviatt et al., 2019). However, the extent to which hurricanes may influence Sargassum occurrence remains unproven.

The abundance of beached *Sargassum* along the coasts of various Caribbean and West African countries ultimately depends on the trajectories of *Sargassum* rafts. However, forecasting the trajectory of *Sargassum* in the midst of hurricanes, ocean currents, fronts and eddies can be challenging (Miron et al., 2020). Moreover, the trajectory of any floating matter will depend on its buoyancy. The buoyancy of *Sargassum* changes as it ages, and due to colonization by epiphytic flora and fauna (Brooks et al., 2019). Mats with differing buoyancy will likely vary in their trajectory, despite having the same initial position. The effect of buoyancy on an object's trajectory is closely tied to the object's density and inertia. The inertia of an object refers to that object's ability to resist change in motion (Brooks et al., 2019).

Studies by Brooks (2019) and Brooks et al. (2019) indicate that the inertia of *Sargassum* rafts cause them to become entrained in cyclonic eddies five times more frequently than non-inertial particles. Brooks et al. (2019) postulate that entrainment of *Sargassum* within eddies may have a positive impact on growth due to increased access to nutrient upwelling and recycled fish excretions. Furthermore, strong vertical velocities caused by eddies can also have an impact on temperature by raising or lowering the depth of the local thermocline (Brooks et al., 2019); this is particularly important for *Sargassum* as temperature influences the growth rate of several *Sargassum* species (Corbin and Oxenford, 2023; Hanisak and Samuel, 1987; Magaña-Gallegos, Villegas-Muñoz et al., 2023).

There is considerable interest in understanding how temperature affects Tropical Atlantic blooms and how temperature effects on growth rate vary across the predominant morphotype species (*Sargassum natans* VIII, *S. natans* I and *S. fluitans* III). *Ex situ* studies conducted by Magaña-Gallegos, Villegas-Muñoz et al. (2023) showed that across a range of temperatures (22–31° C) the fastest doubling rate occurred at 28° C, 25° C and between 22–25° C for *S. fluitans* III, *S. natans* I and *S. natans* VIII, respectively. Irrespective of their optimum temperatures, growth rates across the three morphotypes were generally high across the temperature range of the GASB, although *S. fluitans* III consistently displayed higher rates of growth when compared to *S. natans* I and *S. natans* VIII. *In situ* observations conducted off the coastline of Barbados (Corbin and Oxenford, 2023) also reveal interspecific (*S. fluitans* and *S. natans*) and intraspecific (*S. natans* VIII and *S. natans* I) differences in growth rates, with *S. fluitans* growing faster than *S. natans* and *S. natans* I growing faster than *S. natans* VIII, thus supporting the findings of *ex situ* experiments. Both *in situ* and *ex situ* experiments reported a decrease in growth rates around 30° C (Corbin and Oxenford, 2023) to 31° C (Magaña-Gallegos, Villegas-Muñoz et al., 2023) across all morphotypes.

The findings of Magaña-Gallegos, Villegas-Muñoz et al. (2023) and Corbin and Oxenford (2023) suggest that temperature alone is neither enough to explain the variation in biomass nor morphotype composition between bloom events (Alleyne et al., 2023; García-Sánchez et al., 2020; Schell et al., 2015) and nutrient supply rather than temperature is likely to be the primary driving force of growth of *Sargassum* (Lapointe, 1986; Lapointe et al., 2021; Skliris et al., 2022). Interestingly, during *ex situ* experiments, *Sargassum* collected at the beginning of the *Sargassum* season (spring and summer months) displayed higher growth rates under the same conditions than *Sargassum* collected at the end of the season (autumn) under the same conditions (Magaña-Gallegos, Villegas-Muñoz et al., 2023). Given that *Sargassum* species are able to store nutrients in vacuoles and use them for growth when ambient nutrient concentrations are low and other favourable conditions arise (Gagné et al., 1982; Magaña-Gallegos et al., 2023*a*), Magaña-Gallegos et al. (2023*b*) postulate that the observed differences between *Sargassum* collected at the beginning and the end of the season may be the result of internal nutrient reserves. Thus, while growth responses to temperature proves some understanding of current bloom events, the influence of nutrient reserves, nutrient availability and the role of nutrient–temperature interactions need to be better understood.

4.3.2 BIOGEOCHEMICAL FACTORS AND THEIR INFLUENCE ON GROWTH, MORTALITY AND ABUNDANCE

In this section, the studies concerning the role of nutrient availability within the Tropical Atlantic in determining the growth and abundance of *Sargassum* are summarized (Lapointe et al., 2021; Skliris et al., 2022), while the corresponding gaps in knowledge are indicated in section 5.2.2. Over its broad distribution, *Sargassum* proliferations are supported by a variety of nutrient sources, including: discharges from the Amazon, Congo and Mississippi rivers (Djakouré et al., 2017; Franks et al., 2016; Lapointe et al., 2021; Oviatt et al., 2019; Skliris et al., 2022); upwelling (Oviatt et al., 2019; Skliris et al., 2022); meso-scale eddies (McGillicuddy and Robinson, 1997; McGillicuddy et al., 1998); and from atmospheric depositions from central and south African in the form of Sahara dust and biomass burning (Barkley et al., 2019; Oviatt et al., 2019). These sources provide varying quantities of nitrogen (N) and phosphorus (P) and micronutrients such as iron (Fe), that stimulate the growth of *Sargassum*. Studies by Lapointe (1995) and Lapointe et al. (2015) found that high quantities of N and P present in neritic waters resulted in *S. natans* and *S. fluitans* doubling their biomass in ~11 days. In contrast, oceanic waters with low N and P availability resulted in a reduced doubling rate (~50 days) (Lapointe 1995; Lapointe et al., 2015).

