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Faculty of Environmental and Life Sciences

School of Geography and Environmental Science

A Spatial and Temporal Assessment of Sargassum Blooms in the Tropical Atlantic

by

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Thesis for the degree of Doctor of Philosophy

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Abstract

Faculty of Environmental and Life Sciences

Geography and Environmental Science

Doctor of Philosophy

by

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Since 2011, sargassum algae blooms have been occurring in the Tropical Atlantic basin from North and Central America, through the Caribbean Sea and across to the Gulf of Guinea. The blooms are aggregated and transported by wind and currents, and deposited on coastlines across the region. They pose threats to ocean and coastal biodiversity, human health, coastal stability, industries such as tourism and aquaculture, and ultimately the livelihoods of coastal communities. Since the emergence of this new social-environmental challenge, there has been an increase in research and knowledge of sargassum. Most research has focused mainly on the Gulf of Mexico, the Caribbean and North Atlantic Ocean and significant regional knowledge gaps exist. For example, in the Gulf of Guinea and Central America, there is much we do not know about sargassum. More specifically, in the under-researched geographic areas further data are needed on beaching events, different species and morphotypes, chemical composition, volume of sargassum, and the drivers of the blooms across the basin. This thesis aims to address these knowledge gaps by developing methods and creating datasets to improve the spatial and temporal understanding of the distribution of sargassum blooms across the Tropical Atlantic. Research questions asked are: How can we improve monitoring and detection of sargassum events at multiple scales?; How can we better detect and track sargassum pathways across the Tropical Atlantic?; What opportunities exist to improve beach detection and monitoring in cloud covered regions?

Data are collected from: field campaigns in Ghana and Barbados, time-series analysis of sargassum in West Africa, and GPS tracking of floating sargassum blooms. Results show that i) there is a distinct seasonal pattern to sargassum blooms in the Eastern Tropical Atlantic and a co-variance of the occurrence of blooms with atmospheric and oceanic events; ii) there are alternative methods of detecting blooms which overcome spatial and temporal limitations of remote sensing, including cloud cover; iii) decomposition stages of beached sargassum have distinct spectral profiles which has value for supporting monitoring and improving valorisation potential; and iv) there is a need for more freely available high resolution imagery to monitor smaller blooms in open-ocean areas. It is expected that this information will contribute to effective management of sargassum blooms through tracking floating mat movements and aggregations, providing information for forecasting sargassum events and development of a risk management strategy, and supporting opportunities to valorise sargassum.

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Research Thesis: Declaration of Authorship

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I declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

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Definitions and Abbreviations

Term / Abbreviation	**Definition**
ABD	absorption band depth
AFAI	Alternative Floating Algae Index
AMOC	Atlantic Meridional Overturning Circulation
ANOVA	analysis of variance statistical test
ANSTFSP	Aquatic Nuisance Species Task Force Strategic Plan for 2020 – 2025
AOD	Aerosol Optical Depth
ASF	Alaska Satellite Facility
Cross-scale analysis	Data analysis across multiple temporal and spatial resolutions (see chapter 1 section 1.6.2 for further description).
DAAC	Distributed Active Archive Centres
ETA	Eastern Tropical Atlantic
FAI	Floating Algae Index
Fresh gold sargassum	Following Small et al. (2022) fresh gold refers to sargassum recently deposited on the beach.
GBINSS	The Great Britain Invasive Non-native Species Strategy 2023-2030
GNI	Gross National Income
GODAS	Global Ocean Data Assimilation System
GPS	Global Positioning System
GRDH	Ground Range Detected High-resolution
Hazard	The probability and potential severity of a damaging event e.g. the hazard of a sargassum event (see chapter 1, section 1.1 for further description).

Interdisciplinary	Including elements from Menken et al. (2016), Aboelela et al. (2007), Rosenfeld (1992), Klein and Newell (1997), and Kinnebrew et al. (2021), interdiscplinary research applied principles, methods, data and ideas from across multiple disciplines.
IPCC	Intergovernmental Panel for Climate Change
IW	Interferometric Wide
KD	Diffuse attenuation coefficient
MCI	Maximum Chlorophyll Index
MERIS	Medium Resolution Imaging Spectrometer
MODIS	Moderate Resolution Imaging Spectroradiometer, Terra (T) and Aqua (A)
MSI	MultiSpectral Instrument, Sentinel-2 instrument
MVS	Multi-view Stereo
NDVI	Normalized Different Vegetation Index
NERC	Natural Environment Research Council
NFAI	Normalized Fluorescence Line Height
NFLH	Normalised Floating Algae Index
NGRDI	normalised green-red difference index
NIR	near-infrared
NOAA	National Oceanic and Atmospheric Administration
OLCI	Ocean and Land Colour Instrument, Sentinel-3 Instrument
Old gold sargassum	Following Small et al. (2022) old gold refers to sargassum deposited on the beach that has begun decomposing.
Pelagic sargassum	Refers to the two holopelagic species of sargassum (S. fluitans and S. natans) and their morphotypes.
PSL	Physical Sciences Laboratory

Resilience	A contested term, generally encompassing the capacity which an entity can cope with hazards, as well as adapt in response to changing conditions (e.g. climate change). In this thesis the definition by Masselink and Lazarus (2019) is used where resilience is the capacity of both natural and socio-economic systems to cope with disturbances through adaptation whilst maintaining their essential functions.
RGB	red green blue (camera bands)
RMSE	root-mean-square error
ROI	Region of interest
SAR	Synthetic Aperture Radar
Sargassum bloom or ‘mat’ or ‘raft’ (used interchangeably)	Sargassum that is aggregated and floating on the ocean surface, usually composed of a mix of species/morphotypes (Ody et al., 2019).
Sargassum event	A Sargassum 'event' is a continuous bloom of any sargassum in open oceans, or, an aggregation of landed sargassum with the potential to disrupt local social, economic or ecosystem functioning, or to impact human health. An event can affect one country, or several contiguous countries (Fidai et al., 2020).
SCP	Semi-Automatic Classification Plugin (QGIS software plugin)
SfM	Structure from Motion
SOI	Southern Oscillation Index
TCR	target-to-clutter ratios
Tropical Atlantic	A marine ecoregion including The Gulf of Mexico, Central America, the Caribbean, South America’s Atlantic coast to Cape Frio in Brazil in the west, to the east, the Tropical Atlantic extends to include the African coast from Mauritania to Angola.
UAS	Uncrewed Aerial System
VIIRS	Visible Infrared Imager Radiometer Suite

Vulnerability	Following Wisner et al. (2004), Adger (2006) and others, vulnerability is the susceptibility to suffer harm (damage, loss) from - in this case- sargassum events, and their ability to recover from the impacts.

Chapter 1 Introduction

1.1 Introduction to Thesis

There are approximately 66 countries and territories which have a coastline in the Tropical Atlantic Basin, which as a proportion of global countries is close to one third. In the Western Tropical Atlantic, the marine ecoregion includes The Gulf of Mexico, Central America, the Caribbean, South America's Atlantic coast to Cape Frio in Brazil. To the East, the Tropical Atlantic extends to include the African coast from Mauritania to Angola. The Tropical Atlantic Basin is home to a variety of countries including small island developing states, high-income, post-conflict countries, and low-income countries. Coasts are the most threatened region of the world by natural hazards, from winds and storm surges to increased tectonic activity, with further threats posed by climate change such as sea level rise (Kron, 2013). But despite these threats, it is also one of the most desirable places to live for trade, industry, and businesses meaning that they are often highly valued and densely populated, making hazards increasingly significant (Berz et al., 2001; Kron, 2013). This is compounded by an increasing population settling in coastal areas which would have previously been avoided, therefore more people are exposed to coastal hazards than ever before (Berz et al., 2001). Neumann et al. (2015) showed that coastal population is expected to double by 2060, which highlights the necessity for effective management of coastal hazards and their associated risks. Since 2011, coastal areas in the Tropical Atlantic region have been faced with a new emergent risk: pelagic algae blooms; which have vast environmental and socio-economic impacts and threatens the livelihoods of those living at the coast.

General hazard risk management is built on the premise that reducing vulnerability reduces the risks associated with the hazard (Adger et al., 2005; Cutter, 1996; Paton and Johnston, 2001; Naqvi and Monasterolo, 2021). Vulnerability is the human susceptibility to suffer harm, damage and loss from environmental and social change, and there is a lack of capacity to adapt and therefore a lack of resilience (Wisner et al., 2004; Adger 2006; Folke, 2006; Eakin and Luers, 2006). To reduce the impacts and risks associated with a hazard, strategies to reduce vulnerability and increase capacity to cope are needed (UNDRR, 2015; UNDRR, 2022; Nohrstedt et al., 2021). There is an outdated view that disaster risk reduction refers exclusively to natural disasters that are exogenous and unforeseen irregular extreme shock events to normally functioning societies, rather than being endogenous indicators of unsustainable development and poorly adapted societies (Lavell and Maskrey 2014). However, disaster risk reduction can also apply to recurrent events with small to medium scale impacts (Ventin et al., 2015). Whilst pelagic algae blooms are not as destructive and shocking as some large natural disasters, their impacts share similar characteristics, and management approaches to reduce vulnerability to them are transferable. Sargassum events fall into this description, and can be considered an 'extensive risk', these are described by Twigg (2015) as a lower-intensity, recurrent, small-scale event with significant impacts. Disasters (or extensive risks in this case) are a threat to sustainable development with a diverse set of impacts including destruction of assets, social and economic disruption, damage to the environment, loss of service, injury and illness, and they are a direct result of exposure of people and assets to the hazard, their vulnerability and their capacity to reduce or cope with the potential harm (Twigg, 2015).

Research to reduce coastal communities' vulnerability to emerging environmental hazards largely falls within two branches: climate change adaptation and disaster risk reduction. Climate change adaptation and disaster risk reduction approaches were initially considered to be siloed and spatially and temporally distinct. For example, Thomalla et al. (2006) identified that the climate change adaptation approach includes risk management through strong scientific interdisciplinary basis, with a long-term, top-down, global scale perspective; and the disaster risk reduction approach includes risk management through engineering and natural science, technological solutions, and shifts from response and recovery to awareness and preparedness, and has a short-term local community basis. They suggested that due to working in isolation both branches failed to reduce vulnerability as evidenced by economic losses from disasters increasing substantially since the 1970s. More recent, and more joined up work on climate adaptation and disaster risk reduction shows overlaps and integration between the two research areas. Researchers now call for more clearly elucidated links between climate, poverty, risks and loss (Pelling and Garschagen, 2019). At the international scale, the Sendai Framework for Disaster Risk Reduction outlines priorities and targets for action to prevent and reduce existing vulnerability and risks which include understanding disaster risk, strengthening governance and management, climate change adaptation, investing in disaster reduction for resilience, and enhancing preparedness for effective response (UNDRR, 2015).

As an emergent risk, sargassum blooms can be challenging to approach as there are a variety of uncertainties, particularly under climate change. The Intergovernmental Panel for Climate Change

(IPCC) Sixth Assessment Report (2022), note that to develop climate resilient institutions that are flexible and responsive to emergent risks technical resources, capacity, and information are needed. The concept of resilience has become a core element of climate change adaptation; in a coastal context, Masselink and Lazarus (2019) explain that resilience is the capacity of both natural and socio-economic systems to cope with disturbances through adaptation whilst maintaining their essential functions. Pescaroli and Alexander (2018) show how compound, interconnected, interacting and cascading risks can be used to support disaster risk reduction, and support system-wide resilience. They define the types of risks, which are summarised here:

- Compound risks are the concurrence of natural events which can be correlated to patterns, they focus of the hazard component of disaster risk.
- Interacting risk focus on where the hazard interacts with vulnerability to create disaster risk.
- Interconnected risk includes interactions between human, environment and technological systems.
- Cascading risks are a pathway of environmental triggers which impact socio-technological systems to create vulnerability loops which results in disaster escalation, interconnected risk is a pre-condition for this, and compound risks can impact its magnitude. They focus on the vulnerability component of risk.

Sargassum blooms are an emerging, transboundary and extensive risk, and they are linked to cascading, interconnected, interacting and compound risks. Sargassum events can be hazardous with environmental, economic and social impacts, which affect the livelihoods of coastal communities (Chavez et al., 2020). Many countries have declared national emergencies in response to sargassum events, reflecting the impact they have on coastal communities (van der Plank et al., 2022; UNEP-CEP, 2018). Whilst a nascent system of management has emerged and progress towards introducing sargassum policy has been made, communities remain vulnerable to sargassum events and their impacts as there are gaps in our knowledge about this hazard, its associated risks, and how to manage it (van der Plank et al., 2022).

To reduce the damage and long-term impacts of emergent risks, such as sargassum, research to inform understanding, and early risk mitigation are essential, although there is currently a lack of risk management policy for sargassum in the Eastern Tropical Atlantic (Dominguez et al., 2023). Extant invasive and nuisance species management policies offer insight into how to develop policy and management strategies for sargassum. The most useful risk management strategies for managing invasive flora and fauna in the UK is the Great Britain Invasive Non-native Species Strategy 2023-2030 (GBINSS). GBINSS lists multiple successes including eradicating invasive species, development of biocontrol agents for plants, and implementing new legal frameworks for management. In the US the parallel policy is the Aquatic Nuisance Species Task Force Strategic Plan for 2020 – 2025 (ANSTFSP). This was developed to manage the risks associated with nonindigenous aquatic species. GBINSS and ANSTFSP are similarly structured. The goals of ANSTFSP are coordination (between agencies, government and the private sector); prevention (stopping harmful introductions before they occur); control and restoration (management actions to minimise impacts); early detection and rapid response; research (information to quantify and clarify, supporting all facets of the plan); and outreach and education (addressing public understanding). GBINSS goals are: prevention (reduce non-native species); surveillance, early detection, and monitoring; management (eradicate, control or contain); prioritisation and risk analysis (focus efforts where the risk and likelihood is greatest); evidence (research); awareness raising (promote awareness and behaviour change in general public); and coordination (within government and between government and non-government actors).

A key element from these two risk management strategies is the importance of improved early detection and monitoring as well as research and evidence to support adaptations that reduce communities' vulnerability. In the case of sargassum this translates into the need for an understanding of the variability (both seasonal and annual), regional interconnectivity including the drivers and transport mechanisms, as well as better monitoring to prepare for the hazard. This knowledge could form the genesis of a sargassum risk management strategy for the Eastern Tropical Atlantic region.

This thesis unifies the branches of climate change adaptation and disaster risk reduction by taking an interdisciplinary research approach which utilises technological solutions to monitor and detect sargassum at different scales This work supports the targets of the Sendai Framework as the findings enable better understanding of the sargassum hazard. This has value for supporting local and regional sargassum management priorities, particularly in West Africa. It works towards revealing the potential opportunities from re-using sargassum to support affected communities. This first chapter provides a background to sargassum algal blooms, gaps in the knowledge that this thesis addresses, and outlines the aims and objectives as well as describes the overarching structure of the thesis.

1.2 Historical Distribution of Pelagic Sargassum

There are over 300 species of sargassum in global seas and oceans, it is a brown seaweed which usually grows in benthic or intertidal environments, they can become detached and appear pelagic (Hardouin et al., 2014). But, there are only two known holopelagic species: S. *natans* and S. *fluitans* which were first observed in the Sargasso Sea, a region in the North Atlantic Ocean, in the 15th Century (Parr, 1939; Fine 1970; Lapointe 1986; Dickson, 1894; Wang et al., 2019). Historically, the Sargasso Sea has been associated with ghost stories and missing ships who were caught in the mats of sargassum; Portuguese sailors called it ‘salgazo’ as it reminded them of a small grape plant from home, and from this the name ‘sargassum’ was derived (Dickson, 1894; Dixon, 1925; Lamb, 2018; Webster and Linton, 2013). Holopelagic sargassum forms free floating mats which are aggregated and transported by wind and currents and deposited on beaches, reports of this occurring have been recorded in publications as far back as 1917 in Bermuda, and in print media in Texas in 1866 (Collins, 1917; Webster and Linton, 2013). The first wider study was undertaken by Gower and King (2008) using the Medium Resolution Imaging Spectrometer (MERIS) satellite which provided evidence of pelagic sargassum blooms in both the Sargasso Sea and Gulf of Mexico. In 2011, pelagic sargassum blooms were observed in abundance across the Tropical Atlantic, Gower et al. (2013) found that in this unusual year sargassum could be observed from Northeast Brazil and the Caribbean Sea across to West Africa. No direct link of these anomalous blooms were linked to the Sargasso Sea in numerical backtracking models, but their local impacts were recorded particularly on fishing and tourism industries and the marine ecosystem (Franks et al., 2012). However, Johns et al. (2020) have since shown that sargassum was exported from the Sargasso Sea to the Tropical Atlantic in 2009-2010 due to a North Atlantic Oscillation anomaly event. Since 2011, it has been observed that sargassum continues to persist in the Tropical Atlantic, and what was thought to be an anomaly has become the norm, with the establishment of the phenomenon of the ‘Great Atlantic Sargassum Belt’ which is seen annually from Gulf of Mexico and Caribbean Sea across to West Africa with a seasonal peak in July (Wang et al. 2019).

1.3 Impacts of Pelagic Sargassum

Floating and beached sargassum present a hazard to coastal communities as they have a variety of socio-economic impacts. The aquaculture and fishing industries are a particularly affected interconnecting risk, floating sargassum gets tangled in lines and nets, rudders and propellors cause over-heating, which creates vulnerabilities for fishers' as it impacts their revenue through increasing maintenance costs as they need to repair or replace equipment more frequently (Doyle and Franks, 2015; Ramlogan et al., 2017; Franks et al., 2012). Furthermore, beach accumulation of sargassum has reduced access to fishing grounds as fishers cannot take their boats out to sea, this is especially impactful for small-scale or subsistence fishers as it can create vulnerabilities around access to food (Solarin et al. 2014). Additionally, the increase in blooms have changed availability of fish species and age forcing fishers to adapt their fishing practices, creating further risks to income and food security (Ramlogan et al., 2017). The tourism industry is another interconnecting risk that is impacted by sargassum events as it impairs the capacity of beaches to meet recreational demand by negatively affecting the perception tourists have of a place (Defeo et al., 2021). The visual impact, odour and noise of removal is thought to have caused a decline in tourism, creating further income and health related vulnerabilities for coastal communities Bartlett and Elmer, 2021; Fraga and Robledo, 2022).

Open-ocean floating sargassum mats are an integral part of the ecosystem in the Atlantic Ocean, providing a habitat and refuge for a variety endemic species including fish and crustaceans (Sissini et al. 2017; Alleyne, 2022). As a consequence of the amount of sargassum increasing since 2011, there have been changes in marine fauna population and feeding dynamics such as changes in diet and access to prey which means it creates a hazard for ecosystem functioning (Cabanillas-Teran et al., 2019; Chavez et al., 2020). Accumulation on beaches has also been shown to impact turtle nesting and hatchlings as it reduces nesting sites, creating a risk to turtle populations and ecosystem dynamics (Franks et al., 2012). Blooms also cause hypoxic conditions and reduction in light, especially when it accumulates in near-shore waters creating a risk of mortality of a variety of seagrasses and fauna, including coral, crustaceans and fish (van Tussenbroek et al., 2017; Rodriguez-Martinez et al., 2019). Accumulation and decay of sargassum also impacts water quality making it turbid (van Tussenbroek et al., 2017). Further risks are presented to communities from beach accumulations that are decomposing, it has been shown that gasses produced from the decomposition process can pose a threat to public health, and in extreme situations cases cause hypoxic pulmonary, neurological and cardiovascular lesions, and mild exposure can cause headaches, nausea, and confusion (Resiere et al., 2019). This risk increases the vulnerability of communities through resultant impacts on labour capacity, income and quality of life.

1.4 Justification of Study

Sargassum is an emergent, extensive and transboundary risk, which demands a unique approach to management. It has been shown that reducing the complexity and defining the spatial identity of transboundary risks is essential in managing them (Lidskog et al., 2011). Despite this, existing research on pelagic sargassum has most commonly focussed on the Western Tropical Atlantic including the Gulf of Mexico (see examples: Gower and King, 2011; Webster and Linton, 2013) and the Caribbean (see examples: Van Tussenbroek et al., 2017; Schell et al., 2015; Arellano-Verdejo et al., 2019), with large-scale studies extending across to Cabo Verde or Senegal (see examples: Wang et al., 2019; Johns et al., 2020). The topic of transport pathways has been explored with a view to forecast through the use of ocean current data and models and has either been very localised, often focussing on a few islands or a shoreline (see examples: Webster and Linton, 2013; Marechal et al, 2017), or has been large-scale and again, omitting the Gulf of Guinea (see examples: Putman et al., 2018; Marsh et al., 2022). Although Ody et al. (2019) typify sargassum mats by shape, no studies have attempted to understand both transport pathways and morphology changes along the route. Existing research also largely focusses on floating open-ocean sargassum rather than beaching events (Fidai et al., 2020). Despite the lack of literature, there are reports of sargassum events in West Africa, including in the Gulf of Guinea, which is an overlooked region by many large-scale studies. Four studies have emerged focussing on the Gulf of Guinea: Addico and DeGraft-Johnson (2016) and Oyesiku and Egunyomi (2014) which both sampled sargassum along the coasts of Ghana and Nigeria respectively; Adet et al. (2018) used satellite observations to monitor blooms and beach landings near-shore along the West African coast from Sierra Leone to Nigeria from 2011-2016; and in Nigeria, Solarin et al. (2014) surveyed beaches in 2011 and 2012. Nevertheless, little of the existing research on documenting long-term trends in sargassum, transport pathways, and beaching events focusses on the Eastern Tropical Atlantic.

This thesis aims to develop an interdisciplinary approach to analyse the spatial and temporal distribution of pelagic sargassum in the Eastern Tropical Atlantic, focussing on beaching events, drivers, and transport pathways.

1.5 Research Aims and Objectives

The goal of this work is to extend our knowledge of sargassum in the Eastern Tropical Atlantic by answering these questions with a focus on analysis of the spatial and temporal distribution of pelagic sargassum across the Tropical Atlantic. The research questions asked are:

i) How can we improve monitoring and detection of sargassum events at multiple scales?

ii) How can we better detect and track sargassum pathways across the Tropical Atlantic?

iii) What opportunities exist to improve beach detection and monitoring in cloud covered regions?

To address the research questions, the study objectives are:

1. [GAPS] To explore the state of current research globally and identify gaps in sargassum knowledge.
2. [VARIABILITY] To characterise the annual and seasonal variability of sargassum blooms in the Eastern Tropical Atlantic.
3. [DRIVERS] To explore the co-variance of drivers with sargassum biomass accumulation for the Eastern Tropical Atlantic.
4. [TRANSPORT] To understand the transport pathways of sargassum, their associated changes in shape, along with their growth and mortality.
5. [BEACHING] To investigate how sargassum beaching events can be monitored.
6. [PROPERTIES] To identify the biochemical and phenotypic properties of sargassum and explore the implications for valorisation opportunities.

1.6 Conceptual Frameworks

To address the research questions and meet the thesis objectives, this work employs an interdisciplinary approach to undertake a cross-scale analysis, through application of mixed methods including a systematic review of the literature; analysis of remote sensing data; time-series analysis; qualitative and correlation data analysis; field data from GPS trackers and beach surveys. The use of these concepts are justified in this section.

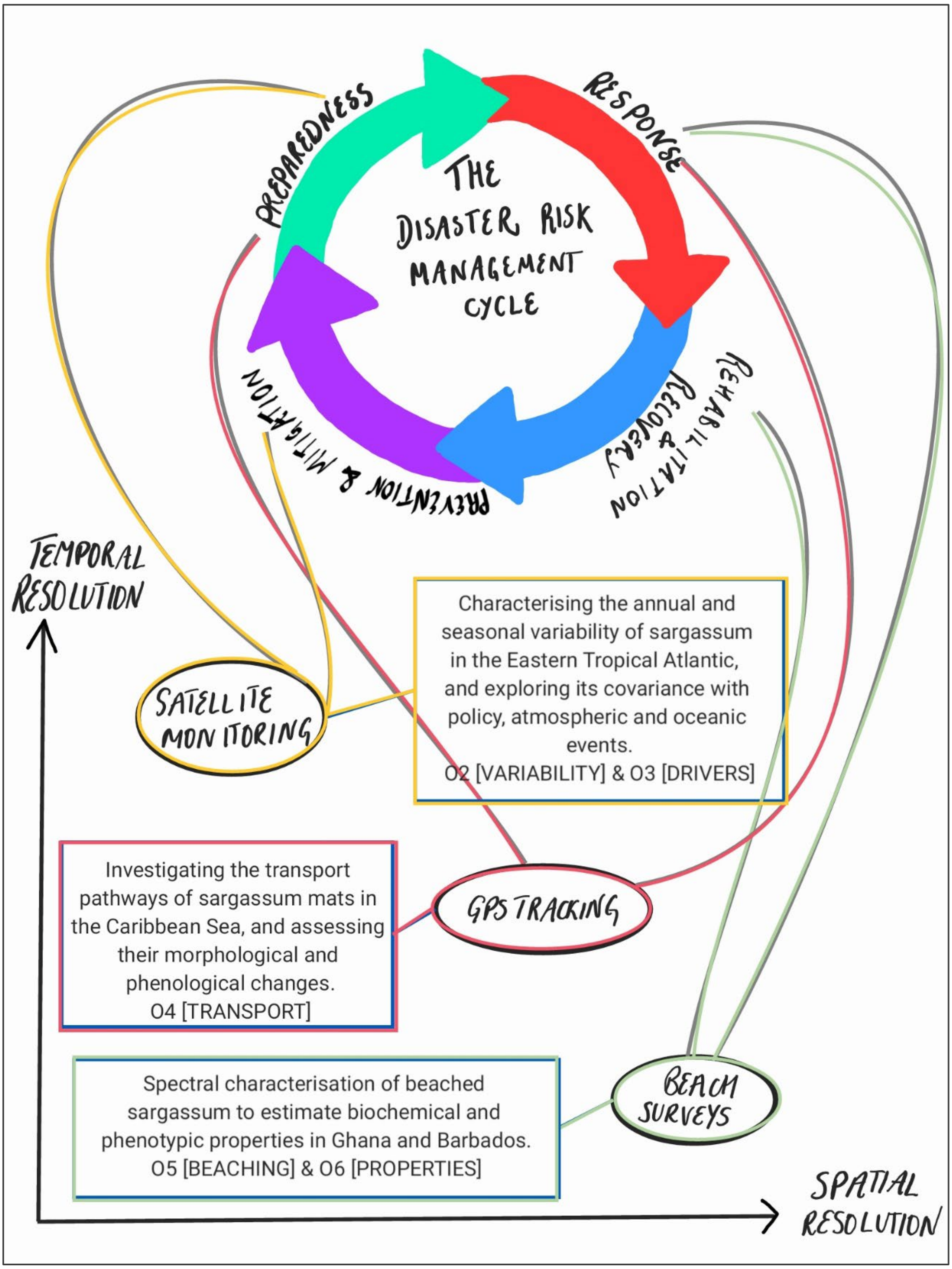
1.6.1 Study design

A variety of data types and analysis methods have been used to achieve the research objectives identified in section 1.5, reflecting the interdisciplinary nature of this thesis (summarised in table 1). The first objective [GAPS] required a review of available empirical literature documenting floating or beached sargassum globally. The second [VARIABILITY], relied on secondary remote sensing data to produce a time-series analysis. The third [DRIVERS] built on the second [VARIABILITY] data analysis and adds a variety of data from different sources which is presented in a graphical or tabular format and uses a mix of quantitative and qualitative assessment to understand co-variance of different events and policy. The fourth [TRANSPORT] and fifth [BEACHING] objectives use a combination of *in situ* data (*in situ* GPS trackers, beach ground and aerial surveys), spatial data, and remote sensing data. The sixth [PROPERTIES] uses a blend of biological and remote sensing analysis.

Table 1 Summary of data and collection/analysis methods used to address each objective.

Objective	Data	Data Collection/Analysis Methods
O1 **[GAPS]**	Empirical Literature Published between 1960 and 2019.	**Collection**: Systematic Review using search engines (Scopus, ISI Web of Knowledge (ISI WOK), Google Scholar). **Analysis**: Metadata of the literature was collated, and the findings within the publications were analysed using quantitative and descriptive analysis to answer research queries covering aspects related to sargassum identification, location, distribution, quantity, and sources.
O2 **[VARIABILITY]**	Biomass estimations spanning 2011 to 2022, covering the Eastern Tropical Atlantic region.	**Collection:** Data for wet biomass estimates for the study area collected using satellite imagery from the University of South Florida Optical Ocean Laboratory. **Analysis**: Time-series analysis using remote sensing methods to establish seasonal and annual variation of sargassum biomass.
O3 **[DRIVERS]**	North Atlantic Oscillation (monthly), Sea Surface Temperature (annual), Sea salinity (annual), Atlantic Meridional Overturning Circulation (AMOC), Southern Oscillation Index (SOI), Oil spill events, Aerosol Optical Depth (AOD), Volcanic eruption records, diffuse attenuation coefficient (KD).	**Collection:** Secondary sources of data including: National Oceanic and Atmospheric Administration (NOAA), NCEP Global Ocean Data Assimilation System (GODAS) data provided by the NOAA PSL, Giovanni NASA Earth Data. **Analysis**: Use of historical timeline and graphical methods with descriptive analysis to give a quantitative and qualitative context for exploration of co-variance of drivers with biomass time-series.
O4 **[TRANSPORT]**	GPS coordinates of bloom transport pathways. Satellite imagery for position validation and detecting morphology/phenology changes. Hindcasts of sea surface temperature, currents and wind stress.	**Collection:** Eight GPS trackers deployed *in situ* on sargassum mats, satellite imagery from sentinel-2 (from Sentinel Hub EO Browser) and synthetic aperture radar from sentinel-1 (from NERC Earth Observation Data Acquisition and Analysis Service). **Analysis**: Remote sensing and GIS-based analyses to determine pathways, travel distance and speed, morphological and phenological changes.
O5 **[BEACHING]** **&** **O6** **[PROPERTIES]**	Aerial imagery of beached sargassum, spectral profiles of beached sargassum, including of different morphotypes and decomposition.	**Collection:** field campaigns in Ghana and Barbados in 2022 to undertake beach surveys. **Analysis:** remote sensing and biological analysis to investigate spectral profiles, classify aerial imagery, and estimate biochemical composition and phenotypical properties.

The objectives are inter-linked and as such chapter 2 addresses O1 [GAPS], chapter 3 O2 [VARIABILITY] and O3 [DRIVERS], chapter 4 O4 [TRANSPORT], and chapter 5 O5 [BEACHING] and O6 [PROPERTIES]. They each detect and monitor sargassum at different scales and connect to different aspects of the disaster risk management cycle, an overview of which is illustrated in figure 1.



Characterising the annual and seasonal variability of sargassum in the Eastern Tropical Atlantic, and exploring its covariance with policy, atmospheric and oceanic events.
O2 [VARIABILITY] & O3 [DRIVERS]

Investigating the transport pathways of sargassum mats in the Caribbean Sea, and assessing their morphological and phenological changes.
O4 [TRANSPORT]

Spectral characterisation of beached sargassum to estimate biochemical and phenotypic properties in Ghana and Barbados.
O5 [BEACHING] & O6 [PROPERTIES]

Figure 1 Thesis as a graphical concept showing cross-scale analysis of chapters and objectives in the context of the disaster risk management cycle.

1.6.2 Remote sensing and cross-scale analysis

Remote sensing methods are used across all three analysis chapters, including spaceborne, airborne and ground-based measurements. Remote sensing has been given many definitions, but they all have in common the concept that it is the gathering of information from a distance; it measures reflected or emitted electromagnetic energy to observe the earth’s surfaces (Campbell, 2002). It has been advantageous to use remote sensing methods during the COVID-19 pandemic as it enabled data collection and analysis despite travel restrictions. But primarily it provides a platform to explore data in both land and water environments, which is crucial for sargassum detection and monitoring. Remote sensing methods are ideal for monitoring vegetation and algal blooms specifically as beyond detecting presence for monitoring it also offers insight into plant properties such as phenological stage, biochemical composition, and structure.. An example of this is Gray et al. (2021), where the phenology and growth of Antarctic green and red snow algae blooms were monitored using cross-scale measurements from ground and space data to determine primary productivity contributions.

Remote sensing methods also provide the opportunity for measuring at different scales. In this context, ‘scale’ refers to the spatial resolution which is the capacity of an imaging system to record fine detail distinguishably, specifically, it is the ground area viewed by the sensor at a given time (Estes and Simonett 1975; Forshaw et al., 1983; Allen and Hoeskstra, 1991; Marceau and Hay 1999). Here, ‘scale’ also refers to the temporal resolution, remote sensing methods can provide the opportunity for sequential data collection, representing changes over time (Campbell, 2002). Thus, remote sensing provides the ideal platform to collect information across a variety of spatial and temporal resolutions. Cross-scale analysis have been undertaken in a variety of environmental monitoring contexts, examples include: detecting wetland dynamics (Ji et al., 2015), forest cover change (Van Den Hoek et al., 2014), mapping land degradation (Dubovyk, 2017), and detecting phenological change (Reyes-González et al., 2021). The data used in the analysis chapters in this thesis spans a variety of temporal and spatial scales, temporally ranging from hourly to one off measurements, spatially ranging from 1.2 cm to 50 km. The capacity of remote sensing to measure across a variety of scales and vegetation properties makes it the perfect tool to address the objectives in this thesis.

1.6.3 Interdisciplinary approach

Sargassum algal blooms interact with the open ocean, near-shore areas, beaches, and communities and have impacts across the blue economy, therefore, to have a holistic understanding it must be viewed from multiple angles. It is common for ecologists, biostatisticians, and remote sensors to collaborate to use interdisciplinary approaches to monitor terrestrial vegetation (Steele and Stier, 2000). However, as sargassum interacts with multiple communities and environments, an even greater degree of disciplines are drawn on in this thesis. Figure 2 shows the different disciplines which contribute principles and methods to this thesis.

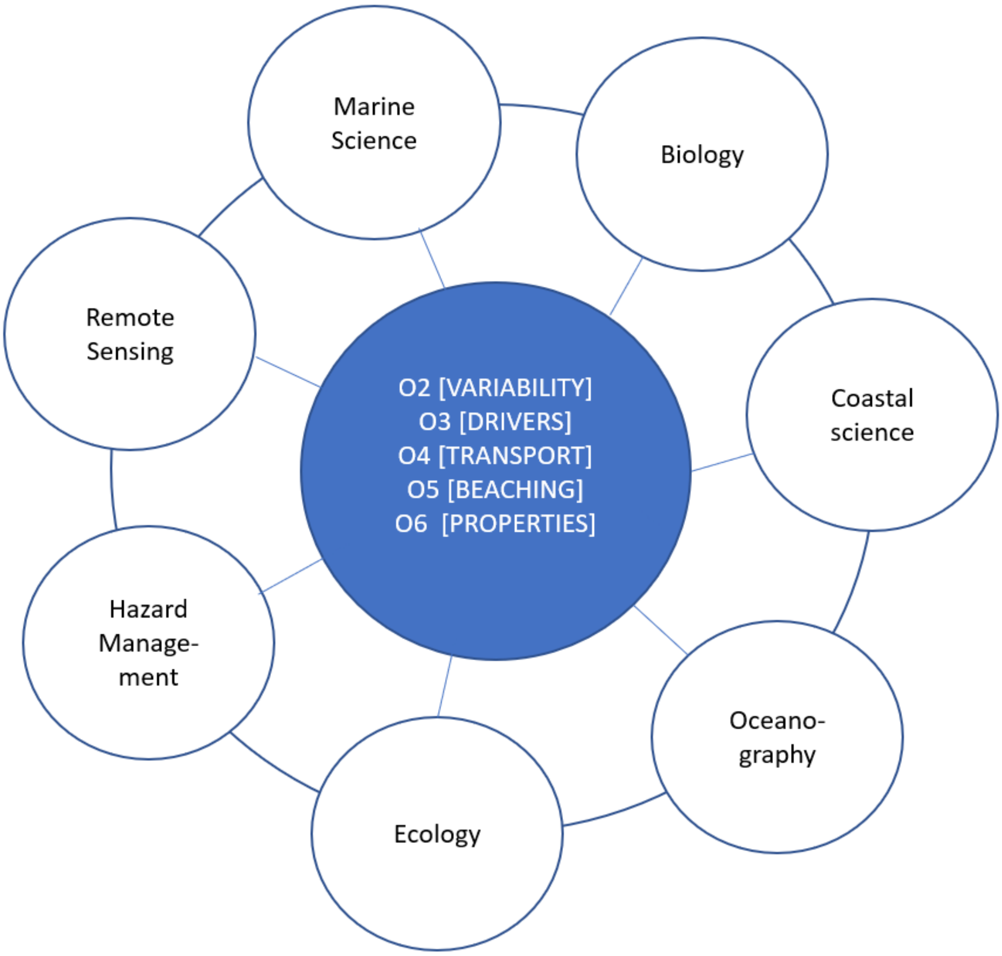


Figure 2 Illustration of disciplines which contribute principles, ideas, and methods applied in this thesis.

There are many types of interdisciplinary research approaches with differing degrees of synthesis from comparing ideas to exchanging data and methods, or going even further and integrating theories, principles, and methods (Menken et al., 2016; Aboelela et al., 2007). Rosenfeld (1992) proposed that interdisciplinary refers to working jointly but still from a discipline-specific base; Klein and Newell (1997) explain it as solving a broad or complex problem by integrating insights from many disciplinary perspectives to give a comprehensive perspective. Interdisciplinary research is critical for addressing our planet's urgent environmental challenges, Steele and Stier (2000) showed that environmental science articles that drew information from diverse journals were more highly recognised, proving that using interdisciplinary approaches have higher and more positive impact.

An interdisciplinary approach gives way to utilising mixed methods, for tackling complex environmental problems bridges of knowledge are needed; for example, combining quantitative spatial data with qualitative data can contextualise or contribute a narrative to observed patterns (Kinnebrew et al., 2021). Interdisciplinary and mixed methods allow research to become socially effective through facilitating policy and social interventions to address socioenvironmental dynamics (Palmer, 2012; Bennett et al., 2017).