Sources contributing to the growth and abundance of *Sargassum* in the Tropical Atlantic appear to have varying effects on the intensity of blooms. Deposits from Sahara dust and biomass burning support the growth of *Sargassum* by providing N, P and Fe to the Atlantic surface ocean (Barkley et al., 2019; Bristow et al., 2010; Franks et al., 2016; Lapointe et al., 2021). Deposited N, P and Fe in the Tropical Atlantic directly provide nutrients for *Sargassum* growth, but Fe also stimulates nitrogen fixation within surface waters, which is co-limited by Fe and P availability (Bristow et al., 2010). Interestingly, Sahara dust and biomass burning both vary seasonally and, as a result, they are able to provide nutrient deposits at different periods during the *Sargassum* season. During the spring and summer months, Sahara dust is largely transported westward over the northern portion of the NERR (Franks et al., 2016). However, during the autumn, Sahara dust is usually restricted to the Gulf of Guinea as positioning of the ITCZ, between ~5 N to 10° N, inhibits transport to South America (Barkley et al., 2019; Franks et al., 2016). In contrast, nutrient deposits from biomass burning are distributed within the Southern (Northern) Hemisphere during spring, summer and autumn (autumn and winter) months (Barkley et al., 2019; Lapointe et al., 2021). In addition to the observed spatiotemporal differences, elements provided by atmospheric nutrient deposits vary in quantity and solubility (Barkley et al., 2019; Lapointe et al., 2021). Nutrient supply of Sahara dust plumes is larger than that of biomass burning; however, deposits from biomass burning have higher nutrient solubilities which may provide more bioavailable nutrients for *Sargassum* as compared to Sahara dust deposits (Barkley et al., 2019; Lapointe et al., 2021). While it is evident that atmospheric deposits can support the *Sargassum* proliferations (Barkley et al., 2019; Bristow et al., 2010; Franks et al., 2016, Lapointe et al., 2021), no direct linkages between increased atmospheric deposits and *Sargassum* biomass have been established.

In contrast to mineral dust deposits, studies by Oviatt et al. (2019) and Lapointe et al. (2021) reveal a strong connection between *Sargassum* area biomass and river discharges in major river flood years. Oviatt et al. (2019) suggest that nutrient injections into the eastern part of the Tropical Atlantic, stemming from Congo River plumes and coastal African upwelling, sustain the growth of *Sargassum* for its journey across the Atlantic to Brazil. Upon arriving in the western Tropical Atlantic, *Sargassum* rafts are supported by new nutrients from Amazon River outflows (Lapointe et al., 2021; Oviatt et al., 2019; Skliris et al. 2022) and possibly hurricanes (Oviatt et al., 2019). River discharges occurring in the eastern and western Tropical Atlantic directly influenced the C:N and C:P ratios in *Sargassum* (Lapointe 2015; Lapointe et al., 2021).

Discharges from the Amazon River increase from winter through spring and peak in the summer; during this period, *Sargassum* influenced by plumes are associated with lower C:N and C:P ratios (i.e. higher N and P contents in relation to C). In contrast, reduced discharges during summer and autumn result in higher C:N and C:P ratios in *Sargassum* and a gradual decline in biomass (Lapointe et al., 2021). While river discharges are capable of stimulating *Sargassum* growth, due to nutrient additions, these freshwater inputs also alter the salinity of surrounding waters (Lapointe et al., 2021). The holopelagic sargassum species only tolerate small changes in the salinity of surrounding water (Hanisak and Samuel, 1987); during river discharges, Lapointe et al. (2021) observed reduced *Sargassum* abundance for waters with a salinity of <31 ppt. Thus, the influence of river discharge on *Sargassum* abundance is likely to vary based on corresponding changes in salinity.

While studies assessing the relationship between seasonal river discharges and *Sargassum* abundance suggest that river inputs may have contributed to bloom formation in 2011, 2014 and 2015, during the record-breaking year of 2018 there was no Amazon flood influence (Lapointe et al., 2021; Oviatt et al., 2019). This suggests that river discharges may influence, but are not the primary driving forces behind bloom events. Rather than river outflows, a recent study by Skliris et al. (2022) suggests that yearly changes in the intensity of blooms are primarily driven by anomaly patterns of regional winds and currents that control nutrient abundance.

During years of exceptionally large *Sargassum* proliferations (2015, 2018), negative phases of the Atlantic Meridional Mode (AMM) occurred, resulting in stronger trade winds and enhanced coastal African upwelling (Skliris et al., 2022). More importantly, during the record-breaking years of 2015 and 2018, the ITCZ shifted southward, taking *Sargassum* that naturally accumulates under the ITCZ towards the nutrient-rich waters of the Amazon River plume and the equatorial upwelling zone (Skliris et al., 2022). The influence of the ITCZ on *Sargassum* distribution is not surprising, given that ocean dynamics within the NERR are strongly affected by the location and intensity of the ITCZ (Johnson et al., 2012). Wind anomaly patterns during 2015 and 2018 also reveal excessive wind-driven equatorial upwelling and strong atypical northwest nutrient transport during winter months (Skliris et al., 2022), accounting for the unusually large winter blooms observed during these years. The observed anomalous wind patterns played a vital role in sustaining *Sargassum* growth through the control of nutrient abundance but also by influencing the aggregation, dispersion and transport of *Sargassum* rafts. Thus, while atmospheric dust deposits and river outflows certainly contribute to growth of *Sargassum*, the intensity of blooms is likely driven by anomaly patterns of regional winds and currents (Skliris et al., 2022).