Where sargassum algal bloom impacts span a variety of environments, countries and communities, it is essential for this thesis to adopt a greater degree of interdisciplinary research by applying principles, methods, data and ideas from across multiple disciplines. This approach allows the research questions to be addressed and provides a platform for sargassum research to be brought together to increase its potential for contributing to effective management and policy implementation. The use of interdisciplinary and mixed methods approaches brings together numbers and narrative which enables us to answer more questions more robustly (Johnson and Onwuegbuzie, 2004; Creswell and Creswell, 2018). The quantitative elements of this work provides precise and numerical data from a combination of *in situ*, remote sensing and other sources. The qualitative strand of this study collects, manages and analyses the data by using thematic and descriptive analysis to form a narrative. The combination allows exploratory quantitative conclusions to be made.

1.6.4 Systematic review

Systematic reviews are a widely used transferable and replicable method to synthesise and analyse key themes and ideas from existing research on a specific topic (Berrang-Ford et al., 2015). Systematic reviews are more transparent, accountable and reproducible than traditional literature reviews (Porter et al., 2014) and have been commonly used in public health and medicine (examples include: Higgins and Green, 2011; Moher et al., 2009; Morton et al., 2011) before a shift to ecology in the 2000s (see Hillebrand and Gurevitch 2016), and then to climate adaptation in the later 2010s (see: Berrang-Ford et al., 2011; Ford et al., 2011; Lorenz et al., 2014). This method has been used in this thesis to document floating and beaching records of sargassum globally between 1960 and 2019 in chapter 2 (O1 [GAPS]). This approach aims to find all publications that contain data that answer a specific research question. Explicitly stated key terms (and synonyms) are searched within a set of inclusion/exclusion criteria (e.g. published in English, in peer reviewed journals). The resulting publications are collated, along with their metadata. The series of questions is then applied to the publications to analyse them and provide a descriptive and quantitative assessment of existing research which highlights knowledge gaps. This is a useful method for this topic as existing literature has not yet been collated, and it provided a foundation to direct the following chapters.

1.7 Thesis Structure

The structure of the remainder of this thesis is as follows:

Chapter 2 delivers objective 1 [GAPS] by investigating the state of research on sargassum blooms globally to ascertain research and knowledge gaps through a systematic review approach, proposes a definition of ‘sargassum event’ and is used to influence the direction of the following chapters.

Chapter 3 delivers objectives 2 [VARIABILITY] and 3 [DRIVERS] by characterising the annual and seasonal variability of sargassum blooms in the Eastern Tropical Atlantic and explores the potential drivers.

Chapter 4 delivers objective 4 [TRANSPORT] by providing a novel method for tracking sargassum pathways and monitoring using remote sensing methods to overcome limitations of cloud cover in the Caribbean Sea.

Chapter 5 delivers objectives 5 [BEACHING] and 6 [PROPERTIES] by presenting an innovative method for monitoring beach landings of sargassum and understanding their biochemical and phenotypic properties from spectral measurements.

Chapter 6 summarises the work presented and reflects on the thesis aims, objectives, methods and results. Suggestions are made for future research, policy guidance is provided, and key messages are highlighted.

1.8 Concluding Remarks to Chapter 1

This chapter introduced the problems addressed in this thesis and briefly outlined the impacts of sargassum algal blooms in the Tropical Atlantic. The chapter summarised the existing literature and justified the aims and objectives for this thesis. Chapter 2 addresses the first aim and provides a deeper investigation into existing literature and research gaps through a systematic review approach.

Preamble to Chapter 2

In this chapter, objective 1 [GAPS] is addressed through using the systematic review method. It collates empirical published literature from 1960-2020 relating to floating and beached records of sargassum. It provides a global context for sargassum and highlights the research gaps which shape the direction of the rest of this thesis.

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Chapter 2 A systematic review of floating and beach landing records of sargassum beyond the Sargasso Sea

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Abstract

Sargassum algal blooms on ocean surfaces and landings of huge sargassum mats on beaches is an emerging global environmental challenge with wide socio-economic and environmental implications. Literature on sargassum growth cycles, travel patterns, species and morphotypes, and quantified impacts have tended to focus on a geographic region, or a specific event. Few, if any, publications document long term continuous monitoring of sargassum blooms in large areas such as the Pacific, or the tropical Atlantic. To address this gap, this paper systematically reviews the global evidence of sargassum bloom monitoring beyond the Sargasso Sea, and identifies gaps in the evidence base of floating and landing influxes. This systematic review uses combinations of two key terms relating to sargassum and monitoring, and utilises the resources in ISI Web of Knowledge, Scopus and Google Scholar. The analysis moves us past a classic literature review, and produces an unbiased assessment of empirical research on sargassum monitoring from 1960 to 2019. We find a significant research focus on open-ocean blooms and floating mats whereas research on beach landings and their associated impacts is comparatively limited. Research is focused within specific countries or water bodies (notably, the Gulf of Mexico, the Caribbean and North Atlantic Ocean) and tends not to comprehensively assess neighbouring or regional shorelines, for example, West Africa and Central America. There was a lack of consistency in the application of methods for quantifying sargassum biomass volume (including dry/wet weight, unit of measurement, and spatial extent of calculations).

Further, in many publications sargassum species identification was omitted. Given current attempts to understand the drivers and impacts of the exponential growth in sargassum in some parts of the world, a consistent and replicable research approach to monitoring sargassum could support creation of a sargassum evidence database. To move this agenda forwards, we propose a definition for a sargassum 'event': a continuous bloom of any sargassum in open oceans, or, an aggregation of landed sargassum, with the potential to disrupt social, economic or ecosystem functioning, or to impact human health. This review highlights the importance of standardising sargassum monitoring methods to facilitate improved documentation of temporal and spatial patterns of sargassum blooms and beach landings.

2.1 Introduction

Pelagic sargassum seaweed was first reported in the Sargasso Sea in the 15th Century and has since been documented in this area (Wang et al., 2019; Lapointe, 1986; Fine, 1970). In recent years, research has described significant pelagic sargassum seaweed blooms (free-floating brown seaweeds) across water bodies and beach landings globally, presenting a new environmental challenge (Langin, 2018). Sargassum blooming events in the Atlantic are thought to be initiated and influenced by a combination of factors including: nutrient discharge from the Amazon River, changes in ocean upwelling, higher sea surface temperatures and ocean pattern changes, such as an unusually strong North Atlantic Oscillation patterns, Atlantic Multidecadal Oscillation and El Niño-Southern Oscillation events (Wang et al., 2019; Sissini et al., 2017; Oviatt et al., 2019; Johns et al., 2020; Sanchez-Rubio et al., 2018). In East Asia, blooms are thought to be caused when sargassum is detached from beds due to strong waves and currents (Komatsu et al., 2014). Some publications have assessed annual or seasonal cycles and transport patterns of sargassum in the Atlantic Ocean and indicated potential origin sources of the blooms (examples include Wang and Hu, 2016; Gower and King, 2011; Putman et al., 2018; Brooks et al., 2018; Sanchez-Rubio et al., 2018). However, there is no comprehensive study assessing the spatial distribution of sargassum bloom events.

Since 2011, sargassum blooms appear to have increased in frequency and magnitude, notably in the tropical Atlantic and the Caribbean region (Wang and Hu, 2017). In 2018, Wang et al. (2019)

estimated there was over 20 million metric tons of sargassum across the Tropical Atlantic in the summer months.

The socio-economic impacts of sargassum blooms and beach landings are notable on the aquaculture and tourist industries; for example, sargassum clogs fishing gear and limits fishing ground, resulting in a reduction in revenue and income and an increase in maintenance costs (Solarin et al., 2014; Ramlogan et al., 2017). Xing et al. (2017) estimated that, in China, seaweed damage cost the aquaculture industry 73 million USD. Additionally, tourism has decreased due to the visual impact and odour of sargassum (Chávez et al., 2020). There are claims that decomposition of sargassum releases toxic gases and can cause potentially fatal health problems in humans (ANSES, 2017; Resiere et al., 2018). Environmental impacts of sargassum blooms have also been observed; for example, turtles looking to nest and neonate hatchlings accessing the sea can be hindered by sargassum beach landings (Maurer et al., 2015). Additionally, surface blooms restrict light penetration through the water column which affects benthic communities (McGlathery, 2001). Despite the negative impacts on communities, sargassum influxes also present opportunities for economic benefit as it has a variety of potential uses including for biofuel energy, soil fertiliser and animal feed, construction blocks, bioplastics and pharmaceutical products (Thompson et al., 2020; Milledge et al., 2016; Chávez et al., 2020).

Large sargassum influxes are generating high levels of concern among policy makers due to their impacts on economies, health, and society. Internationally, the United Nations Environmental Programme (UNEP) has created a Working Group on sargassum within the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) to identify key sargassum challenges and responses. Regionally, conventions have been developed to acknowledge the issue and highlight the need for solutions; in the Tropical Atlantic this can be seen within the UN's Abidjan and Cartagena Conventions (UNEP, 2018). However, critical information that could help policy makers and communities cope better with sargassum is missing. For example, there is a lack of data on: the drivers of sargassum – specifically input sources for specific regions; the temporal and spatial spread of significant sargassum bloom events; the quantity of sargassum in oceans and landing on beaches; and the distribution of species and morphotypes of sargassum within bloom events (which can influence re-use opportunities).

This paper aims to contribute to our understanding of the spatial and temporal distribution of Sargassum by exploring the spectrum and prevalence of use of methods employed to monitor blooms and beach landings. Methods to document sargassum are categorised herein as either remote sensing-based or *in situ*. Remote sensing methods include applying algorithms to identify sargassum blooms in airborne and spaceborne imagery, largely focusing on surface blooms in open ocean areas. *In situ* methods encompass site visits, often by boat, to survey or take samples of sargassum blooms or deposits. Understanding which methods are being used, how effective they are, where and how they are considered, can help support the development of higher quality monitoring globally.

The paper is structured as follows: Section 2 introduces the systematic review method – a methodology designed to reduce the potential for bias in a traditional literature review. Results are presented in section 3, focussed around the key questions asked in the systematic review, notably: Is the research related to floating or landing events, and if so where did it occur (beach, near-shore or open-ocean)?; What is the spatial extent of sargassum research? Does the literature indicate a source of sargassum?; What was the temporal scale of analysis?; Which species of sargassum were identified?; What data has been used to document the occurrence of sargassum blooms and beach landings? What was the volume of sargassum (if calculated)? The key findings are discussed in section 4, around the main themes found in the systematic review. Section 5 concludes the paper, drawing out remaining research gaps.

2.2 Method

Systematic literature reviews are an important method for synthesising medical evidence (Bastian et al., 2010) but are increasingly used in relation to analysis of environmental change (Berrang-Ford et al., 2015). The systematic review method utilises search engines to identify all academic literature relating to a specific topic (Moher et al., 2016). The systematic review method offers a robust methodology to identify and analyse empirical published evidence, however, it has limitations. Some publications will be omitted due to: the way in which the search engines index their results (see Beel and Gipp, 2010); because the journals appear only in print form and not online; or because some search engines, e.g., ISI WOK, quality controls their collections and only includes long-established journals. Nonetheless, it remains a highly used and robust research tool (Moher et al., 2016).

For this paper, the systematic review method was used to identify all empirical research on sargassum monitoring from 1960 to 2019. Multiple systematic review researchers recommend using trusted high-quality academic data bases, such as Scopus, or ISI Web of Knowledge (ISI WOK), see (Webb et al., 2015). For example, Berrang-Ford et al. (2011) justify the use of ISI WOK as it is powerful and comprehensive; Falagas et al. (2008) use Scopus as it offers a wider journal range. Our search was supplemented with Google Scholar. The search was undertaken using all combinations of synonyms for 'sargassum' and 'monitoring' (see Supplementary materials for details). A total of 106,571 results were returned from all three search engines and a reference manager was used to organise the results. A two-step filtering framework was applied to publications. The first step was to read the abstracts and titles of all publications to determine if they satisfied the inclusion criteria, as well as to remove duplicate results. A total of 283 publications were then taken forward to the second filtering step, which involved reading the papers in full to determine whether they still satisfied the inclusion criteria. Reasons for exclusion were: non-empirical research; a focus only on the Sargasso Sea; or, a focus on benthic species of sargassum (see Supplementary Material for details). Once all the papers had been identified, the metadata of the literature was collated, and the findings within the publications were analysed to answer seven research queries covering aspects related to sargassum identification, location, distribution, quantity and sources:

1. Is the research related to floating or landing events, and if so where did it occur (beach, near-shore or open-ocean)?
2. What is the spatial extent of sargassum research?
3. Does the literature indicate a source of sargassum?
4. What was the temporal scale of analysis?
5. Which species of sargassum were identified?
6. What data has been used to document the occurrence of sargassum blooms and beach landings?
7. What was the volume of sargassum (if calculated)?

Finally, a paper quality review was undertaken by rating each publication on a scale of 1-5 based on clarity, justification and replicability of methods, presentation of results and relevance of themes to the research queries (based on criteria adapted from Porter et al., 2014). The aim of performing the quality review was to understand any quality patterns within publications documenting sargassum floating or landing events. The final dataset contains 76 publications spanning 60 years; for ease of reading, the empirical publications are numbered in square brackets [1] –[76] and are provided in the annex.

2.3 Results

The number of publications documenting sargassum has grown in recent years; of the 65 publications in the past decade, 29 (45%) were published in 2018 and 2019 (figure 1). Despite the boom in publications in recent years, there remain several identifiable knowledge gaps where research is limited.

2.3.1 Floating and landing publications

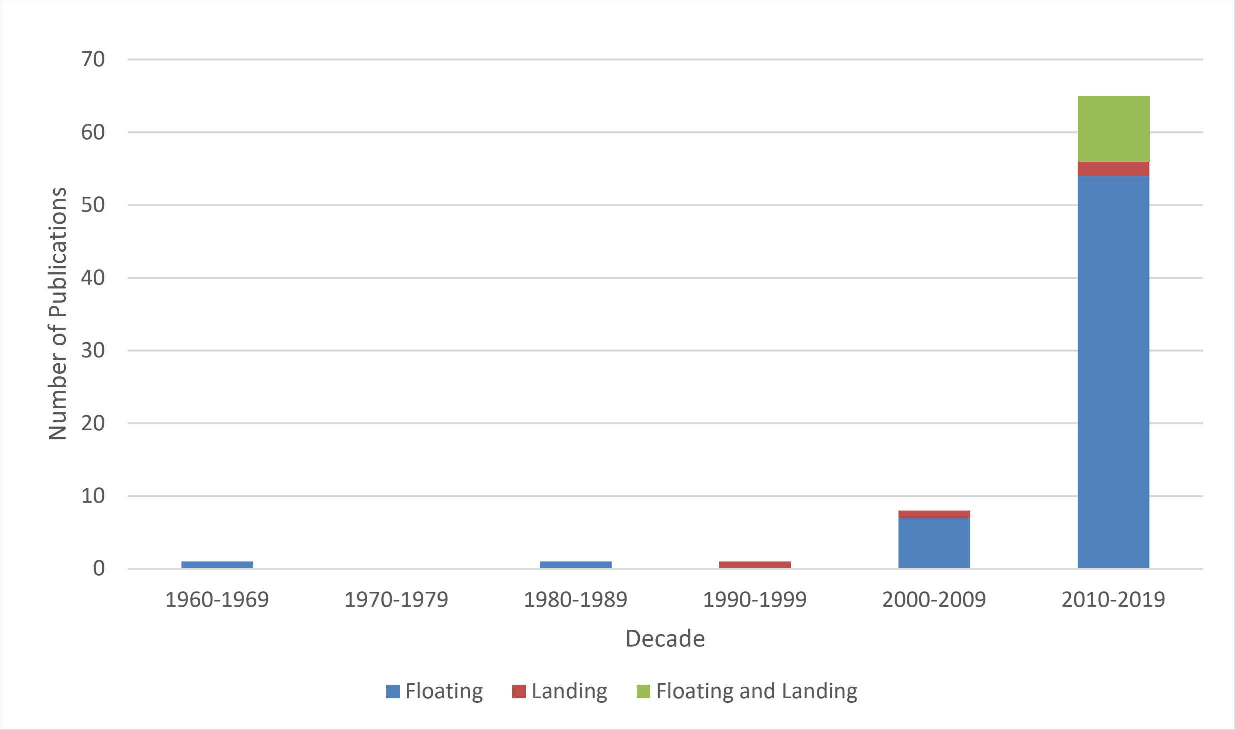

Figure 1 Publications by decade and the type of Sargassum documented. Publications on floating and landing sargassum events were identified by the location of evidence of sargassum indicated. Floating includes studies which collected sargassum data from the open ocean and near-shore environments. Landing includes studies which collected Sargassum evidence from beaches only.

Sargassum is reported to have a more significant impact on the coast and near-shore and on the communities whose livelihoods depend on access to the coast (Louime et al., 2017). Yet only 5% of publications focussed only on landing sargassum; a significant proportion focussed on floating sargassum (83%), and more recently a combined analysis of both. Only four publications undertook work on landed sargassum and these were based in Brazil (Atalaia beach, north-eastern Amazonian coast), Germany (island of Heligoland), San Andres Island (Caribbean Sea) and beaches of the Mombasa Marine National Park and Reserve, Kenya. Publications that encompassed both floating and landing sargassum (12%) include data from Nigeria [2], Ghana [1], Atlantic Ocean or specific countries in the Western Atlantic [23,24,66,14,4,3] and the East China Sea [35]. Surprising gaps in sargassum landing research are noted in Caribbean Sea and Islands, the Western Pacific, the coasts of West Africa and Gulf of Mexico (figure 2).