Although the identification of nutrient sources is an important aspect of understanding current bloom events, further research is required to assess: (1) the specific quantities and ratios of nutrients needed; and (2) interactions between nutrients, temperature and salinity and how these factors impact blooms. Reports on river outflows (Lapointe et al., 2021) and anomaly patterns in regional winds (Skliris et al., 2022) both indicate that increased N availability drives *Sargassum* proliferations in the Tropical Atlantic. However, a recent preliminary study by Magaña-Gallegos et al. (2023*a*) in Mexico observed a decreasing C:N (accumulation of nitrogen) and an increasing N:P (phosphorus limitation) when applying nutrients to growing *Sargassum*, suggesting that P was more important for growth during trials. Interestingly, research by Lapointe et al. (2021) shows that N and the N:P ratio in *Sargassum* have increased since the early 1980s and this may have resulted in *Sargassum* becoming more

P-limited. It is also plausible that nutrient reserves within *Sargassum* influenced the uptake of N vs P, thus contributing to the complicated relationship among nutrient availability, nutrient uptake and growth (Magaña-Gallegos et al., 2023*a*; Magaña-Gallegos et al., 2023*b*).

4.3.3 BIOLOGICAL FACTORS AND THEIR INFLUENCE ON GROWTH, MORTALITY AND ABUNDANCE

It is generally accepted that the morphotypes responsible for Tropical Atlantic blooms (*S. natans* I, *S. natans* VIII and *S. fluitans* III) are genetically distinct (Amaral-Zettler et al., 2017; González-Nieto et al., 2020; Siuda et al., 2017; Dibner et al., 2021) and have different ecological, biological and chemical traits (Alleyne et al., 2023; Davis et al., 2020; Martin et al., 2021; Magaña-Gallegos et al., 2023*a*). However, very little is known on how genetic differences and adaptive strategies of the three morphotypes influence growth and mortality. Conducting experiments on benthic *Sargassum ilicifolium*, Yeh et al. (2021) show that temperature, irradiance and salinity influence the growth rate and survival of young algae. Similarly, an early study by Hanisak and Samuel (1987) showed that the growth rates of *Sargassum* species are also influenced by environmental factors. More importantly, Hanisak and Samuel (1987) found that holopelagic species were more stenohaline than benthic species and required higher light conditions. Given that differences in the biology of holopelagic and benthic species can lead to differences in growth rates under the same environmental conditions, it is likely that genetic differences among the three morphotypes also influence growth, mortality and abundance. In addition to genetic differences, adaptive strategies used by brown algae also affect growth rates. One example of this can be observed in a study conducted by Chapman and Craigie (1977) and Gagné et al. (1982) that assessed the annual cycles of growth and the internal storage of nutrients in the brown algae *Laminaria longicruris*. When placed in an environment that had high nutrients all year round, the alga displayed high growth rates that followed the seasonal pattern of light, and there was little storage of inorganic nitrogen. When nitrogen was only abundant during the winter months, growth accelerated at this time and continued through early summer, while internal reserves of nitrogen were utilized. In low-nutrient environments, larger reserves of nitrogen were built up and used to maintain a high growth rate through most of the summer (Gagné et al., 1982). These findings suggest that the environmental history of algal species trigger different adaptive responses that affect growth rates.

It is also important to acknowledge nutrient cycling within the *Sargassum* community when looking at the environmental history, as fish schools traveling with rafts excrete copious amounts of nutrients that can be utilized by the *Sargassum* (Lapointe et al., 2014). The microbial community likely plays a role in nutrient acquisition and recycling, although it also contains potential pathogens such as *Vibrio* spp. (Michotey et al., 2020; Theirlynck et al., 2023). *Sargassum* in the Sargasso Sea has both photic (Carpenter and Cox, 1974) and aphotic (Phlips and Zeman, 1990) N fixation by cyanobacterial epibionts. In the GASB, both Hervé et al. (2021) and Theirlynck et al. (2023) showed a high presence of phototrophs that could assist in nitrogen fixation and of dissolved organic matter (DOM)-degrading bacteria that aid in recycling of organic matter, and both processes could enhance the growth of *Sargassum*. But biological N fixation has a high iron requirement and may cause surface water depletion of either P or Fe (Wu et al., 2000), thereby limiting growth; thus, the interactions among the microbial omposotion, nutrient availability and *Sargassum* growth are likely to be complex.

5. Knowledge gaps

This section outlines a gap analysis that sought to identify the key knowledge gaps and research deficiencies in current *Sargassum* research. It draws from insights from both a desktop study and consultations with a number of *Sargassum* scientists/experts, government officials and private sector actors. These key informants (KIs) represented universities, companies and organizations from North and South America, the Caribbean, Europe and Africa. Of the 47 individuals initially identified, the response rate was 25%, suggesting that improvements in the method of engagement are needed for any follow-on study.

Despite the modest response rate, the perspectives and insights garnered from the 12 KIs form a valuable foundation for understanding the current state of *Sargassum* research. The subsequent narrative is structured to align with the logical framework presented in the preceding section. The 12 KIs were assigned codes (Table 2) for ease of referencing, using the following format (KI Sarg 1–12).