2.3.2 Spatial extent of floating and landing sargassum research

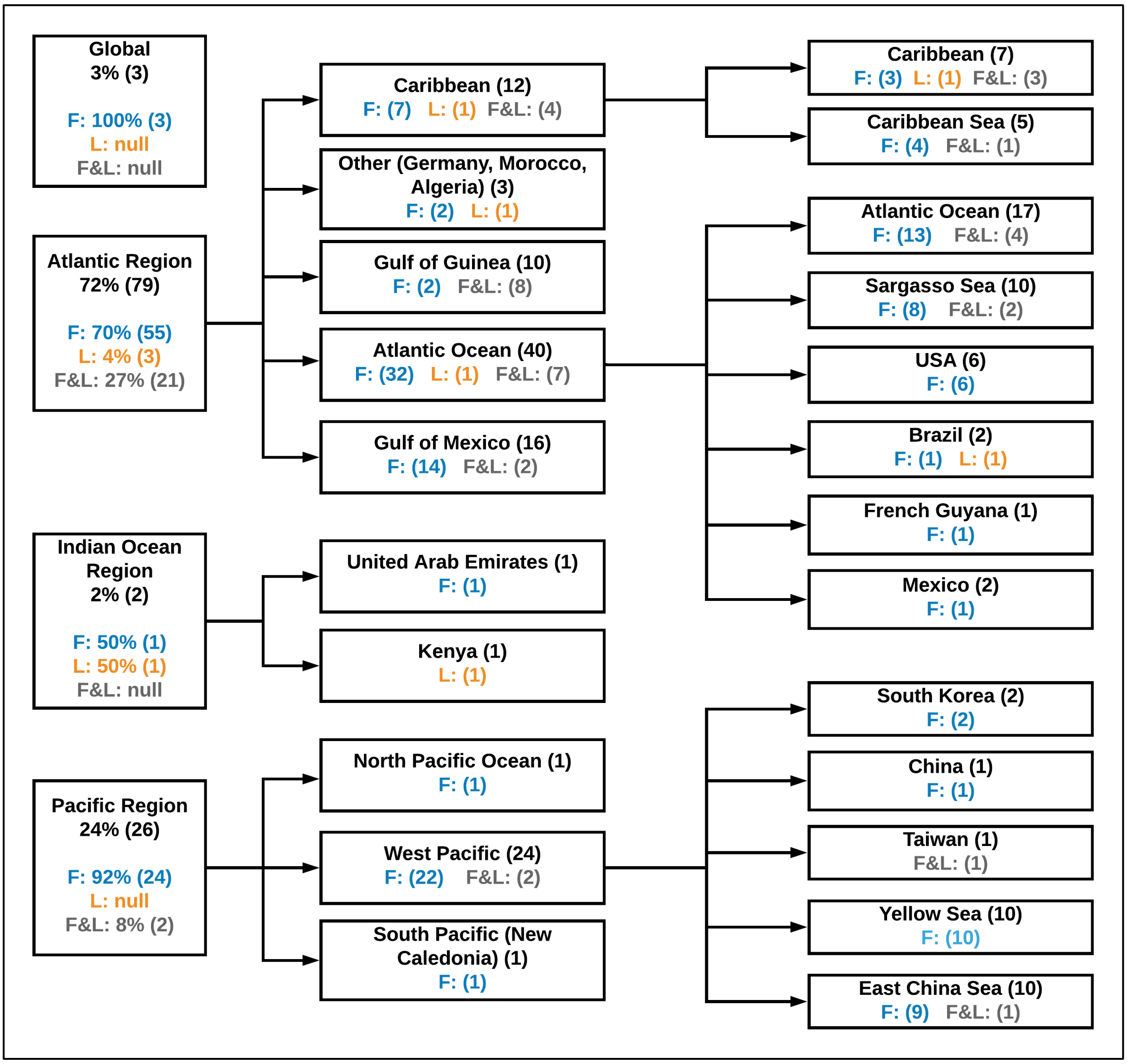

Figure 2 Global distribution of publications documenting evidence of floating (F) and landing (L) sargassum. Seventy-six publications collected evidence in 110 locations. The number in brackets refers to the number of publications which identified Sargassum in that location.
Caribbean (7) includes publications which referred to the 'Caribbean' as their study area, as well as Caribbean Islands (including US territories) and the San Andres Island Archipegalo.
The Sargasso Sea is included as a location as publications which included this region as well as other areas were included in the literature analysis.

Research has been undertaken in Africa, the Americas, Asia, and Europe; in the Atlantic, Pacific and Indian Oceans, with three publications undertaking a global survey of sargassum [18,21,59] (figure 2). We hypothesise that coastlines adjacent to water bodies experiencing significant impacts of sargassum would be the focus of more research than those experiencing fewer and less severe influxes; however, there are gaps, for example there is no research with a focus on Belize, Colombia and Japan. West Africa has two pockets of research in Nigeria and Ghana, which considers their own and neighbouring coastlines [2]. In the Caribbean region, there is a focus on floating sargassum on monitoring the general area, only four publications examined individual islands within the Caribbean – Virgin Islands, San Andres Island, Puerto Rico and Barbados [7,16,48,66].

2.3.3 Input sources for the sargassum

Of the 76 publications, only 13 (17%) speculated or indicated a theory on the origin of the sargassum in their respective study areas (table 1). However, it is important to note that most publications speculate the origins of the sargassum and conclude that the source is uncertain, with two concluding that it was unknown [23,61].

There is a significant number of publications focusing research on bloom origins around the Atlantic (n=10/13). From a deeper analysis of Atlantic based publications, it can be seen there is an emphasis on the tropical West Atlantic and Caribbean area. The Gulf of Guinea and West Africa are not always studied as a separate region but are often encompassed in publications focusing on the Tropical or Equatorial Atlantic. Three of the publications present research on the Pacific region around East Asia. There are no publications focussing on other regions of the world which explore the origin of sargassum blooms.

Table 1 Theorised sources for areas affected by sargassum.
Agreement occurs when >60% of publications suggest the same source. No agreement is given when there are less than two publications for the location.

Sargassum location	Theorised source	Publications	Agreement/ disagreement
Caribbean, Caribbean Sea, Sargasso Sea and Gulf of Guinea	-Guiana Current/North Brazilian current system -North of the mouth of the Amazon -Tropical Atlantic North of Brazil -Equatorial Atlantic between South America and Africa -North equatorial recirculation region -Gulf of Mexico -Tropical Atlantic	[8, 14, 23, 24, 29, 50, 67]	No agreement
Gulf of Mexico	-Northwest Gulf of Mexico -Gulf of Mexico	[8, 21]	Agreement
Pacific Region. Yellow Sea and East China Sea (including South Korea, Japan and China coastal areas)	-Zhejiang Coast -Zhejiang province -inner part of Yellow Sea	[34, 35, 52]	Agreement
South Atlantic	-Sargasso Sea -West Africa -Mexican Coast	[61]	No agreement
San Andres Island	- North of the Estuary of the Amazon River, off the coast of Brazil	[16]	No agreement

2.3.4 Temporal distribution of sargassum research

As expected, most of the research to date (78% of all papers) document the experience of individual locations, such as an area of sea, or an island, rather than a specific event, e.g. the 2018 bloom event. Location-based research provides either recurrent or one-off data for a specific area based on an expectation of potential sargassum presence. Regular location monitoring (such as [3,11,47,50]) is useful for a variety of reasons such as assessing presence, extent and frequency. Event-based monitoring (in response to the occurrence of a blooming or landing event) was present in 16% of the publications. The notion of a sargassum ‘event’ is rarely and inconsistently defined. Whether a publication collected evidence by location or in response to an 'event' was often inferred for this analysis, but not stated explicitly in the research. Research which appeared to focus on specific events generally collected evidence of sargassum immediately after or in response to the emergence of a bloom over water bodies or the appearance of sargassum mats in coastal or beach areas. For example, in response to a bloom off the coast of Florida, Marmorino *et al.*(2011) [39] used airborne imagery to collect evidence of the sargassum raft. Similarly, Oyesiku and Egunyomi (2014) [46] responded to reports of sargassum in Nigeria by visiting the site and collecting samples. Some publications collected data by both monitoring locations and responding to sargassum events; for example, Hu *et al.*(2015) [28] utilised remote sensing to regularly monitor the Gulf of Mexico and Atlantic area and the AVIRIS sensor for event response.

2.3.5 Prevalence of sargassum species in research outputs

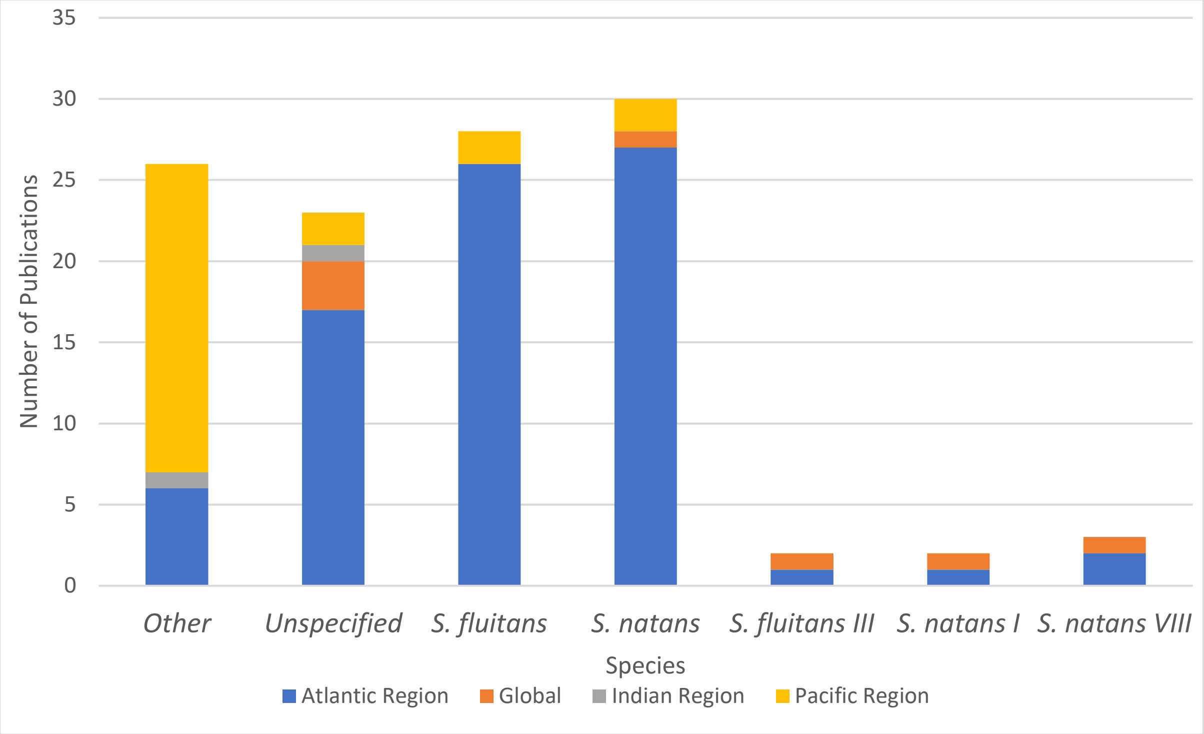

Figure 3 Sargassum species (floating and beach landings) distributed by Ocean Region and determined by publication study area.

To effectively valorise sargassum biomass, a critical piece of information is the biochemical composition of the landing seaweed. There are more than 300 sargassum species globally, and several morphotypes within some species, each of which potentially has a different chemical signature (Hardouin et al., 2014). Composition analysis of many sargassum species has not been investigated yet and, in relation to this, key questions remain: what is the abundance of the different sargassum species and/or morphotypes in the seaweed mats? Are some sargassum species more typically found in some locations than in others? Interestingly 32% (n=24) of publications did not distinguish between different species of sargassum in their research (figure 3).

Publications such as [9,31,34,35] show that *S. horneri* can be found as floating in the East China and Yellow Sea. However, Liu et al. (2018) showed that these were detached sargassum (i.e., the force of waves and currents cause the seaweed to disconnect from the bottom and they are buoyant due to having gas vesicles) rather than pelagic. It is possible that 'other' species of sargassum are also detached and not pelagic, although more research is needed to confirm this. It is apparent that the dominant holopelagic species are *S. fluitans* and *S. natans* and their respective morphotypes, particularly in and around the Atlantic region. Only three publications, identify morphotypes of these sargassum species [3,17,58]. This further heightens the uncertainty around sargassum nomenclature and identification. Schell et al. (2015) [58] identified that the dominant species in 2014/2015 was the morphotype *S. natans* VIII in the Caribbean. However, by the end of 2019, no other publications have compared morphotype dominance in any study area or time periods. If sargassum monitoring publications, investigated the species and morphotypes of sargassum, this could improve understanding of past trends, as well as improving prediction of future events.

2.3.6 Types of methods and data used to document the occurrence of floating sargassum blooms and beach landings

The methods used to detect and monitor sargassum were varied, with 46% employing a remote sensing based approach, 28% *in situ* (i.e. direct surveys and sampling of sargassum*)* and 26% employed a combination of both remote sensing and *in situ* methods (Table 2).

Table 2 Main methods used in analysis of sargassum by world region or sea.

Region	Main methods used	Publications
Atlantic Ocean Region (70%, n=53)	Remote sensing 47% *In situ* 25% *In situ* and remote sensing 28%	[1, 3, 5, 12, 17, 26, 32, 46, 54, 56, 57, 58, 66, 2, 4, 7, 10, 13, 28, 29, 45, 47, 48, 55, 61, 64, 71, 72, 8, 11, 14, 15, 16, 19, 20, 21, 23, 24, 25, 27, 30, 33, 38, 39, 50, 51, 60, 63, 65, 67, 68, 69, 70]
Pacific Ocean Region (24% n=18)	Remote sensing 33% *In situ* 39% *In situ* and remote sensing 28%	[9, 31, 35, 37, 42, 43, 62, 36, 4, 41, 74, 75, 6, 34, 52, 53, 73, 76]
Indian Ocean Region (3% n=2)	Remote sensing 50% *In situ* 50% *In situ* and remote sensing 0%	[44, 49]
Global (4%, n=3)	Remote sensing 100% *In situ* 0% *In situ* and remote sensing 0%	[18, 22, 59]

Table 2 shows that for the Atlantic region most publications utilise remote sensing based methods, whereas for the Pacific region, *in situ* approaches have been more commonly used. For global evidence collection, understandably only remote sensing based methods are used due to the scale of the study area. Remote sensing publications are most commonly based on satellite data sources including Moderate Resolution Imaging Spectroradiometer (MODIS), Medium Resolution Imaging Spectrometer (MERIS) and Landsat, which were often accompanied by ground truth data or higher spatial resolution dataset for a small subset of the study area, examples include [4, 28, 30, 47]. A minority of publications used unmanned aerial vehicles (e.g. drones) or other alternatives for aerial photography [39, 64]. Open-ocean sargassum detection methods were most commonly based on the red-edge concept, such as floating algal index (FAI) [27]. In contrast, there was less clarity about the sampling methods used within *in situ* research. Often sampling methods were not clearly stated (and hence were considered to be lower quality research, see supplementary materials). Those publications that documented their methods most commonly used boats to access sargassum rafts, examples include [35, 42, 55].

2.3.7 Estimation of sargassum biomass

To be able to manage sargassum influx, affected communities need to anticipate expected quantities and volumes that are likely to land on the shore. Only twelve publications (16%) attempted to estimate the volume of sargassum, and the calculation methods employed differed across the literature. Various approaches for landed and floating sargassum were adopted for volume calculation, including: i) determination of biomass weight based on wet [19] or dry sargassum weights [40,44]; ii) calculation of the size of the measured area, by assessment of individual rafts [42], or quantification of pixels in an aerial image [19,23,52,69]. This range of methods generated an array of results. Estimates of biomass volume include: an average of 1400 tons of wet weight per square degree grid per MERIS count in the Tropical Atlantic (based on 11 different areas and dates) [19], to 15 million tons in July 2017 and 32 million tons in July 2018 [23], and 2.05 tons per square nautical mile in the Gulf Stream (estimated through sampling) [26]. A further complication is the lack of a clear distinction within many papers between an imperial tonne or metric ton. These inconsistent practices in calculation and display methods contribute to an inability to compare changes in sargassum volume both temporally and spatially; it also prevents long term analysis of sargassum prevalence.

2.4 Discussion

The systematic documentation of locations affected by floating and landings of sargassum presented in this work is the first analysis of its kind and identifies some unexpected results relating to the distribution and quality of sargassum research outputs. Despite the global distribution of pelagic sargassum research, there are surprising gaps. For example, Belize shares the same Caribbean coastline as Mexico, and could be equally prone to sargassum influxes, yet there is currently an absence of literature documenting sargassum in Belize. Unless all areas in a possible sargassum impact area are monitored for sargassum landings, it will not be possible to fully appreciate the extent of sargassum in the Caribbean. Similarly, there is no published research on sargassum in West African countries such as Cameroon and Gabon, yet based on their geographic location, it would make sense to assume that sargassum is likely to be landing there. Figure 2 illustrates other areas where few publications have been undertaken and where research could be intensified, such as South America, East Africa, and North and West Africa. To fully understand and prepare for the impacts of sargassum on stretches of coastline, spatial gaps in research need to be filled.

It is worth noting that only 17 publications undertake empirical research on monitoring sargassum in the wider Atlantic Ocean (excluding Gulf of Mexico, Sargasso Sea and the Caribbean), which speaks to the scarcity of research on pelagic sargassum over the course of 60 years. It further appears that the proportion of sargassum research in a country may correlate with its relative wealth. For example, countries with a higher gross national income per capita (GNI) – using The World Bank (2018) – such as the USA (which has n=6 publications), undertook substantially more research than those with a lower GNI, such as Togo (n=1), Liberia (n=1), Guyana (n=1) and others in West Africa (n=2), Central America (n=0) and South America (n=3). The relative levels of economic development of countries could be reflected in their investment in research into pelagic sargassum and offer an explanation for spatial research gaps globally. Development of local empirical evidence bases on sargassum is very important as the potential solutions to manage the influx of sargassum in the future would require location specific information, and local strategies.

It was surprising to find that one fifth of the publications did not specify the species of sargassum, and only three publications reported on the morphotypes of the specimen. This exemplifies the challenges in correctly identifying some of the sargassum species, and some issues with their nomenclature. As an example, *S. aquifolium* appears to have a variety of synonyms according to Algae Base (Guiry, 2020), which could contribute to hesitation in identifying sargassum species in research publications. However, for the three morphotypes that affect the Caribbean and Western Africa clear morphological criteria and molecular markers have been established to identify them (Amaral-Zettler et al., 2017). Another important aspect to consider is that sargassum species may possess such similar qualities, such as their biochemical composition, that there is little need to distinguish between them. A limited number of publications have investigated aspects of the biochemical composition of holopelagic sargassum biomass (Oyesiku and Egunyomi, 2014; Addico and deGraft-Johnson, 2016; Baker et al., 2018), and more recently of the three individual morphotypes (Milledge et al., 2020; Davis et al., 2021). However, wider and more comprehensive research into composition of holopelagic sargassum species and of their morphotypes would offer transparency of differences and could unite species that are currently thought to be distinguished. Further research on this topic for specific species and morphotypes would enable this issue to be addressed, and it may also offer clarity on taxonomy. Additionally, detailed knowledge of sargassum composition would facilitate understanding of sargassum uses, impacts and management options.

The limited number of publications estimating quantities of sargassum and their methodological inconsistencies prevent construction of a long-term record of sargassum influxes and spatial-temporal analysis. Although, more recent publications are starting to do this (García-Sánchez et al., 2020); there are management implications of this as it generates uncertainty. For example, sargassum landing on beaches has occurred regularly in the past; however, in years (or seasons) with significantly high sargassum influx, such as 2015 (which had 20 times the historical amount (Wang and Hu, 2016)), management strategies are imperative to prevent socio-economic and environmental losses. Inconsistencies in estimating volumes of sargassum prevent effective management as authorities cannot accurately anticipate and prepare for sargassum influxes. It can be speculated that this is especially true for developing countries which have less to invest in monitoring and management. Therefore, to facilitate effective management, estimations of volume should be provided in a standardised manner, ideally alongside landing forecasts.

There are many sargassum management questions that remain outstanding, including *how long do beaching events last?*, *where does sargassum occur most regularly?*, *what are the local socio-economic impacts and how can they be mitigated?*, *what are the environmental impacts on specific areas/habitats?*. None of these can be assessed or quantified when there is little research on beach landings of sargassum. Focussing research on floating and open-ocean sargassum and overlooking analysis of the magnitude and severity of beach impacts leaves management queries unanswered. A further under-researched area which hinders management capacity is a lack of research on event response. With the majority of publications focussing on regular monitoring of open-ocean areas, event response research is limited. These research gaps hamper detailed analysis on how sargassum interacts with communities and its impacts on livelihoods and economies. In Mexico, management plans have been put into place, as reported by print media, such as installing ‘trial and error’ hard engineering solutions including barriers (Mexico News Daily, 2019). Although attempts at management are possible in the absence of detailed impact data, it can be argued that with more robust research on beach landings of sargassum and on sargassum events, more reliable solutions can be introduced with a higher potential for success.