5.1 Biomass estimation and spatial distribution of *Sargassum*

Over the years, methodologies for detection and monitoring of *Sargassum* have undergone a transformative evolution, owing much of their success to the utilization of advanced satellite technologies. Due to the high reflectance of *Sargassum* in the near-infrared spectral bands, satellite and airborne instruments have been used to detect and quantify *Sargassum* (Wang, 2018). A diverse array of satellites, each equipped with specialized sensors, has become instrumental in providing researchers with invaluable data for observing and tracking large-scale *Sargassum* distributions across the Atlantic Ocean. These sensors include, but are not limited to, MODIS, VIIRS (Visible Infrared Imaging Radi-

Table 2. Key informant codes

University/Company/Organization	Key informant code
University of Nottingham England	KI Sarg 1
University of South Florida, USA	KI Sarg 2
University of the West Indies, Cave Hill, Barbados	KI Sarg 3
University of the West Indies, Cave Hill, Barbados	KI Sarg 4
Collecte Localisation Satellites, France	KI Sarg 5
Federal University of Santa Catarina, Brazil	KI Sarg 6
Trinidad and Tobago's Institute of Marine Affairs, Trinidad	KI Sarg 7
University of Southampton, England	KI Sarg 8
University of York, England	KI SARG 9
University of Southern Mississippi, USA	KI Sarg 10
University of the West Indies, Mona, Jamaica	KI Sarg 11
Lagos State University, Nigeria	KI Sarg 12

Table 3. Key high-resolution satellite images used for detecting and quantifying *Sargassum*

	MODIS-A&T (NASA)	VIIRS (NASA)	OLCI-A (ESA/ Copernicus)	MSI-A&B (ESA)	OLI (NASA)	DOVE (ESA)	WV-2 (ESA)
Spactial resolution	1 km	750 m	300 m	10 m	30 m	3 m	~2 m
Temporal resolution	1 day	1 day	4 days	5 days	16 days	Daily	Irregular
Algae index	AFAI	AFAI	MCI	MSI-MFAI	FAI	RGB	FAI

Source: Adapted from Wang and Hu (2021) and Ody et al. (2019).

ometer Suite), OLCI (Ocean and Land Colour Instrument), MSI, Operational Land Imager (OLI), Dove and WV-2 (WorldView-II). Additional details on their respective capabilities and functionalities can be found in Table 3.

While satellite remote sensing of *Sargassum* has been the foundation for establishing distribution of pelagic masses of *Sargassum*, it has been evident for some time that major gaps exist that impair the accuracy in estimating the spatial distribution of *Sargassum* (Wang and Hu, 2016, 2021). Key questions raised include how large must *Sargassum* patches be in order to be detected, can satellites detect scattered clumps, can satellites determine depth of rafts. We will explore these key questions and more in the subsequent sections.

5.1.1 THE EFFECTS OF ATMOSPHERIC INTERFERENCE ON REMOTE SENSING

Detecting *Sargassum* faces recurring challenges due to factors such as cloud coverage, sun glint, aerosols and other atmospheric factors that can lead to serious errors in forecasting events, (indicated by KIs Sarg 2, 3, 7, 8 and 10). The presence of cloud cover, particularly in the eastern tropical Atlantic, as well as strong glint effect, can lead to large gaps in satellite images. This, in turn, drastically reduces both the nominal spatial coverage and the frequency of observation by satellite sensors, as observed in a study by Ody et al. (2019). KI Sarg 8 shared that sensors that can 'see through cloud cover' are not as readily available as the visible and infrared data. Consequently, most progress in satellite detection of *Sargassum* has been focused on the western tropical Atlantic, where cloud cover is comparatively less prevalent (KI Sarg 8).

Increasing access to high-resolution satellite data and the development of advanced image processing techniques are necessary to improve spatial mapping accuracy, as highlighted by Wang and Hu (2021) and emphasized by KI Sarg 12. KI Sarg 2 proposed a solution to reduce data gaps over open waters due to clouds and sun glint by merging multiple satellite sensors (e.g. MODIS/Terra, MODIS/Aqua, OLCI/3A, OLCI/3B, VIIRS/SNPP, VIIRS/NOAA20, VIIRS/NOAA21) (KI Sarg 2). According to KI Sarg 3, the use of AI techniques in satellite imagery analysis has shown promising results in 'filling' blind areas. This KI believes that continued improvements in the use of AI and further development of radar satellite products to 'see through clouds' can improve coverage and improve satellite detection.

5.1.2 FINE SCALE AND SUBSURFACE DETECTION

Sargassum in the ocean can take the form of clumps, mats, or rafts, often smaller than the size of a pixel. The extent to which coarse-resolution sensors may overlook such smaller-scale structures remains unclear, as noted by KIs Sarg 3 and 10. KI Sarg 10 further explained the complex dispersion pattern of *Sargassum*, highlighting its tendency to aggregate into long lines/rafts followed by fragmentation and dispersal into smaller clumps, too small to identify in imaging algorithms. The challenge arises when these initially 'unidentified' *Sargassum* clumps consolidate later on, just before reaching the targeted area, significantly impacting the accuracy of forecasting, as emphasized by KI Sarg 10.