2.5 Conclusions

The outstanding sargassum research gaps relate to input sources, locations and species identification, as well as the quantity in the oceans and the amount landing on beaches. The rapid growth in publications on sargassum over recent years is a welcome step towards understanding sargassum blooms and its geographic spread. However, there is a need to improve the robustness and extent of research to ensure in-depth understanding of the complex issue and support a comprehensive management plan for all affected communities.

First, the spatial coverage of research should be expanded to represent many missing countries and coastlines, notably in Central America and West Africa. This will better support sargassum management within integrated coastline management across geopolitical boundaries. The spatial gaps in research likely contribute to the lack of agreement on where the blooms emerge and the potential cycles and triggers.

Second, our analysis shows that most sargassum publications have focused on longer-term regular monitoring of specific locations and not addressed ‘event’ response effectively. To aid the production of comparable research on sargassum events, the notion of a sargassum event needs to be more clearly defined. Longer term records of sargassum are needed to monitor temporal changes in frequency of events and quantities landed – both of which are required to better understand how to reuse or manage the events. Research focussing on influx and blooming events should generate a longer and more detailed temporal record. To address the lack of a definition of a ‘sargassum event’, we propose the following: A sargassum ‘event’ is a continuous bloom of any sargassum in open oceans, or, an aggregation of landed sargassum with the potential to disrupt local social, economic or ecosystem functioning, or to impact human health. An event can affect one country, or several contiguous countries.

Third, at present sargassum species identification and reporting is not standardised, creating incomparability issues in the sargassum evidence base. Standard species identification should clarify which species are dominant in different regions and enable determination of the variation of dominant species seasonally and annually. Important questions need to be answered, such as *do the mats in the tropical Atlantic have the same species mix throughout the season or does it differ? Are* *different species dominant in different regions of the Atlantic Ocean? Are mats of one type of species invading other coastal areas or restricted to one location?* These cannot be addressed if the species and morphotypes of sargassum are not always recorded in publications. Similarly, a robust and standardised method for estimating volume needs to be developed and implemented to enable research gaps to be addressed and effective management strategies to be implemented.

Finally, there is a key research gap in understanding the nature and extent of the impact of sargassum landing on the socio-economic activities of the affected communities. Further research on short- and longer-term impacts of sargassum landing on coastal communities would be crucial to developing any sargassum risk mitigation strategy.

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Author Contribution Statement for Chapter 2

YF: methodology, data collection, formal analysis, investigation, visualisation, writing – original draft
JD: supervision, writing – review/editing
ET: supervision, conceptualisation, writing – review/editing
TT: writing – review/editing

Supplementary Material to Chapter 2

SM2.1 Methodology for Selecting Literature

The systematic review method adopted is outlined below and illustrated in figure 1. Three stages were undertaken to select and analyse peer-reviewed publications.

1. A selection of keywords and synonyms were used to create a 'tiered search' (table 1). This approach was used to ensure a comprehensive search and consistency. Where synonyms for key search terms 'sargassum' and 'monitoring' were used. The same tiered search was applied and repeated across three search engines: ISI Web of Knowledge, Elsevier Scopus and Google Scholar in December 2019. This was to ensure that as many publications as possible were included in the study.

2. A filtering framework was applied in the form of the inclusion/exclusion criteria outlined in table 2. The first stage of filtering involved reading the titles and abstracts of all results generated by each search engine and assessing if they fell within the inclusion criteria (table 2); publications which had clear features in the exclusion criteria (i.e. not empirical or a focus on benthic species of sargassum) were not carried forward to the next filtering stage. A second researcher independently determined whether the publication results from a search should be included for analysis, which was done with the aim of removing bias and opinions from the filtering framework. Before continuing to the second filtering stage, using Mendeley literature manager, duplicate publications were removed to prevent reading the same publications multiple times. The second stage of the filtering framework encompassed reading the entire publication and determine if it still satisfied the inclusion/exclusion criteria (table 2) and should be included as evidence in the systematic review.

3. The final stage, to facilitate structuring the analysis of the publications consistently, was to address a set of core research questions: Is the research related to floating or landing events, and if so where did it occur (beach, near-shore or open-ocean)?; What is the spatial extent of sargassum research? Does the literature indicate a source of sargassum?; What was the temporal scale of analysis?; Which species of sargassum were identified?; What data has been used to document the occurrence of sargassum blooms and beach landings?

What was the volume of sargassum (if calculated)? Each publication also underwent a quality assessment (table 3).

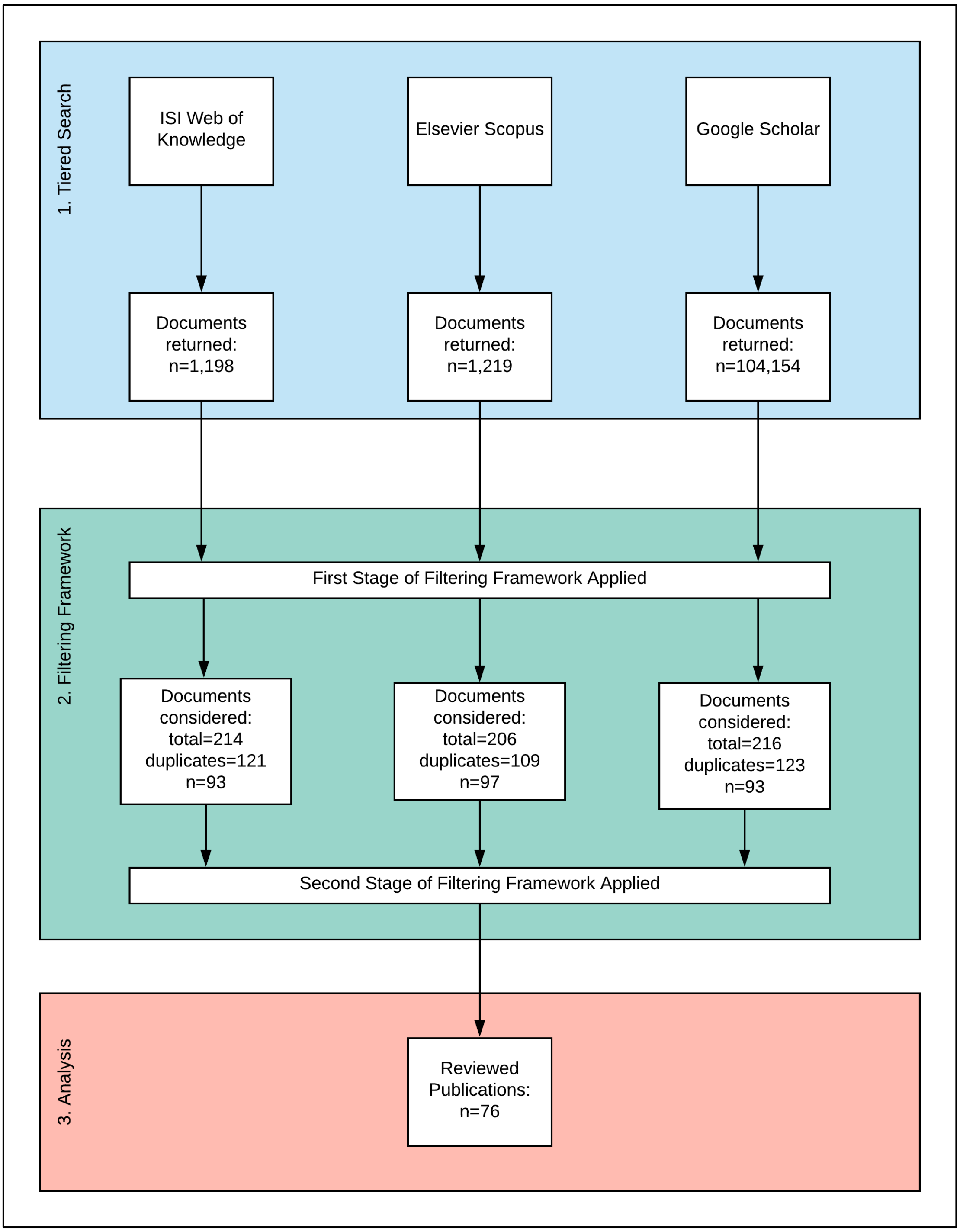

Figure 1 Flowchart showing systematic review and filtering framework process.

Table 1 Tiered Search Terms (asterisks indicates truncated search term).

Tier 1	**Tier 2**
sargassum Fucales Sargassaceae	Monitor* Track* Distribution Record* Remote sensing Satellite Imagery

Google Scholar returned a significantly higher number of results for each search, for example, “sargassum + distribution” returned 39,700 results, compared to 122 in ISI Web of Knowledge and 391 in Scopus. Consequently, Google Scholar required a modified approach due to the volume of results. Each page of results on Google Scholar has 10 results; these were filtered through (as per the first filtering stage) in order and when a full page was reached without a relevant paper (based on the title and abstract) then the search was terminated. ‘Seaweed’ was considered as a tier 1 search term, however it rendered a very high volume of results which were largely beyond the scope of this investigation, therefore it was not included.

SM2.2 Selection Criteria for Systematic Review Evidence

Table 2 Inclusion/Exclusion criteria applied to select publications for review

Inclusion Criteria	Exclusion Criteria
• English language • Any publication dates • Any data dates • Journal articles, conference papers, PhD thesis • Empirical studies • Sargassum evidence is focused on beach landings or surface floating	• Non-English language • Others (editorials, reviews, book chapters etc) • Non-empirical literature • *Sargassum* evidence is benthic, i.e. growing in beds or deep ocean • Studies which focus only on sargassum in the Sargasso sea*

*As noted in the introduction, *Sargassum* has a historical presence in the Sargasso Sea and is expected to be present in the area, therefore studies focussing on this area are omitted as they do not present a new environmental challenge.

Publications which were unclear on whether sargassum was floating, landing or attached to substrate were excluded from the study as confidence in recording pelagic sargassum was needed. Studies such as Kunii (2000) and Mattio (2015) did not describe their data collection methods and study areas clearly enough to enable understanding of where sargassum evidence was found. A total of six studies were excluded due to this.

Publications which may not have focused on sargassum but may have focussed on other species such as turtles, whose habitat is sargassum rafts, were included if they provided evidence of sargassum also.

SM2.3 Quality Assessment Criteria and Results

Table 3 Description of quality scores applied to publications, adapted from Porter et al. (2014).

Rating	Assessment	Example
5	- **Methods** used are highly appropriate for the research at hand, clearly executed and critically justified. Methodology is highly detailed and can be replicated. Additionally, the application of multiple methods to provide triangulation is another mark of the highest quality evidence. - **Results** are clearly presented with appropriate, supporting figures where appropriate. - Outlook of the research speaks directly to, and actually develops, the questions posed in the systematic literature review. - **Species** are identified clearly with correct/updated nomenclature and taxonomy and may identify forms of sargassum species.	**[71]**
4	- **Methods** used are appropriate for the research at hand, clearly presented and justified. Methodology is highly detailed and can be replicated. - **Themes** covered by the research are closely related to the questions posed in the systematic literature review. - **Species** of sargassum are identified or speculated.	**[35]**
3	- **Methods** used are appropriate for the research at hand, with some explanation and justification but may not be covered in detail/depth. - **Themes** covered by the research are closely related to the questions posed in the systematic literature review. - **Species** of sargassum are not clearly identified but may be speculated or have outdated nomenclature.	**[3]**
2	- **Methods** used are described with limited detail and not clearly justified or explained. - **Themes** covered by the research satisfy the exclusion/inclusion criteria but do not include many research-related characteristics of the systematic review. - **Species** of sargassum are not identified or recognised.	**[63]**
1	- **Methods** used are not described in any level or detail. - **Results** may be unclear or poorly explained without appropriate figures. - **Themes** covered by the research satisfy the exclusion/inclusion criteria but do not include many research-related characteristics of the systematic review. - **Species** of sargassum are not identified or recognised.	**[33]**

Less than 7% of studies were awarded a quality score of 5 and over half of the studies scored 3 or below; this is reflective of the need for better quality research within the field.

Annex

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Preamble to Chapter 3

In the first of three analysis chapters, chapter 3 introduces the first notions of sargassum drivers, detection and monitoring at low spatial resolution and high temporal resolution, addressing objectives 2 [VARIABILITY] and 3 [DRIVERS]. Through using daily satellite imagery, a time-series analysis of sargassum biomass in the Eastern Tropical Atlantic region is undertaken and a historical timeline of atmospheric and oceanic events is presented, these datasets are explored together to ascertain if there is co-variance between these events and sargassum biomass in West Africa.

Using remote sensing and qualitative assessments, this chapter addresses the following research gaps identified in the systematic review: the regional lack of research in the eastern Tropical Atlantic; higher temporal resolution and longer term analysis; and the uncertainty around the sources and drivers of the blooms. This chapter also contributes to the thesis research question i) How can we improve monitoring and reporting of sargassum events at multiple scales?

The concepts in this chapter relate to the management of sargassum through ‘prevention and mitigation’ and ‘preparation’. Understanding the trends over the past decade and the potential events that could cause higher volumes and influxes of sargassum can contribute to forecasting and preparedness of communities to take management measures or adaptation to the blooms and influxes. The drivers explored in this chapter (atmospheric and oceanic events) are considered compound risks linked to sargassum (the concurrence of natural events which can be correlated to patterns, focusing on the hazard component of disaster risk, see Chapter 1, Introduction to Thesis); the concurrence of these natural events are explored, and where possible, are correlated with patterns of sargassum biomass to better define the hazard.

Chapter 3 Exploration of drivers affecting the annual and seasonal variability of floating pelagic sargassum biomass in the Eastern Tropical Atlantic

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Abstract

Pelagic sargassum (*S. fluitans* and *S. natans*, henceforth sargassum) blooms are an emerging environmental challenge across the Tropical Atlantic region. Vast blooms of holopelagic sargassum, known as golden tides, have appeared across the tropical Atlantic Ocean in the boreal Spring and Summer months since 2011. When the floating blooms make landfall, they have a variety of socio-economic and ecological impacts on coastal communities, including on aquaculture, the tourist industry and biodiversity. Whilst the trigger for the initial seeding event is largely undisputed (anomalous North Atlantic Oscillation 2009-10), the drivers of movement and causes of proliferation within and across regions of the Tropical Atlantic remain unclear. In addition, to date there has been limited focus on West Africa, and there remains a gap in our knowledge about the annual and seasonal variability of sargassum affecting the West Africa coast. This paper addresses these two research gaps, by (1) providing a first attempt at characterising the seasonal and annual trends of sargassum influxes in Eastern Tropical Atlantic, and (2) exploring the hypothetical drivers of movement and proliferation. The first aim is achieved through applying the Alternative Floating Algae Index (AFAI) to imagery from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite sensor to estimate the wet biomass in the Eastern Tropical Atlantic between 2011 and 2022.

The output is a time-series which is used to characterise the annual and seasonal variability of sargassum for the region. The second aim is achieved through assessing the co-variation of sargassum biomass with hypothetical drivers including atmospheric, oceanic, and policy change. A historical timeline of large-scale oceanic, atmospheric and policy events is established, and the co-variance of the time-series and timeline is explored. The time-series analysis reveals that there is an annual peak in September and a second smaller sargassum peak between March and May. The exploration of potential drivers reveals that there are multiple potential factors that could be influencing sargassum biomass, and that further research is necessary. The results presented support current attempts to understand the drivers and impacts as well as the prediction of future patterns and beach landings of sargassum, specifically in the Eastern Tropical Atlantic region. We anticipate that our findings will better characterise the threats made by sargassum and provide management insights for blue economy policy makers in both West Africa and the wider Tropical Atlantic region.

3.1 Introduction

The appearance of large Sargassum blooms in the tropical Atlantic presents a new environmental challenge for affected communities. Since 2011, ocean surface blooms and beach landings of the holopelagic sargassum species *S. natans* and *S. fluitans* have been impacting coastal communities in the Caribbean, the Gulf of Mexico, the equatorial Atlantic and the Gulf of Guinea (Wang et al., 2019). Wind and currents aggregate Sargassum plants into large rafts or windrows of varying size and shape (Ody et al., 2019). These large influxes are associated with environmental challenges for coastal ecosystems, including: impacts on biodiversity and species population dynamics such as mortality of benthic flora and fauna; changes to beach nourishment; beach erosion and shore stability; pollution; oxygen depletion; reduced light; deterioration of water quality (Chávez et al., 2020; van Tussenbroek et al., 2017). Further to these, communities also experience socio-economic challenges, particularly relating to the fishing and tourism industries (Ramlogan et al., 2017; Solarin et al., 2014), as well as public health threats (including pulmonary, neurological, and cardiovascular conditions) (Resiere et al., 2018). Sargassum influxes can also present an opportunity for communities. There is ongoing exploration into the valorisation of sargassum as animal feed, biofuel, bioplastics, fertiliser, construction blocks and more (Milledge et al., 2016; Thompson et al., 2020). Due to these spectra of associated impacts and opportunities, sargassum influxes are of consequence to coastal Atlantic communities.

Sargassum blooms have high annual variability, and in the Western Tropical Atlantic, the seasonality of sargassum has been largely established with consensus that the season spans the boreal spring and summer months (Wang et al., 2019; Wang and Hu, 2017; Gower and King 2011). However, the seasonality of Sargassum influxes is not yet established for other regions, including West Africa and the Gulf of Guinea. Ody et al. (2019) noted that sargassum aggregations were observed in September to November of 2017 near the West African coast and across the North Tropical Atlantic to the Lesser Antilles in June and July 2017. In the Western and Central Tropical Atlantic, forecasting systems have been developed for sargassum transport and beach landings. For example: Marsh et al. (2021) used an ocean model hindcasting to predict the movement of blooms in the Central Atlantic, Eastern Caribbean and Jamaica; Marechal et al. (2017) use surface current models to develop the Sargassum Watch System (SaWS) for the Lesser Antilles; Wang and Hu (2017) use hindcasting to provide early warnings for the Caribbean Sea and Central West Atlantic. The Centre for Resource Management and Environmental Studies (CERMES) also produces a sub-regional sargassum outlook bulletin which is a 3-monthly island-scale forecast for the Eastern Caribbean. Despite rapid growth in research and forecasting of pelagic sargassum, there remains uncertainty relating to the nature, extent, timing, and driving processes of sargassum influxes and events, particularly in the Gulf of Guinea (Fidai et al., 2020).

Sargassum research from the Eastern Tropical Atlantic includes Addico and DeGraft-Johnson (2016) and Oyesiku and Egunyomi (2014) which both sampled beached sargassum along the coasts of Ghana and Nigeria respectively for chemical composition analysis. Adet et al. (2018) used satellite observations from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor using fluorescence values to detect near-shore blooms along the West African coast from Sierra Leone to Nigeria from 2011-2016; due to cloud cover the study’s analysis was restricted and in some years as few as 2 months were analysed, limiting the potential to assess seasonality and annual variability from the data. In Nigeria, Solarin et al. (2014) surveyed beaches in 2011 and 2012 and observed that sargassum events coincided with the rainy season (May-August). From this summary it is apparent that the limited research in West Africa has focused mostly on beaching events, rather than open-ocean blooms and data collection is typically short-term with no seasonal or annual variation characterised. Furthermore, there appears to be a lack of agreement on the transport pathways and origins of the blooms in West Africa. For example, Gower and King (2020) have acknowledged the potential that sargassum influxes are extending to the Gulf of Guinea from the Tropical Atlantic or

Amazon plume. Contrastingly, Brooks et al. (2018) and Franks et al. (2016) suggest that blooms are exported from the Gulf of Guinea to the Tropical Atlantic. Oviatt et al (2019) bring these ideas together to suggest a third option, notably that sargassum enters the Gulf of Guinea by the equatorial counter current and is circulated south before being returned to the Tropical Atlantic via the South Equatorial Current. These contrasting suggestions on transport pathways and bloom origins highlight uncertainties surrounding the movement of sargassum in West Africa.

Drivers of sargassum blooms have been researched to date with a Caribbean or Western Central Tropical Atlantic focus. Multiple theories explaining sargassum growth and dispersal are emerging, such as the role of nutrient-rich waters from the Amazon River Plume (propagated by deforestation, agro-industrial and urban activities), warmer sea surface temperatures, and equatorial upwelling combined with a southern-shifting Inter-tropical Convergence Zone (Skliris et al., 2022; Djakoure et al., 2017). Iron and phosphate from Saharan dust transported to the Caribbean have also been theorised to be a further source of nutrients (Mendez-Tejeda and Rosado Jimenez, 2019). Alongside this, a negative phase of the Atlantic Meridional Mode (AMM) and El Nino, stronger trade winds, and stronger northwest-ward nutrient transport have supported increases in sargassum blooms and secondary winter blooms (Skliris et al., 2022). Other explanations include warming temperatures, climate change, changes in wind regimes, and exceeding biosphere tipping points (Wang et al., 2019; Johns et al., 2020). In Ghana, an investigation into community perceptions showed that some coastal communities assume that sargassum blooms are driven by oil and gas exploration activities which began in 2010 shortly before sargassum appeared - although the authors question these assumptions (Atiglo et al., *in review*). However, there appears to be limited investigation into the movement and perpetuation of the blooms in the Eastern Atlantic region. A lack of long-term large-scale sargassum bloom data for the Eastern Tropical Atlantic has prevented investigation into the drivers and causes of sargassum blooms, and consolidation of potential theories.

A final challenge for detecting and monitoring sargassum in West Africa is the accessibility of useable satellite data. The Inter-tropical Convergence Zone is associated with dense cloud cover which prevents optical satellite imagery from being used easily in the Eastern Tropical Atlantic, as noted by Marsh et al. (2021). Other satellite sensors such as microwaves, do not provide a coverage with high spatial details over the ocean. Consequently, there is a lack of characterisation of seasonal and annual variability, investigation into drivers, forecasting and agreement on transport pathways.

Collectively, these research gaps hinder effective management of pelagic sargassum events (as defined by Fidai et al., 2020) in the Eastern Tropical Atlantic region.

3.1.1 Aims

Whilst the trigger for the initial seeding event is largely undisputed (anomalous north Atlantic oscillation 2009-10), the drivers of movement and causes of proliferation within and across regions of the tropical Atlantic remain unclear. In addition, to date there has been limited focus on West Africa, and there remains a gap in our knowledge about the annual and seasonal variability of sargassum affecting the West Africa coast. This paper addresses these two research gaps, by (1) providing a first attempt at characterising the seasonal and annual trends of sargassum influxes in Eastern Tropical Atlantic, and (2) exploring the hypothetical drivers of movement and proliferation.

To achieve this, the following research questions are addressed: i) what datasets and methods are suitable to detect oceanic sargassum in the Eastern Tropical Atlantic? ii) How much floating sargassum is there in the Eastern Tropical Atlantic, and what is the seasonal and annual variability? iii) are there any large-scale atmospheric, oceanic, or other events that co-vary with the presence of sargassum biomass in the Eastern Tropical Atlantic region between 2011 and 2022?

3.2 Methods

3.2.1 Location

The area investigated follows the coastline from Guinea as the western bound through Sierra Leone, Liberia, Cote D’Ivoire, Ghana, Togo, Benin, Nigeria in the East, and south to Cameroon, Equatorial Guinea, Gabon, Congo, Democratic Republic of Congo and ends in Angola, south of Luanda. The Tropical Atlantic Ocean along these coastlines including the Gulf of Guinea and Bight of Biafra is collectively referred to as the Eastern Tropical Atlantic in this study (shown in figure 1).

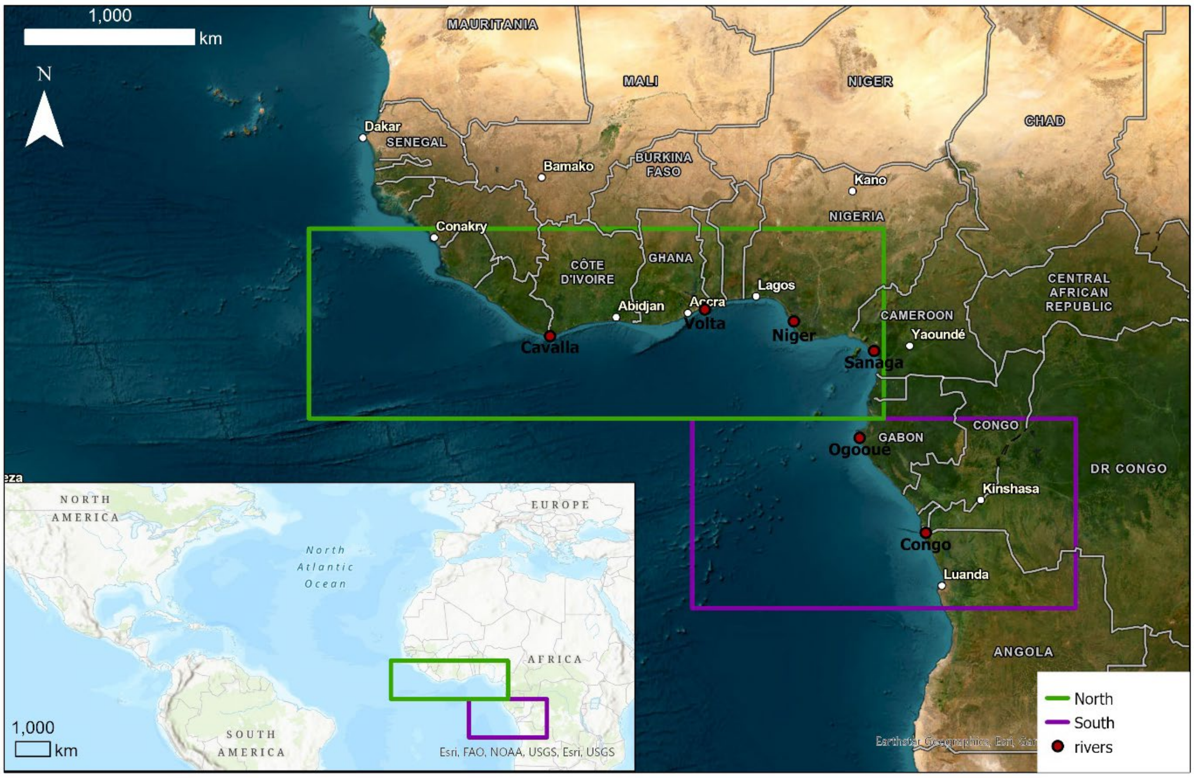

Figure 1 Map showing study location, where the 'North' study area is highlighted in green and the 'South' in purple. The sargassum detection and methods were undertaken in ocean areas only, the boxes are representative of the boundaries of the gridded satellite imagery used for detection. The locations of where the major rivers join the Atlantic are also included.

This study area was selected as it is an under-researched region affected by sargassum blooms and beach deposits, and has communities whose livelihoods are highly vulnerable to sargassum impacts (Fidai et al., 2020). Due to the speculation around the effects of river discharge and nutrients the major rivers joining the Atlantic system in the region were included (Volta, Sanaga, Niger, Congo, Cavalla, Ogooué Rivers). The study region was further split into two sub-study areas, the North (from Guinea to Gabon) and the South (from Gabon to Angola). This separation was identified as the south study area experiences lower sargassum biomass and it enables investigation into temporal and spatial variability of sargassum biomass within the Eastern Tropical Atlantic. The North study area is focused on the Gulf of Guinea and the South on where the Congo River joins the Atlantic Ocean. The years 2011-2022 were selected as reports of a significant increase in sargassum biomass and the Great Atlantic Sargassum Belt in the Tropical Atlantic were identified from 2011, and has persisted through this time period (Wang et al, 2019).

3.2.2 Sargassum detection and quantification

To identify the most appropriate method for detecting sargassum in the study region, a literature search was undertaken to find empirical publications that detect pelagic sargassum using remote sensing methods in Google Scholar and Scopus literature search engines (search terms: “sargassum + detection + Atlantic”; “sargassum + remote sensing + Atlantic”; “sargassum + monitoring + Atlantic”). Relevant publications (remote sensing based, empirical, on pelagic sargassum in the Tropical Atlantic, with full text access) were read (n=18), and their detection method(s) was noted, along with the study location, sensor/satellite used and any associated limitations of the method. These were then compiled and summarised into a table which is presented in the results section. Based on this exploration, the index selected for use in this work was the Alternative Floating Algae Index (AFAI) using the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite.

AFAI was first developed by Wang and Hu (2016) and it examines the red-edge reflectance to detect floating vegetation. The formula for AFAI is outlined below (1) where Rrc refers to Rayleigh-corrected reflectance, NIR near infrared wavelength (748 nm), SWIR shortwave infrared wavelength (869 nm), and RED the red wavelength (667 nm).

$$AFAI = R_{rc,NIR} - R'_{rc,NIR}$$

$$R'_{rc,NIR} = R_{rc,RED} + \left(R_{rc,SWIR} - R_{rc,RED}\right) X \ (\lambda_{NIR} - \lambda_{RED})/(\lambda_{SWIR} - \lambda_{RED}) \qquad (1)$$

The output of this method is three classifications for pixels: ‘no-observation’, ‘sargassum-containing’ and ‘sargassum-free; operational implementation of this method involved four main steps. The first step to create the ‘no-observation’ classification was achieved by applying the formula (1) to the MODIS images, then masking clouds and cloud shadows, sunglint, and removing ambiguous pixels such as no-data pixels, thereby creating a ‘no-observation’ classification, where pixels containing these features were masked. Additionally, images which contained more than 50% cloud coverage were removed as the outputs would be unreliable. In the second step, the AFAI classification was undertaken to identify ‘sargassum-containing’ pixels. This was done by creating a sargassum-free ocean background image by applying a four-degree polynomial surface fit to smooth the masked image. The sargassum-free ocean background smoothed masked image was then subtracted from the AFAI masked image to generate background AFAI values with a median filter. Then the AFAI global-scope threshold (1.79×10^{-4}) was applied to segment the image to determine sargassum-free and sargassum-containing pixels. Next, linear unmixing of sargassum-containing pixels was undertaken using for minimal and maximal sub-pixel coverage to estimate the fractional sargassum coverage within a pixel. In the third step, data binning of individual valid sargassum-free and sargassum-containing pixels into grids at monthly intervals for the period 2011-2022 was undertaken to calculate the mean sargassum fractional coverage for each month and grid to enable a time-series of area coverage for each study area to be produced. Finally, Wang et al. (2018) established an index-biomass density model where MODIS AFAI values correspond to sargassum density which enables calculation of sargassum biomass per area. The model was developed from in-situ measurements of sargassum biomass weight per area, where the wet weight of a 1 m^2 quadrat was measured, and digital photos were taken and used to calculate the areal density. The AFAI-Biomass density model was developed by converting the in-situ data to MODIS AFAI using simulations (considering maritime and coastal aerosol types for atmospheric conditions) and applying a regression model to the satellite-derived AFAI. The model was applied directly to percentage coverage maps from AFAI outputs to create a wet biomass estimate for the study areas across the time period. The model gives a time-series of monthly wet sargassum biomass estimations in metric tons at 50 km spatial resolution (provided by Chuanmin Hu, University of South Florida). The time-series graphs are presented and discussed in the results section, the magnitude of the peaks and annual accumulation are calculated, as well as Mann-Kendall and Sen’s Slope values to determine trend over time, and the significance of the trends (using Python 3.8.10), for each study region (North and South).

3.2.3 Assessing co-variance

To explore co-variance of potential events and sargassum biomass, a variety of data was used. Potential drivers were identified from existing literature and included: nutrient inputs, ocean events and atmospheric events. Data which can contribute or represent these categories were included and where monthly data was available statistical trend analysis was undertaken using Mann-Kendall Test Statistic and Sen’s Slope. Ocean data relating to long-term trends such as sea surface temperature, the North Atlantic Oscillation (NAO) index, and ocean salinity, were collated, explored, and presented using Python 3.8.10 or ‘Microsoft Excel’ software. A historical timeline was established which included standalone events and extreme trends or values in long-term trends (supplementary material). This qualitative approach was used to support the analysis to give a broad exploration of potential drivers and events over the entire time-period, *which gives a bigger picture of how the* *events may be interlinked across the time period*. Table 1 summarises the events, the datasets used and their sources.

Table 1 Summary of factors assessed for co-variance, including a description and data source. All URLs and data were accessed and downloaded in May 2023.

Data	**Description /** Data Type and Processing	**Data Source**
Ocean		
North Atlantic Oscillation (NAO)	Monthly NAO index (calculation based on the Rotated Principle Component Analysis by Barnston and Livezey 1987). Downloaded in ASCII format and processed in MS Excel.	National Oceanic and Atmospheric Administration (NOAA). URL: https://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/norm.nao.monthly.b5001.current.ascii.table
Sea surface temperature	Daytime Sea Surface Temperature (measured in Celsius) derived from MODIS Aqua Satellite data. Downloaded in csv format and processed in MS Excel.	Giovanni NASA Earth Data, Aqua MODIS Global Mapped 11µm Daytime Sea Surface Temperature (Data Product: MODISA_L3m_SST_Monthly_9km_vR2019.0) URL: https://giovanni.gsfc.nasa.gov/
Sea salinity	Salinity, measured as monthly mean, measured in kilograms, for 5.0m sea depth. Downloaded in netCDF format and processed in ArcGIS Pro.	Behringer and Leetmaa (1998) from NCEP Global Ocean Data Assimilation System (GODAS) data provided by the NOAA Physical Sciences Laboratory, Boulder, Colorado, USA, URL: https://psl.noaa.gov
Atlantic Meridional Overturning Circulation (AMOC)	The AMOC system of ocean currents circulates water within the Atlantic Ocean, moving warm water and nutrients across the globe; it is important for heat transport. Trends and anomalies were noted. Information/data from empirical publications.	Srokosz and Bryden (2015)
El Nino Southern Oscillation (ENSO)	Measured by the Southern Oscillation Index (standardised index based on sea level pressure differences between Tahiti (French Polynesia) and Darwin, (Australia)). Downloaded in csv format and processed in MS Excel.	National Oceanic and Atmospheric Administration (NOAA) URL: https://www.ncei.noaa.gov/access/monitoring/enso/soi
Oil spills	Major events in the Atlantic and West Africa. Information/data from empirical publications.	Ogbuka et al. (2022); Fosu (2017); Stout et al. (2017)
Atmospheric		

Data	Description / Data Type and Processing	Data Source
Saharan Dust	Aerosol Optic Depth (a measure of the aerosols, including dust, distributed within a column of air from the instrument to the earth's surface) derived from MODIS Terra satellite data. Downloaded in csv format and processed in MS Excel.	Platnick et al. (2015) from Giovanni NASA Earth Data, (Data Product: MYD08_M3 v6.1) URL: https://giovanni.gsfc.nasa.gov/
Volcanic eruptions	Volcanic eruptions in the Atlantic region, which were also associated with ash, gas clouds or material production.	Smithsonian Institution; Global Volcanism Program URL: https://volcano.si.edu/
Nutrient inputs		
Volcanic eruptions	(see above)	
Suspended sediment	Diffuse attenuation coefficient for downwelling irradiance (derived from MODIS Aqua data) measures how light dissipates with depth in water. Additionally, any notable impacts/events on water pollution quality or policies which came into effect 2009 onwards in the West African region were recorded.	DOI: 10.5067/AQUA/MODIS /L3M/KD/2022 from Giovanni NASA Earth Data URL: https://giovanni.gsfc.nasa.gov/

3.3 Results and Discussion

3.3.1 What datasets are available to detect oceanic sargassum?

Pelagic sargassum has been detected using satellite imagery using a variety of sensors and indices. These have been investigated and the most commonly used are summarised in table 2.

Table 2 Summary detection indices and sensors, with associated publications and noted limitations. Abbreviated sensors: MODIS: Moderate Resolution Imaging Spectroradiometer, Terra (T) and Aqua (A); MERIS: Medium Resolution Imaging Spectrometer; OLCI: Ocean and Land Colour Instrument, Sentinel-3 Instrument; VIIRS: Visible Infrared Imager Radiometer Suite; MSI: MultiSpectral Instrument, Sentinel-2 instrument.

Index	Publications	Locations of Studies	Satellite sensors used	Limitations/challenges
Normalized Different Vegetation Index (NDVI)	Hu (2009); Dierssen et al. (2015); Hu et al. (2015)	Greater Florida Bay, Gulf of Mexico, Central west Atlantic, Caribbean, North Atlantic, Yellow Sea, East China Sea	MODIS (T&A)	• Missed sargassum mats. • Composites result in mats being counted multiple times. • Coarse resolution. • Cloud masking.
Maximum Chlorophyll Index (MCI)	Gower et al. (2006); Gower and King (2008; 2011; 2020), Gower, Young and King (2013); Hu et al. (2015); and Ody et al. (2019)	Gulf of Mexico, Caribbean, Tropical Atlantic	MERIS, OLCI	• MERIS is not in use since 2012. • Can only detect large rafts (>1200m). • Potential for sargassum misclassification / challenge distinguishing from other algae or floating material. • Cloud and sunglint impacts observations. • Limited detection of decomposing sargassum. • Cosmic rays affect sensors. • Double counting of mats due to compositing. • Quantification and validation challenges.
Floating Algae Index (FAI)	Hu (2009); Hu et al. (2016); McCarthy et al. (2016); Ped et al. (2016); Wang and Hu, 2020	Gulf of Mexico, North Atlantic Ocean, East China Sea, Yellow Sea	MODIS (T&A), Landsat 5 Enhanced Thematic Mapper, Landsat 7, OLCI, MSI	• Coarse spatial resolution of MODIS. • Cloud masking. • Coarse temporal resolution as a consequence of compositing. • Threshold to establish sargassum is a challenge/arbitrary as its narrow and clouds, haze and other factors overlap. • Distinguishing cloud and shadows from sargassum. • Shape of sargassum mats is not always identifiable.
Alternative Floating Algae Index (AFAI)	Wang and Hu (2016; 2018); Maréchal et al. (2017); Ody et al. (2019); Minghelli et al. (2021)	Central West Atlantic	MODIS (T&A) VIIRS	• Coarse temporal resolution due to monthly composites. • Coarse spatial resolution. • Computationally demanding. • Estimations of volume do not consider vertical depth.
				• Coarse spatial resolution (9km). • Restricted to near-shore.

Normalized Fluorescence Line Height (NFLH)	Adet et al. (2018)	West African coast (Sierra Leone to Nigeria)	MODIS (A)	• Monthly composites, low temporal resolution. • Cannot distinguish from other floating algae. • Cloud cover prevents data analysis in some months.
Normalised Floating Algae Index (NFAI)	Sutton et al. (2019)	Tropical Atlantic from the Gulf of Mexico across to Sierra Leone	MODIS (A), MSI, OLCI	• Not validated with ground data so accuracy of method is not confirmed. • Mixed resolution outputs. • Weekly composite (medium temporal resolution). • Sun glint contamination (particularly for MSI data).