The three-dimensional structure of *Sargassum*, with portions extending below the surface of the water, poses difficulties in estimating volumes solely from remote sensing imagery as noted by KIs Sarg 3, 4, 5, 11 and 12. While satellite remote sensing offers large-scale coverage, typically capturing surface images, it lacks the ability to capture detailed three-dimensional information required for accurately quantifying *Sargassum* biomass. KIs Sarg 4 and 5 highlighted that the lack of subsurface data can result in inaccurate projections, either underestimating or overestimating total *Sargassum* biomass likely to impact a coast (i.e. false detections). Such inaccuracies could have significant implications for effective management efforts and for entrepreneurs seeking to capitalize on *Sargassum*.

The KIs offered insights in addressing these identified gaps to increase forecasting accuracy. KIs Sarg 3, 4, 5, 11 shared the harmonized view that combining remote sensing with *in situ* measurements (ground truthing) is necessary to examine what actually exists versus what the satellites can detect. Furthermore, KIs Sarg 9 and 11 underscored the importance of implementing synchronous *in situ* methodologies that adhere to best practices. This is crucial for ensuring data consistency, comparability and reliability.

KI Sarg 11 emphasized that lack of funding is a recurrent challenge. Acquiring precise *in situ* assessments of *Sargassum* biomass and distribution spanning large geographic areas are costly. For instance, deployment of underwater drones to build three-dimensional (3D) maps of a *Sargassum* mat to depict the vertical distribution and biomass of *Sargassum*. In response to this challenge, KI Sarg 11 provided the following suggestions to assist or negate the funding issue:

1. Collaborative partnerships, within countries and between countries
2. Crowdfunding
3. Public-Private sector partnerships
4. Government grants
5. International aid

KI Sarg 12 echoed similar recommendations, emphasizing the need for more coordinated research and management efforts. Furthermore, this informant proposed the establishment of in-country hubs dedicated to *Sargassum* research, training and capacity development.

5.2 Linkages between physical factors and bloom events

While it is widely acknowledged that physical factors play a role in *Sargassum* bloom events, the specific mechanisms and processes involved are still not yet fully understood (Putman et al., 2018; Putman et al., 2020; Almela et al., 2023). The interactions between ocean currents, swells, waves, wind patterns, upwelling events, surface temperature, nutrient availability, light and other physical drivers are complex and often synergistic (Putman et al., 2018; Marsh et al., 2021; Skliris et al. 2022). Understanding these physical mechanisms driving *Sargassum* growth and dispersion is key for more accurate predictions of long-term changes in the abundance and distribution of *Sargassum*. In the following sections, we will explore the research gaps in the linkages between the key factors and bloom events.

5.2.1 OCEANOGRAPHIC AND ATMOSPHERIC FACTORS

KI Sarg 4 highlighted the difficulty in predicting the precise dispersion of *Sargassum* due to the influence of multiple independent factors. This informant further explained that given the complex interactions of coastal currents, wind, swells, waves, eddies and mesoscale features, as well as the variations of *Sargassum* patches, determining the precise paths and rates of *Sargassum* dispersion is challenging, especially nearshore. KI Sarg 6 also underscored the necessity for an improved understanding of circulation patterns in coastal areas. This knowledge is crucial for deducing how these areas contribute to replenishment of nutrients within water masses, potentially leading to upwelling. A notable concern raised by KI Sarg 12 was the lack of access to oceanographic data and limited research on the impacts of climate change on physical factors.

Based on these findings, it is evident that more research should be dedicated to experimental exercises to understand how different physical conditions and factors affect the growth and dispersion of *Sargassum* under different climate change scenarios and under different conditions. This, in combination with local knowledge, can help to further understand bloom extension. KI Sarg 3 suggested that coupling ocean drift models to nearshore hydrodynamics to understand when, where or if *Sargassum* will land, how it behaves regarding coastal geometry, bathymetry, sea state and local winds could help to address the knowledge gaps. Coordinating and collaborating with oceanographic research centres to extract, use and model oceanographic data is essential for advancing knowledge, as indicated by KI Sarg 12.

The impact of tropical cyclones on *Sargassum* growth is not fully understood, for example, the extent to which strong wave action could break apart rafts, increasing the surface area for nutrient uptake (Putman and Hu, 2022). This was echoed by KI Sarg 8, who stated that there is much uncertainty of the impact of vertical mixing of the water column (churning) in improving nutrient availability which could increase *Sargassum* growth. While it is acknowledged that vertical mixing has the potential to increase nutrient uptake, wave actions that disaggregate rafts may also remove positive feedbacks of agglomerated *Sargassum*, such as nutrient recycling by fauna. Redistribution of *Sargassum* may also occur, resulting in small clumps that are invisible to satellites (Putman and Hu, 2022). To add to the complexity, Putman and Hu (2022) suggested that the high winds and strong wave action might result in the submergence of *Sargassum*, detachment of the air-filled vesicles, possibly resulting in sinking and dying. Detecting and quantifying *Sargassum* rafts through high-resolution satellite data may be required to assess the possible dissipation effect and help to decipher the observed before and after changes (Putman and Hu, 2022).

5.2.2 NUTRIENTS

Studies by Wang et al. (2019) and Johns et al. (2020) indicate that nutrient availability plays a crucial role in controlling interannual variability of *Sargassum* proliferations in the central tropical North Atlantic. Despite this, the contribution of nutrients has been relatively understudied compared to other limiting factors including surface temperature and irradiance, as highlighted by Skliris et al. (2022). According to these authors, the limited nutrient concentration spatiotemporal coverage inhibits the ability to assess the interannual variability of *Sargassum* distribution in the tropical Atlantic. Furthermore, the lack of measurements hampers the accurate assessment of variations in external nutrient inputs, such as atmospheric deposition and riverine fluxes. To address these gaps, the authors recommended finding suitable indicators of nutrient availability for *Sargassum* growth.

KIs Sarg 8 and 10 further emphasized that the particular sources of nutrients that contribute to *Sargassum* proliferations, their availability and the specific mechanisms of these interactions are poorly understood. They explained that while it is evident that nutrients are required for *Sargassum* growth, there is less understanding of the specific nutrient requirements needed under which conditions, the interactions between various nutrients (such as nitrogen, phosphorus and iron) and their impacts on bloom dynamics.

It was suggested that while previous studies on brown algae provide essential knowledge, future studies focused on biological factors that influence the growth and mortality of Tropical Atlantic blooms are required to better understand if and/or how differences in morphotypes affect *Sargassum* populations.

The research conducted by Lapointe et al. (2021) represents a notable contribution to the knowledge on *Sargassum* nutrient dynamics. The research sheds light on the effects of nitrogen and phosphorus supply on *Sargassum*, examining variations across different seasons and geographic locations. Building upon the groundwork laid by Lapointe et al. (2021), future research should encompass a diverse range of regions, depths and distances from the shore, and capture the full spectrum of environmental factors and nutrient sources influencing *Sargassum* growth. Furthermore, the integration of *in situ* studies with remote sensing observations (for instance satellite-derived chlorophyll concentrations), as suggested by Skliris et al. (2022), represents a synergistic approach to enhance the accuracy and scalability of nutrient assessments.

5.3 Drivers responsible for the continued proliferation of *Sargassum* in the Tropical Atlantic

Several critical gaps persist in understanding the drivers responsible for the continued proliferation of *Sargassum*. The majority of the KIs (75%) stated that these gaps mainly relate to the growth and mortality of *Sargassum*, the extent to which these processes are driven by a range of physical factors and whether differences exist between species and morphotypes. Additionally, questions have been raised about whether the various species/morphotypes are adapting to 'new' conditions, adding complexity to the understanding of *Sargassum* dynamics.

5.3.1 REMOTE SENSING TO SUPPORT MONITORING

Continuous and long-term monitoring of *Sargassum* influxes is lacking in many regions, indicated by KIs Sarg 1, 3 and 7. As a result, there are gaps of knowledge in the spatial and temporal distribution patterns of *Sargassum* populations. KI Sarg 1 suggested that long-term monitoring at high spatial and spectral resolution will provide insights into the drivers and mechanisms underlying *Sargassum* population dynamics. This KI added that remote sensing algorithms, specifically designed for detecting and quantifying *Sargassum* populations from satellite imagery, be developed. This may involve calibrating and validating the algorithms using ground-based measurements and field observations (e.g. using buoys, drifters and video capture) to ensure accurate and reliable results (KI Sarg 1).

5.3.2 GROWTH AND MORTALITY MECHANISMS AND PROCESSES

There are no records of sexual reproduction in the holopelagic *Sargassum* species/morphotypes and the algae are thought to spread exclusively by clonal reproduction by fragmentation (Godínez-Ortega et al., 2021). There is little data on the growth rates of the *Sargassum* species currently proliferating in the tropical Atlantic and the optimal conditions for growth (Corbin and Oxenford, 2023). Furthermore, there is uncertainty on whether *Sargassum* in a thick mat grows or dies faster or slower than a single thallus. Corbin and Oxenford (2023) explained that incorporating physiological data of *Sargassum* growth and mortality is critical for forecasting bloom episodes and population changes; however, there are currently insufficient modelling capabilities for predicting how *Sargassum* grows, fragments and dies and whether growth differs by morphotype.

According to KIs Sarg 3 and 12, little is known about the lifespan of *Sargassum*, individual thalli or the population as a whole and the key drivers of mortality/sinking (e.g. potentially old age and loss of gas bladders, high temperature, low salinity, low nutrients, strong downwelling, storms, etc.). KI Sarg 3 further shared that these, together with growth/asexual reproduction (fragmentation), ultimately control the population size. It was recommended by this KI that more *ex situ* studies (to determine mortality responses) and *in situ* studies (to evaluate sinking rate of rafts under a variety of conditions) be conducted. KI Sarg 12 also agreed that more studies be conducted and specified targeted research towards understanding the life cycle, (clonal) reproduction and dispersal of *Sargassum*.

5.3.3 ABIOTIC INTERACTIONS

It is still unclear how *Sargassum* growth in the natural environment depends on the variability of temperature, nutrient availability, salinity and light in the tropical Atlantic (KIs Sarg 1, 2, 5, 8 and 12) and how this differs by morphotype (KIs Sarg 3 and 6). KIs Sarg 7, 9 and 12 noted that there are theories on the role of climate change, but these need to be corroborated with more scientific studies and spatial modelling. The effect of ENSO (El Niño-Southern Oscillation) cycles on *Sargassum* bloom events has also been recognized as an area that requires further investigation. Although it is understood that nitrogen is a very important factor for the growth of *Sargassum*, KI Sarg 9 pointed out that there is still high uncertainty surrounding the extent of the contributions of different nitrogen sources and their influence on *Sargassum* growth. For instance, there is still much speculation as it relates to the extent to which anthropogenic pollution and river discharge provide nitrogen to support the *Sargassum* growth. KI Sarg 8 highlighted the importance of *in situ* and mesocosm experiments and recommended developing models or algorithms to predict bloom occurrence and intensity based on the key drivers.