It was found that the most commonly used index was MCI (n=7). The strengths of MCI for detecting marine and floating vegetation include detecting surface chlorophyll and that it is a sensitive detector of the ‘shifted red-edge’ which is advantageous for vegetation detection (Gower and King, 2011). In terms of pairing MCI with sensors, MODIS has advantages over MERIS, including daily coverage with two instruments to increase coverage, and a wider swath (nearly double MERIS) which also supports this, however, there is an increase in errors caused by radiance from atmospheric scattering (Gower and King, 2011; Gower et al., 2013). When using the OLCI sensor, MCI output requires in-situ observations to support interpretation (Ody et al., 2019). However, it is worth noting that studies using MCI for sargassum were using it before the 2011 increase in biomass, more recent studies have opted for using AFAI and AFAI over MCI; AFAI and FAI were equally common for detecting sargassum (n=5). The most commonly noted limitation of FAI is in distinguishing clouds from sargassum (Wang and Hu, 2016); however, AFAI overcomes some of the limitations and improves the detection of sargassum through the use of cloud masking. Majority of the publications found and investigated focused on the Western Atlantic, or across the basin. NFLH was used in the near-shore along the West African coast (Sierra Leone to Nigeria) between 2011 and 2016 to detect sargassum using MODIS (Adet et al., 2018). However, the method was limited by coarse spatial resolution, affected by cloud cover, and restricted to near-shore waters. No further remote sensing based detection papers were found that focused on the Eastern Tropical Atlantic area.

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Through investigating existing detection methods and assessing their limitations, we concluded that the most appropriate method for this study region was to apply AFAI using MODIS data. The reasons for this include: the study region is large and open-ocean based, MODIS data offers complete temporal coverage for the time period and full spatial coverage of the ocean study region as well, allowing a single sensor and dataset to be used. Despite the coarse resolution associated with this method, as the Eastern Tropical Atlantic is frequently impacted by cloud cover, the compositing method employed is advantageous to enable an estimate of sargassum biomass in a monthly period. Additionally, it overcomes many of the limitations of FAI including differentiating cloud from sargassum, and the lower signal to noise ratio compensates for the lower resolution. This method also allows calculation of wet biomass to be estimated, going beyond percentage cover or area estimation that most other methods offer. Although, a weakness of AFAI is that it considers all floating vegetation in the region and does not differentiate between sargassum and *Trichodesmium* for example, thus the output can be used as an indicator of sargassum but it may also include other floating vegetation. Wang and Hu (2016) indicate that AFAI extracts 95% of sargassum-containing pixels, but the biomass calculation has a relative uncertainty of ~12%.

3.3.2 How much floating sargassum is there in the Gulf of Guinea, and what is the seasonal and annual variability?

The time-series analysis revealed distinct patterns and variation between the North study area and the South study area (figure 2).The monthly sargassum biomass time-series for the North study area has a Mann-Kendall Test Statistic of 4.60 and a p-value (4.31×10^{-6}) indicating a statistically significant increase in biomass over the time period 2011-2022; this is supported by a positive Sen's Slope value (1655.32) which also indicates a positive rate of change in the data over time. The monthly sargassum biomass time-series for the South study area has a Mann-Kendall Test Statistic of 0.279, where it is close to 0 it suggests there is slight positive trend in the data, the Mann-Kendal p-value (0.78) indicates that there is not enough evidence to conclude that there is a significant trend; similarly the Sen's Slope value (8.275) is positive suggesting a slight positive rate of change, however the small magnitude suggests the trend is minimal. It is apparent that both study areas have distinct biomass patterns, volumes, and trends,, as such their co-variance with potential drivers has been explored separately (see supplementary material for combined dataset), with the South overall experiencing less biomass than the North. The magnitude of the peaks in each study area are vastly different, the peak in the North study area was nearly 19 times greater than the South, as the maximum biomass in the North was 2,672,800 tons in September 2020, and 141,717 tons in the South in March 2017. Comparatively, Wang et al. (2019) showed that for the entire Great Atlantic Sargassum Belt (Gulf of Mexico, Caribbean, Tropical Atlantic across to Sierra Leone) there was a peak of over 20 million tons in June 2018.

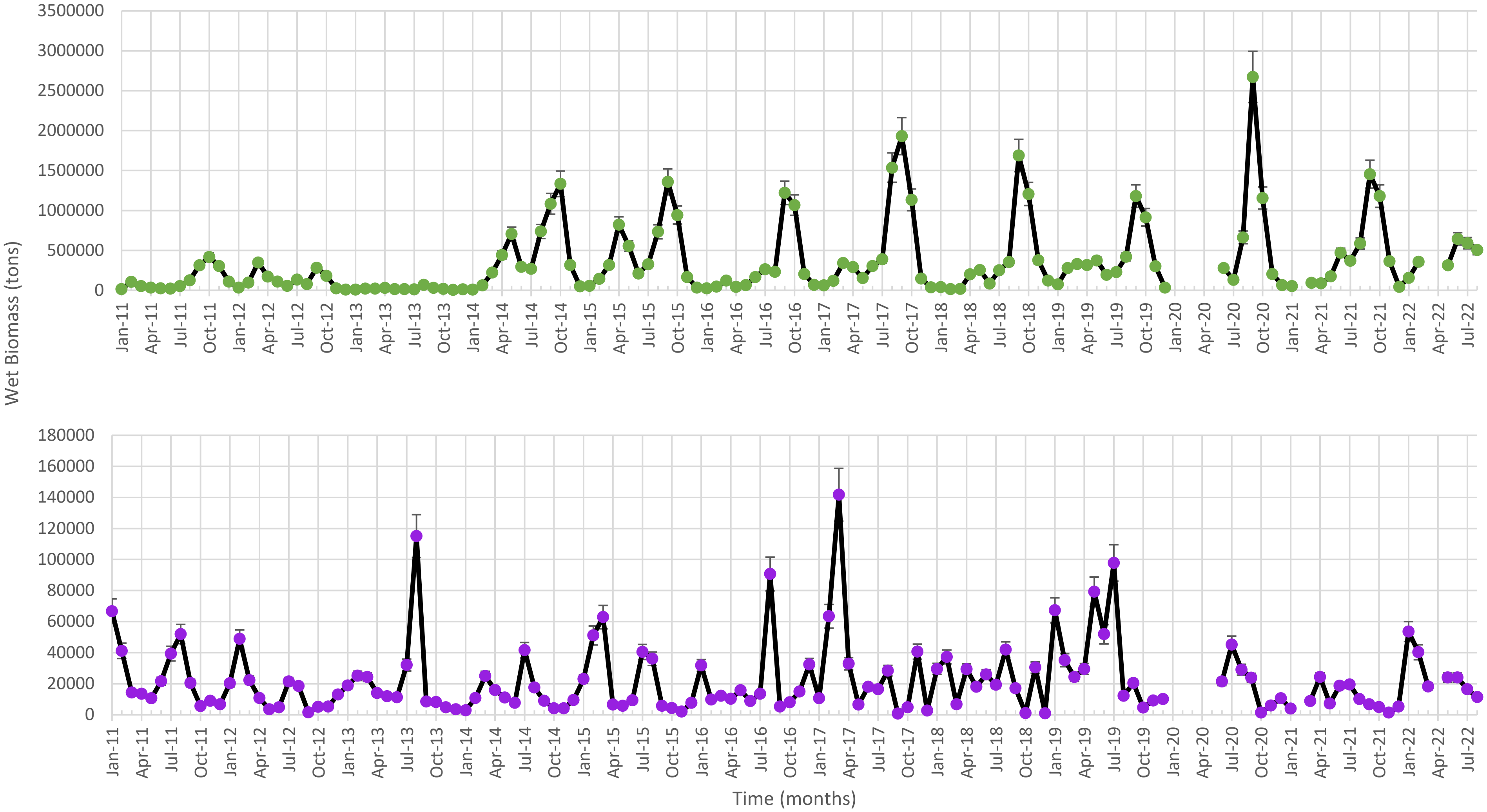

Figure 2 Time-series of wet biomass (in metric tons) detected in the North study area (top) and South (bottom) of the Eastern Tropical Atlantic using AFAI and MODIS between January 2011 and August 2022. The error bars represent the 12% relative uncertainty of sargassum wet biomass estimations.

In the North study area, most years appear to experience a small peak (most commonly between March and May but varying between February and June) and a large peak in September. Seven of the eleven complete years (2015-2021) experienced a peak in the month of September, with October, March, or August peaking in the other four years. The September peak ranged between 1,180,470 tons in 2019 to 2,672,800 tons in September 2021. The smaller peak earlier in the year occurred in eight of the eleven years which ranged from 107,532 tons in February 2011 to 822,123 tons in April 2015. There were two peaks in 2012, however it is anomalous in that the earlier peak in March (347,256 tons) was greater than the peak in September (283,776 tons). The rainy season in West Africa is typically between May and October, and the primary sargassum peaks in this region appear to overlap with this season.

Despite the initial assessment that the North and South study areas appear to have dissimilar biomass patterns over the time period, it is apparent that they both experience two peaks in each year, with one dominant and one smaller. However, in the South study area, it is less consistently the later peak in the year that is the main peak. For six of the 11 years the main peak was in July or August, for the other years, it was in January, February, March or April and it ranged from 24,286 tons in April 2021 to 141,717 tons in March 2017. The minor peak was very varied by month across the year, with no clear pattern, 2016, 2017 and 2019 experienced two minor peaks; minor peak months included January (x2), February, March, May, July (x3), August (x2), November and December. The year 2018 experienced a lot of fluctuation with no clear peaks. The rainy season is more variable in the South study area with September to April being the rainy season in Angola, and November to March in the Democratic Republic of Congo which appears to align with the primary peak in this region. The variation in timing of the rainy season between the North study area and South and sargassum biomass peaks appear to generally align.

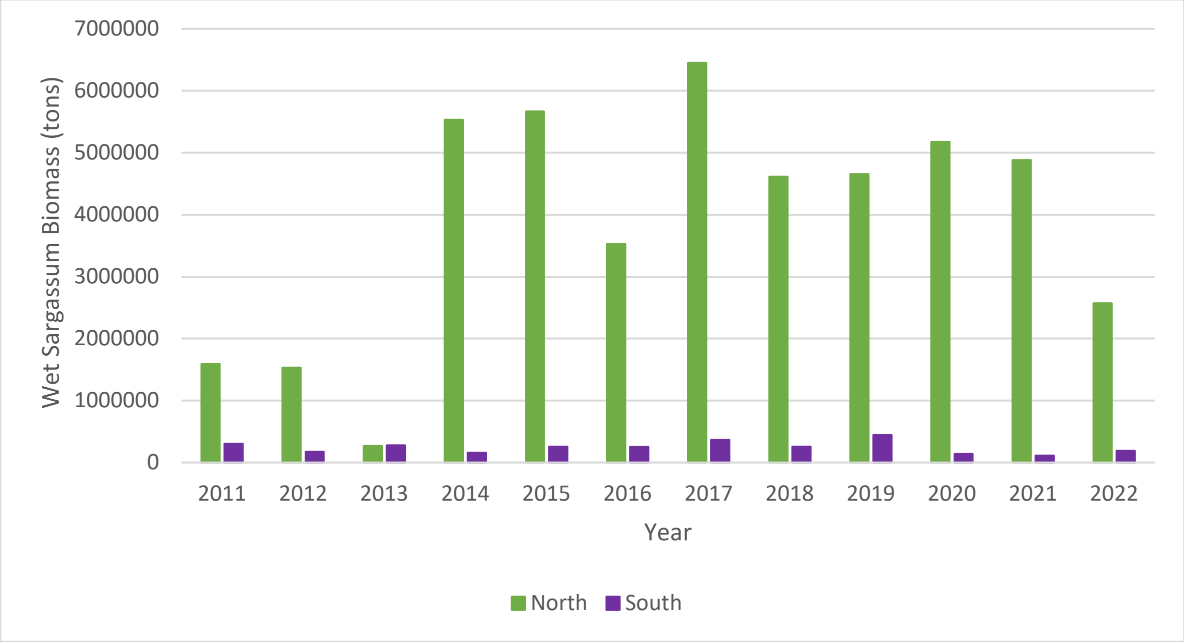

Figure 3 Annual accumulation of wet sargassum biomass for the Eastern Tropical Atlantic North and South study areas, January 2011 – August 2022.

In the North study area, the years with highest annual biomass accumulation were 2017 (6,450,252 tons), 2015 (5,668,610 tons) and 2014 (5,532,239 tons), which is unexpected as 2020 is the year with the highest September peak in monthly biomass (figure 3). In the South study area, 2019, 2017 and 2011 have the highest biomass accumulation of 441,534 tons, 366,749 tons, 301,008 tons respectively. Wang et al. (2018) showed that the years that reported the highest biomass in the Great Atlantic Sargassum Belt were 2015 and 2018. This demonstrates that the biomass accumulations in the Eastern Tropical Atlantic are not necessarily congruent with the rest of the Tropical Atlantic. To offer a sense of decadal change for the years with complete data (2011-2021) a linear regression was applied, for the North ($R^2 = 0.42$), which indicated a gradually increasing trend, and South $R^2 = 0.008$ which is not statistically significant, therefore sargassum biomass in the South region is stable.

The time-series and annual accumulation graphs (figures 2 and 3) also reveal the limitations of this detection and estimation method as gaps in the data set impact annual biomass accumulation figures. Gaps in the dataset are observed for 8 months in the North study area and 7 months in the South during the study period, these occurred due to high cloud cover in the images. Where five of these are consecutive in 2020 it makes identifying a second peak impossible and offers an explanation for this year not having the highest biomass. It also highlights the challenges surrounding the Inter-tropical Convergence Zone and dense cloud cover in the region for monitoring. There is a need for alternative monitoring and detection methods in this region for more reliable and higher resolution analysis. Another consideration is the depth of the mats, the method used for determining biomass aggregations does not consider the vertical direction, meaning that this time-series is indicative of the lower bound estimations.

To summarise the annual and seasonal variability identified in the time-series: in the North study area there are usually two peaks, a primary peak in September and a minor peak between March and May, with a small increase in biomass over the time period 2011-2022. In the South study area, there are also usually two peaks, with a primary peak most commonly occurring in July or August and usually one or more minor peaks occurring at another time in the year, along with a generally consistent annual biomass. The primary peaks of both study areas appear to fall within local rainy seasons.

3.3.3 Does sea-surface temperature, atmospheric and riverine/coastal nutrient inputs co-vary with sargassum in the Eastern Tropical Atlantic region between 2011 and 2022?

In this section, we explore if sea-surface temperature, atmospheric, and riverine/coastal nutrient inputs co-vary with sargassum biomass in both the north and south study areas. This is achieved through using the data outlined in table 1, and applying a cross-correlation analysis. We also explore connections to existing empirical literature. The UNEP Sargassum White Paper (UNEP, 2021) categorises proximal factors into causal pathways. Proximal factors are those elements that change local levels of abundance, or affect the movement of the sargassum. We do not suggest that proximal factors contribute to the presence or absence of sargassum. The factors explored here are broadly categorised into these pathways including: ‘sargassum exists elsewhere’, ‘transfer into a consolidation region’, ‘persistence/proliferation in a new consolidation region’, and we further these categories with the addition of ‘transport within a consolidation region’. To support this a historical timeline of events has been established (supplementary material).

Sea Surface Temperature: The Mann-Kendall Test Statistic was calculated to explore the trend in sea surface temperature (figure 4); for the North study area the results (value = 3.079; p-value 0.002) showed a significant increasing trend in the data, supported by a Sen's slope value of 0.006; and for the South study area the Mann-Kendall Test Statistic (value=1.432, p-value=0.152) suggests a tendency towards an increasing trend that is not significant, the Sen's Slope value of 0.006 supports this. These trend results indicate a potential co-variance of sea surface temperature with sargassum biomass, as the North study area has a significant increasing trend for both biomass and sea surface temperature, and the South study area has a slight increasing but not statistically significant trend for both biomass and sea surface temperature. Magana-Gallegos et al. (2023) found that in an *ex-situ* environment, different sargassum morphotypes respond to temperature differently; with maximum growth at 28°C for S. *fluitans* III, 22-25°C for S. *natans* VIII, and S. *natans* I at 25°C, all three experienced decreased growth at 31°c. When a correlation analysis was conducted for each study area, a non-significant negative trend was observed suggesting that when temperatures are lower, sargassum biomass is higher (figure 4). In every year, August has the lowest sea surface temperature in the North (usually between 25.7°C and 26.5°C, figure 4), and within the range of optimum temperatures for S. *natans* I and S. *natans* VIII identified by Magana-Gallegos et al. (2023). It also falls one month before the sargassum biomass peak suggesting a delayed temporal co-variance, which supports a negative co-variance. The South region also sees a sea surface temperature low in August in most years, but this does not co-vary as consistently with biomass. It is important to note that there could be simultaneous factors constraining growth at the same time in the South. The annual average sea surface temperatures for the Eastern Tropical Atlantic in all years fall in the range of 25.6-26.7°C in the South and 27.34-28.23°C in the North, this variation could be indicative that different morphotypes are dominant and thrive in each of the study regions. These observations raise further questions: could this suggest that (i) sargassum grows and reproduces outside of the Eastern Tropical Atlantic region in cooler waters and are transported to the east; or (ii) sargassum grows in the region but not at the maximum rate? Sargassum biomass and sea surface temperature appear to *experience a negative positive co-variation*, but the mechanisms of this require further investigation.