5.3.4 LAND-BASED SOURCES

Understanding the links between land-based sources of nutrients and *Sargassum* proliferation is vital for implementing effective mitigation strategies. KI Sarg 6 identified the need for better understanding of how land processes, changes in uses and area influence the water quality in the tropical Atlantic. Additionally, this KI noted that further research is needed to understand how these factors, combined with ocean warming, are driving blooms. KI Sarg 6 suggested that mining, deforestation, agriculture, livestock farming and lack of sewage treatment are stressors that should be explored using modelling and mesocosm experiments. Certainly, international cooperation and concerted efforts are essential to effectively address a global challenge of this nature and KI Sarg 7 underscored the importance of global plans to reduce impacts from land-based sources of pollution.

6. Discussion

The state of research on *Sargassum* dynamics-related science is quite advanced and has amassed many thought-provoking pieces of literature and valuable contributions to knowledge. Research to date on the phenomenon of *Sargassum* influxes has provided key insights into the magnitude and complexity of this environmental issue. The results section above cited over 75 articles that specifically address the estimation and spatial distributions in *Sargassum* biomass, including seasonality, interannual variability and long-term trends. In addition, current biomass estimates in oceanic and coastal waters were also outlined. The section also examined the role of antecedent events, such as wind and ocean circulation, on the timing and distribution of the bloom events, including available statistical analyses to test such linkages. Finally, the state of research above outlined a comprehensive summary of papers that provide evidence of the current understanding of what physical (temperature, weather patterns, ocean currents/circulation, fronts, eddies, gyres), biogeochemical (nutrient availability) and biological factors (genetic differences between species/morphotypes and adaptive strategies) control *Sargassum* growth, distribution and abundance and mortality.

Research on the estimation and spatial distribution of *Sargassum* and understanding the spatial distribution of bloom events has received significant investment of human and financial resources needed to produce operational remote sensing products that support early warning systems. The uptake of forecasting products that inform decision-making has improved over the years given the track record of accurate outlooks and the guidance provided on the implications of the forecasts. However, other research areas need to be prioritized to develop more precise forecasts that promote collaboration at the science–policy interface. Validation studies including ground truthing exercises are needed to better understand the amount of *Sargassum* that beaches and how that relates to oceanic biomass estimates.

Less attention and financial resources have been invested in studies that investigate the linkages between the physical, biogeochemical and biological factors that influence growth and mortality. These studies are required to better understand how *Sargassum* growth and mortality can improve the accuracy of forecasts. There are insufficient model capabilities for predicting how *Sargassum* grows, fragments and dies and whether growth differs by morphotype. *In situ* and *ex situ* studies that can support these investigations usually require significant funding and skilled personnel with the expertise to interpret findings.

This warrants specific interventions to motivate scientists to pursue research in the thematic areas where less attention has been placed. Thematic research calls supported by innovative financing mechanisms should be encouraged where multi-country research teams are mandated. Multi-country teams are ideal for facilitating knowledge exchanges and the opportunity for country visits that can provide insight on transboundary issues. The outcomes of the research should be published not only as journal articles, but key findings can be packaged to support the advancement of solutions to address the crisis. Scientists should also consider teaming up with innovators to ensure successful implementation. Alternatively, projects could consider the incorporations of experts that can facilitate the transfer of knowledge from the scientific community to innovators.

6.1 Existing gaps in current *Sargassum* research

The gap analysis revealed key research deficiencies that currently exist in *Sargassum* science specific to the areas of interest defined earlier. Several challenges, including human and financial resources, and perceptions of priority areas have hindered the rapid development of research that investigates the root causes of *Sargassum* influxes.

Although substantial funding has now been mobilized to support many research initiatives across the Caribbean region and West Africa, this has generally been in support of developing effective mitigation activities, improving monitoring and prediction, strengthening networking and information sharing among stakeholders, including raising public awareness and education (Oxenford et al., 2021).

Table 4. Key research gaps and proposed interventions

Key research gaps	Proposed interventions
Atmospheric interference on remote sensing	The use of synthetic aperture radar to address cloud cover in satellite imagery. Use of high-resolution satellite imagery can also enhance existing products.
Fine scale and subsurface detection	The deployment of underwater drones to build three-dimensional (3D) maps of a *Sargassum* mat to depict the vertical distribution and biomass of *Sargassum* should be considered.
Oceanographic and atmospheric factors	More research should be dedicated to experimental exercises to understand how different physical conditions and factors affect the dispersion of Sargassum blooms under different climate change scenarios and under different conditions, including biogeochemical controls. This, in combination with local knowledge, can help to further understand bloom expansion.
Remote sensing to support monitoring	Group on earth observations (GEO) and GEO Blue Planet initiatives can lead on designing and implementing monitoring programmes, given their existing relationships with countries
Growth and mortality mechanisms and processes	In situ and ex situ studies can be designed and implemented by national fisheries management authorities or coastal and marine-related institutions for year-round investigations
Abiotic interactions	In situ and mesocosm experiments are recommended to support the development of models or algorithms to predict bloom occurrence and intensity based on the key drivers.
Land-based sources of nutrients	Support can be provided to UNEP's Global partnership on nutrient management to accelerate actions to address the 'nutrient challenge'.
Social network analysis	Network insight helps to inform interventions and the institutional arrangements to build on strengths and address weaknesses. An SNA exercise can be conducted in-person at a side event at an upcoming international *Sargassum* conference.

Inadequate funding and support have been made available to researchers dedicated to conducting experimental exercises to understand how different physical conditions and factors affect the dispersion and distribution of *Sargassum* blooms.

We propose interventions to address key research gaps in Table 4 before making general recommendations for future research and effective implementation of collaborative efforts.

6.2 Recommendations for future research

The development of a global *Sargassum* research strategy and action plan can promote synergies among the numerous projects and initiatives at national, multi-country and subregional levels to avoid unnecessary duplication and promote the efficient use of resources. The plan should outline priority areas of research based on the gaps identified, roles and responsibilities of researchers, indicative budgets and a proposed timeline for implementation. This strategy and action plan can be championed by a dynamic transatlantic research consortium that will be instrumental in coordinating and implementing the tailored interventions and activities outlined.

The research consortium can be established by merging and expanding the *Sargassum* Network (SargNet) and GEO Blue Planet's *Sargassum* Working Group and the informal grouping of *Sargassum* innovators. This can be a first step in recruiting the researchers best suited for implementing the global *Sargassum* research strategy and action plan. A social network analysis of innovators working on *Sargassum* valorization initiatives should be considered in the future to support the selection of persons with high social capital and influence. Biannual conferences (twice a year) will be instrumental in bringing members of the consortium together to present research and develop proposals for future investigations.

Updates on the status of implementation of the plan can be published annually in the IOC-UNESCO State of the Ocean Report (StOR), where *Sargassum* influxes can be featured as a separate challenge. The publication date of the StOR with the special feature on *Sargassum* influxes can be considered a proposal for an UN International day to raise awareness of the issue.

The consortium will also be integral in conducting a feasibility assessment of the mitigation of *Sargassum* influx root causes with recommendations for collective response planning. The outcome of this assessment will determine how new and existing national strategies for *Sargassum* influx response and management can support collaborative efforts globally to support mitigation.

Exploring sustainable financing mechanisms to support research and development for mitigation options should consider innovative solutions like blue bonds and climate finance facilities. Pathways to climate philanthropy that promote blended finance models to encourage private sector involvement and cross-sectoral collaboration should also be investigated to support existing research initiatives and the design of investigations that aim to address complex issues.

While the scope of this work only covered dynamics, other areas such as impact (social, ecological, including coastal and deep-sea communities) and valorization are equally important and should be explored in future research initiatives.

7. Conclusion

The comprehensive review presented in this White Paper has provided empirical evidence that suggests that the *Sargassum* phenomena can be considered a 'wicked problem', influenced by a complex interplay of both natural and anthropogenic factors. The state of research on *Sargassum*-related science is quite advanced, with valuable contributions to knowledge that provide insight on the source and causes of influxes. However, many unanswered questions and research gaps still exist that need to be addressed to inform decision-making and support policy development.

Further research and development is needed to investigate the root causes that are, in most cases, transboundary issues. This will require substantial human and financial resources and high levels of social capital to sustain arrangements such as multi-country research consortiums that promote mitigation options. A dynamic *Sargassum* scientific community exists that can propel the development of an effective science–policy interface in promoting response planning and exploring sustainable valorization initiatives. It is anticipated that this paper will advance the understanding of the phenomenon and the funding strategies and sustainable financing mechanisms needed to shore up important contributions to knowledge. It may also be useful when considering similar large-scale algal bloom events in other regions.

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Appendices

APPENDIX I. COMPILATION OF KEY *SARGASSUM* RESEARCHERS

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CARIBBEAN	
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Rafael Méndez-Tejeda	University of Puerto Rico at Carolina
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EUROPE

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APPENDIX II. SOCIAL NETWORK ANALYSIS

A social network analysis (SNA) (Wasserman and Faust, 1994) was conducted of the *Sargassum* scientific community working variously on: estimation of biomass and spatial distribution of *Sargassum*; linkages between physical factors and bloom events; and physical, biogeochemical and biological drivers.

The first step in the SNA was the identification of key actors (see Appendix I) in the *Sargassum* scientific community (n = 208) before examining the structure of their relationships. The scientific community was identified based on: geographic location, through an investigation of authorship of *Sargassum*-related publications related to the subjects of interest; composition on *Sargassum* project teams; and participation at conferences where *Sargassum* sessions were hosted.

The intended method sought to examine the structure of social relationships in the *Sargassum* science community to uncover the formal and informal connections among individuals. An attempt was made to investigate and map a knowledge and information exchange network specific to the subjects of interest. However, the response rate was very low and was not conclusive.

It is recommended that this SNA exercise is repeated and conducted in-person at a side event at an international *Sargassum* conference to accurately capture the relationships in other related networks, e.g. donor or financial.

Understanding the interactions among stakeholders within social-ecological systems, in this case *Sargassum* influxes, is important to every aspect of adaptive management. In this instance, the interactions of interest are the partnerships and collaboration on research and investigation on estimation of and spatial distribution of holopelagic *Sargassum* spp., linkages between physical factors and bloom events, and physical and biogeochemical and biological drivers. Interaction is necessary for planning, negotiating, implementing, evaluating and adapting management strategies. Examining interactions by mapping the relationships among actors shows how those involved are connected. Both formal and informal networks require attention. Network insight helps to inform interventions and the institutional arrangements to build on strengths and address weaknesses.