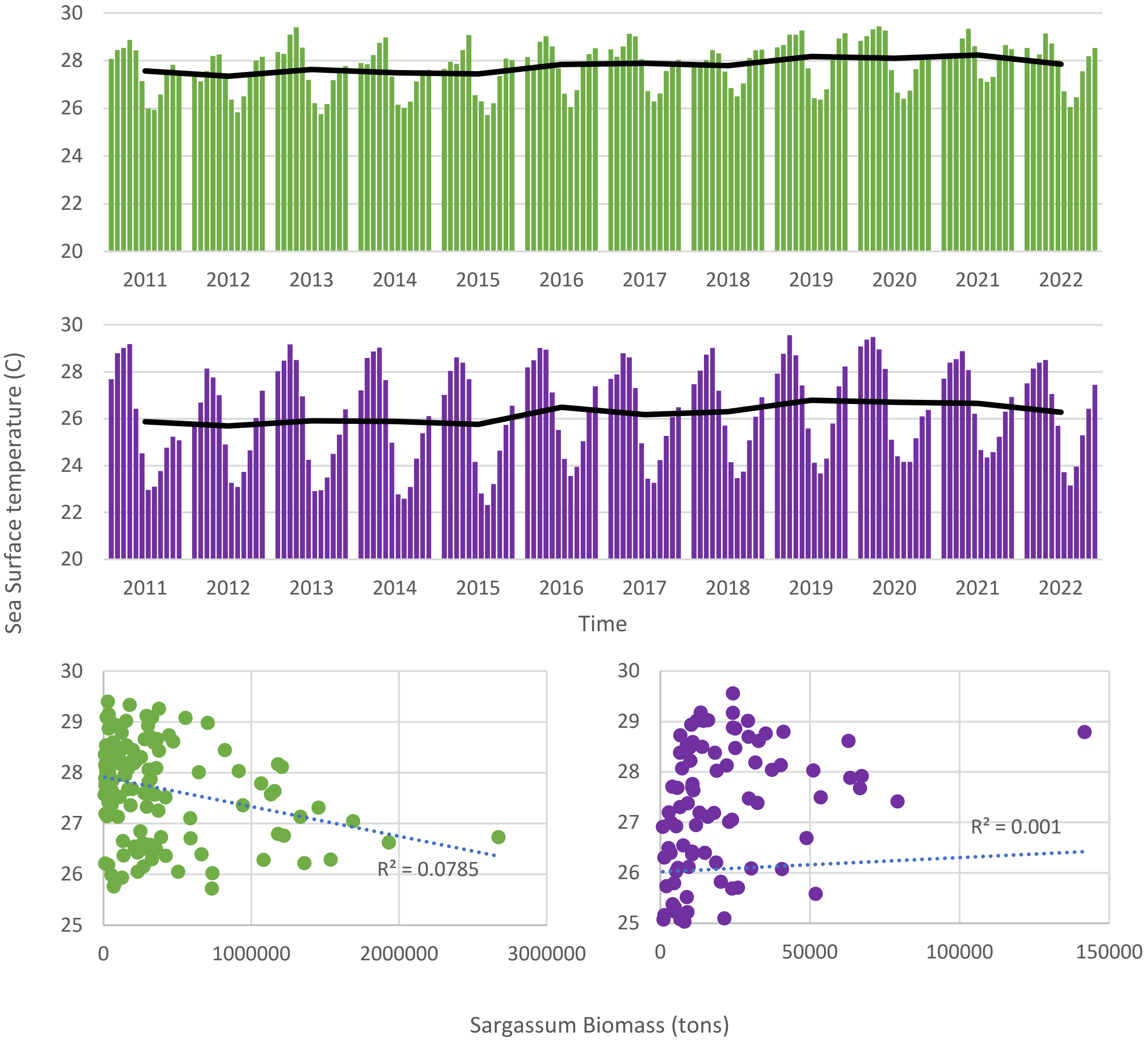

Figure 4 Monthly sea surface temperature (bars) with annual average (black line) for the Eastern Tropical Atlantic for North (green) and South (purple) study areas, and correlation analysis for sargassum biomass and sea surface temperature for each study area (north: green, south: purple).

Saharan dust: To estimate Saharan dust in the Eastern Tropical Atlantic, aerosol optic depth (AOD) offers an indicator (figure 5). For the North Study Area, the Mann-Kendall Test Statistic has a value of -0.6 and a p-value of 0.549, this indicates a non-significant tendency towards a decreasing trend; the Sen’s Slope value of -0.00015 supports a weak decreasing trend. Similarly, for the South study area, the Mann-Kendall Test Statistic has a value of -0.395 and a p-value of 0.693, which also indicates a non-significant tendency towards a decreasing trend; the Sen’s Slope value of -0.00012 supports a weak decreasing trend. This statistical analysis suggests there is *no co-variance in the trends of sargassum biomass and AOD for 2011-2022*. However, digging deeper we can observe some aligning occurrences; 2013 is the lowest year for AOD for the North and third lowest in the South, and both the North and South study areas having low biomass in this year. The peak year for AOD in both study areas is 2015, which has second highest biomass for the North study area but is much lower in the South. Upon finer examination of the monthly AOD it can be observed that in the North January-March sees the highest peaks of AOD with the exception of 2015 which was December. March 2012, February 2016, and February 2020 are the three highest monthly AOD peaks; March 2012 also saw a biomass peak, March 2016 saw a minor peak (one month delay), which *supports a monthly co-variation*, however there is missing biomass data for 2020 due to cloud thus we cannot confirm if the pattern is the same for this year. In the South study region, every year shows an August peak in AOD, except 2014 which shows a September peak, this suggests the biomass peak comes one month sooner than the AOD peak. In a study focusing on the Dominican Republic, Mendez-Tejeda and Rosado Jimenez (2019) suggested the possible influence of Sahara dust as a source of nutrients for sargassum growth due to the iron and phosphate contents. Xu-Yang et al. (2022) found that Saharan dust deposits were transported across the Atlantic and in Guadeloupe deposits contained iron, calcium, and potassium, contributing to nutrient cycles in the region. Whilst some publications acknowledge the role of Saharan dust nutrients, it has been considered less important than other nutrient inputs such as riverine and upwelling sources and upward fluxes (Wang et al., 2019; Johns et al., 2020; Skliris et al., 2022). However, Xian et al. (2020) showed that Saharan dust is found in higher concentrations in West Africa, compared to the Caribbean (specifically Barbados and Puerto Rico) suggesting it may be more significant for the Eastern Tropical Atlantic. Given the suggestions of existing literature, the statistical trend results, and the finer scale exploration of the data, we cannot make a confident conclusion about the co-variance of dust with sargassum biomass in either study area; we suggest that there is *no overall long-term co-variance, but there may be co-variance in shorter temporal periods* which needs to be explored further.

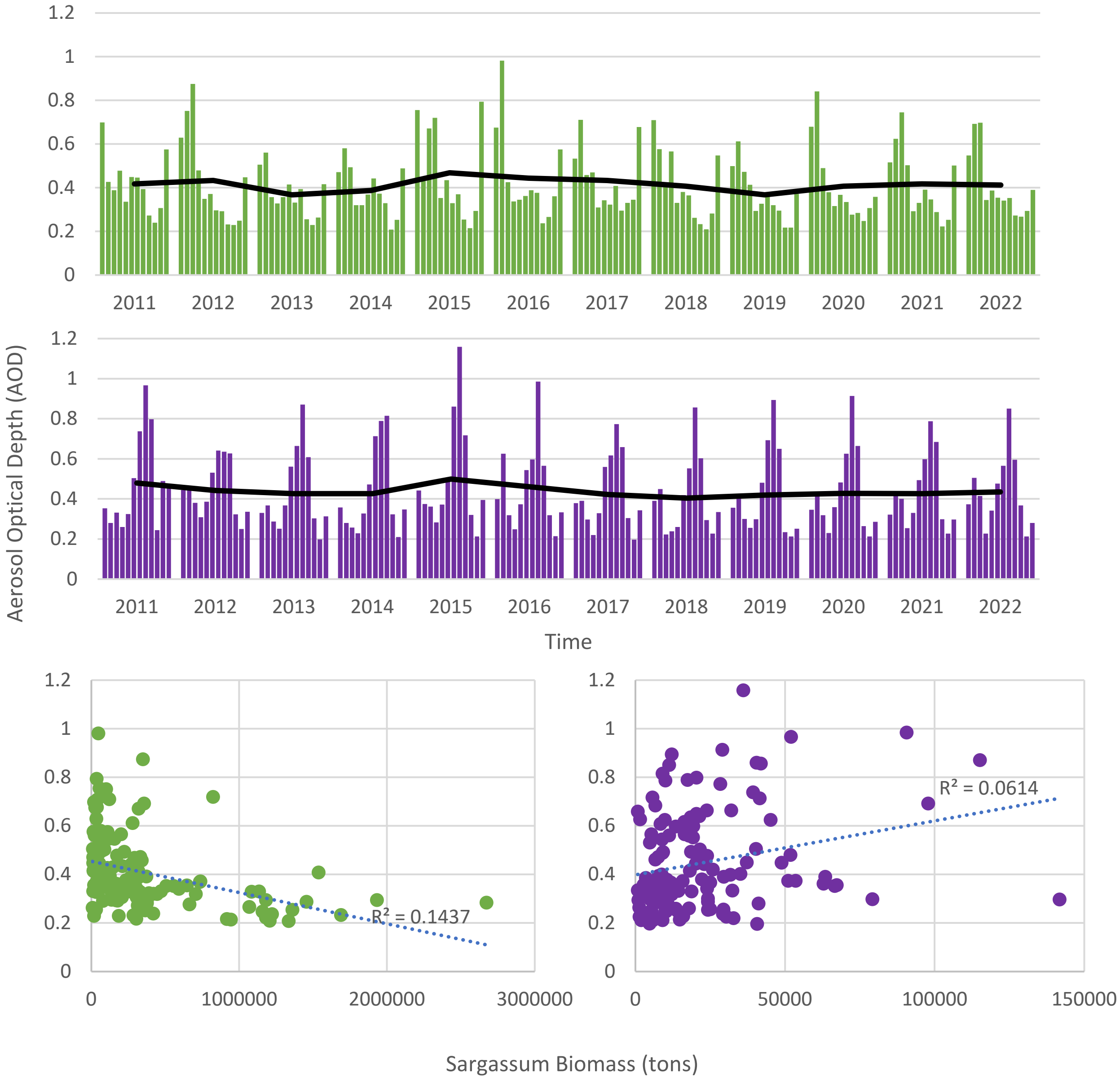

Figure 5 Monthly AOD (2011-2022) for each study area North (green) South (purple), with annual average indicated (black line), and correlation analysis for sargassum biomass and AOD for each study area (north: green, south: purple).

Water quality and river pollution: It has been suggested that nutrients from a variety of sources may be stimulating sargassum growth across the Tropical Atlantic Basin, including nutrients from rivers in the Eastern Tropical Atlantic such as the Congo which are transported by the Canary and Benguela Currents (Oviatt et al., 2019). Here we explore the anthropogenic interaction and pollution of rivers in the Eastern Tropical Atlantic. There are a variety of policies regarding water resources in West Africa, including Ghana's National Water Policy June 2007 which encourages efficient use of fertiliser to reduce pollution of water bodies; similar legislation addressing water pollution and use includes: Water Resources Commission Act 1996, and Nigeria's Water Resources Master Plan 2013. In Ghana small-scale illegal gold mining (known locally as galamsey) has gained popularity since the gold price increase in 2008, wastewater from the process is discharged back into rivers which usually contains mercury, phosphate, lead, copper, and iron pollutants and threatens or impairs water quality and aquatic life (Kazapoe et al., 2023; Faseyi et al., 2022; Miyittah et al., 2020). Similarly, in Nigeria the Minerals and Mining Act 2007 grants water use permitting rights when they concern mining exploration and operation. Whilst there are legislation relating to water policy, there is a failure to fully implement restrictions and a poor regulatory framework to address the implications of activities on the environment and water resources (Kazapoe et al., 2023). Macroalgae such as sargassum sequester large amounts of trace metals and many of these that relate to wastewater from mining have been found in sargassum, therefore there is the potential for interaction of blooms and water pollution (Davis et al., 2012; Tonon et al 2022). Iron particles have been shown to have a fertiliser effect on the growth of another sargassum species (S. *vulgare*) suggesting that it would support an increase in biomass; similarly, phosphate has also been correlated with intensification of fertility (Nassar et al., 2002; Gouvea et al., 2020). Mercury has been associated with the release of dissolved organic matter from sargassum (Heyes et al., 2018). Due to this combination of factors resulting from lack of enforcement of legislation, rivers joining the Atlantic system could have pollutants and nutrients which can support sargassum growth. To explore this, the diffusion attenuation coefficient for downwelling irradiation[1] (KD) is used (figure 6) as an indicator for water pollution, turbidity and suspended sediment. The Mann Kendall Test Statistic for the North study area was calculated as 0.683 with a p-value of 0.495, which indicates a weak positive trend that is not significant, this is supported by a Sen's Slope value of 2.062×10^{-5}. For the South Study area, the Mann-Kendall Test Statistic (2.153) and p-value (0.0313) suggest a statistically significant increasing trend, which is supported by a Sen's Slope value of 0.000194 that indicates a slightly positive trend. These KD statistical trends do not align with the trends of sargassum biomass in both study areas, suggesting that there is *no co-variance* for the time period 2011-2022. Exploring the data more deeply, KD is generally higher in the South study area (where the Congo River joins the Atlantic) with a peak in 2015 (KD > 0.159), 2017 and 2020 are also higher KD years, 2017 is the second highest year for biomass suggesting the potential for co-variance, however there is no co-variance with the other peak years. Comparatively, the North study region has generally lower KD with peaks in 2016 and 2019. It is possible that there is a delay where the following years see peaks in biomass (2017 and 2020).

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[1] The diffusion attenuation coefficient for downwelling irradiation (KD) is a measure of how light dissipates in water, it is an indicator of turbidity and is related to the concentration of scattering particles in the water column.

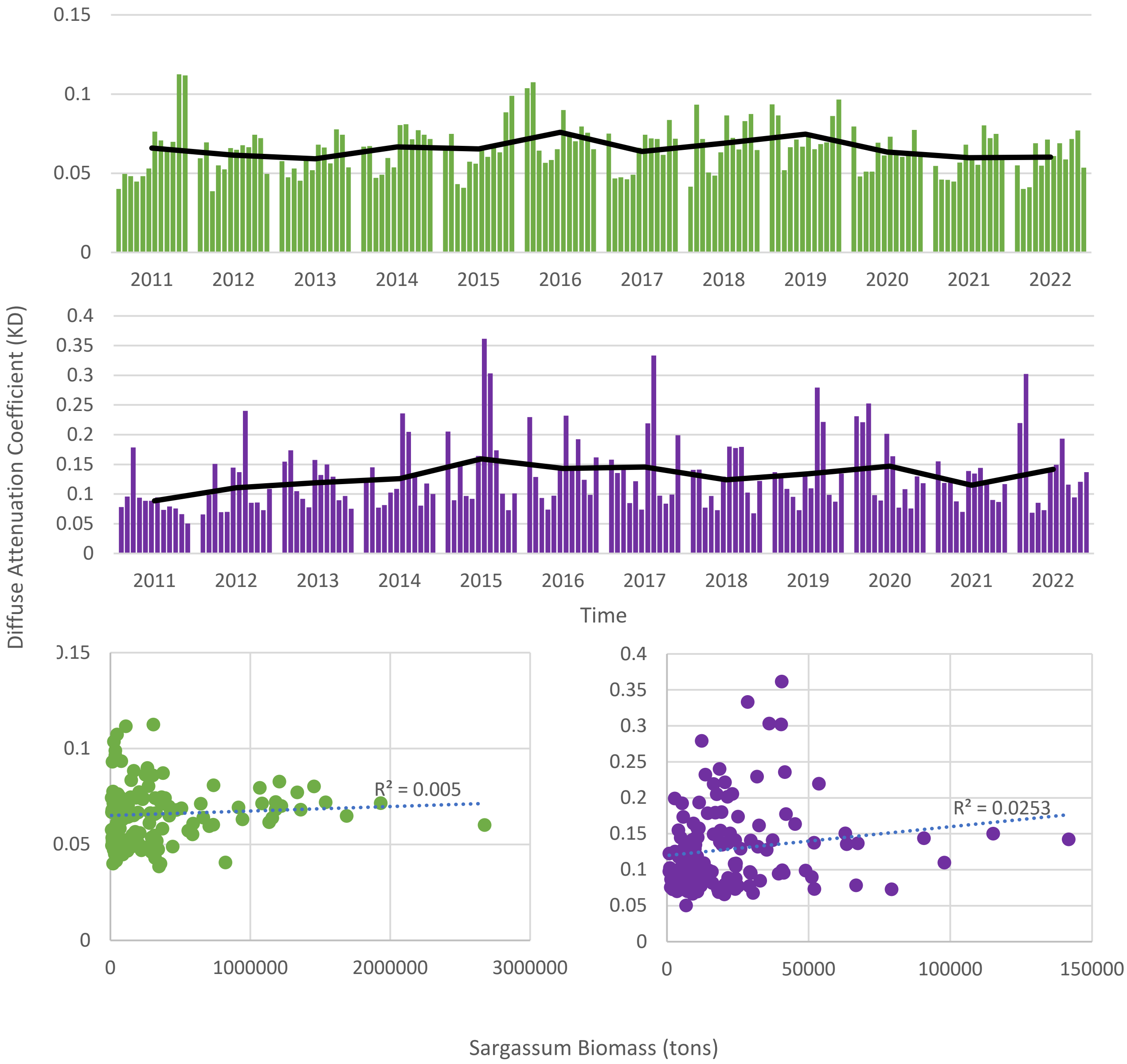

Figure 6 Monthly Diffusion attenuation coefficient for downwelling irradiation (KD) 2011-2022 (bars), North (green) and South (purple) study areas, with annual average (black line), and correlation analysis for sargassum biomass and KD for each study area (north: green, south: purple).

Monthly peaks in KD vary, where it most commonly occurred in the North in November and with more variation in the South but August and July being most common, suggesting potential co-variance with sargassum biomass peaks (supplementary material). A further cause of uncertainty in the data is distance from coast, we expect to see increased turbidity and sediment close to the coastline and less in the open ocean; the scatter plots and linear regression illustrate that the data is quite clustered with no clear trend, observing the near-shore and open ocean separately might enable distinguished trends to emerge, further work should include comparison of sargassum biomass and KD close to the coastline to the open ocean. Complex current and circulation patterns of nutrients and delays in heavy metal uptake by sargassum mean that co-variance is challenging to confirm from this data, thus more in-depth research is required to confirm the impact of riverine nutrients on sargassum blooms.

3.3.4 Are there any other large-scale atmospheric, oceanic, or other events that co-vary with sargassum in the Eastern Tropical Atlantic region between 2011 and 2022?

In this section we explore events which may co-vary with sargassum biomass in the Eastern Tropical Atlantic, including ocean salinity, NAO, volcanic eruptions, AMOC, ENSO and oil spills. The events explored are motivated by existing empirical literature which consider these factors. The analysis is a combination of quantitative and qualitative assessments which are discussed to draw out preliminary areas for further research, and further explored in the historical timeline (supplementary material). We continue to explore these events in the context of the categories for proximal factors into causal pathways outlined in the UNEP Sargassum White Paper (UNEP, 2021). For these events, it was not possible to access data specific to the north and south study areas separately, highlighting a need for more information and research in these areas.

Salinity: The impacts of salinity on sargassum growth have previously been explored with publications suggesting that low salinity hinders pelagic sargassum growth (Hanisak and Samuel, 1987), but Machado et al. (2022) note that this research was based in the Sargasso Sea and may not apply to Atlantic blooms and may vary between morphotypes. Similarly, for S. *muticum*, another species of sargassum, Steen (2004) found that in low salinity growth and reproduction are slower. Beyond this, there appears to be limited empirical publications on salinity and pelagic sargassum blooms. As such the co-variance of salinity is explored for the Eastern Tropical Atlantic; figure 7 shows the mean salinity for the period 2011-2022 is consistently between 0.035 and 0.036 kg the Mann-Kendall and Sen’s Slope results support that there is no statistically significant trend during this time period. However, it is worth noting that this is an annual mean for the whole Eastern Tropical Atlantic and there may be local variations which cannot be reported from this dataset. The upper bound or maximum salinity also has no statistically significant trend, but examining the minimum value shows a statistically significant increasing trend (value = 2.537, p-value = 0.0112, Sen’s Slope = 9.75×10^{-5}). The significant increasing trend of minimum salinity might indicate favourable conditions for sargassum biomass particularly as the trend of sargassum in the North study area also showed a gradual increase in biomass; however the lack of trend in mean and maximum salinity suggest it may not have a direct influence or that there are other mitigating factors to consider. We suggest that our analysis indicates that there is potential *co-variance of pelagic sargassum and salinity*, supporting previous studies, but that further exploration is required.

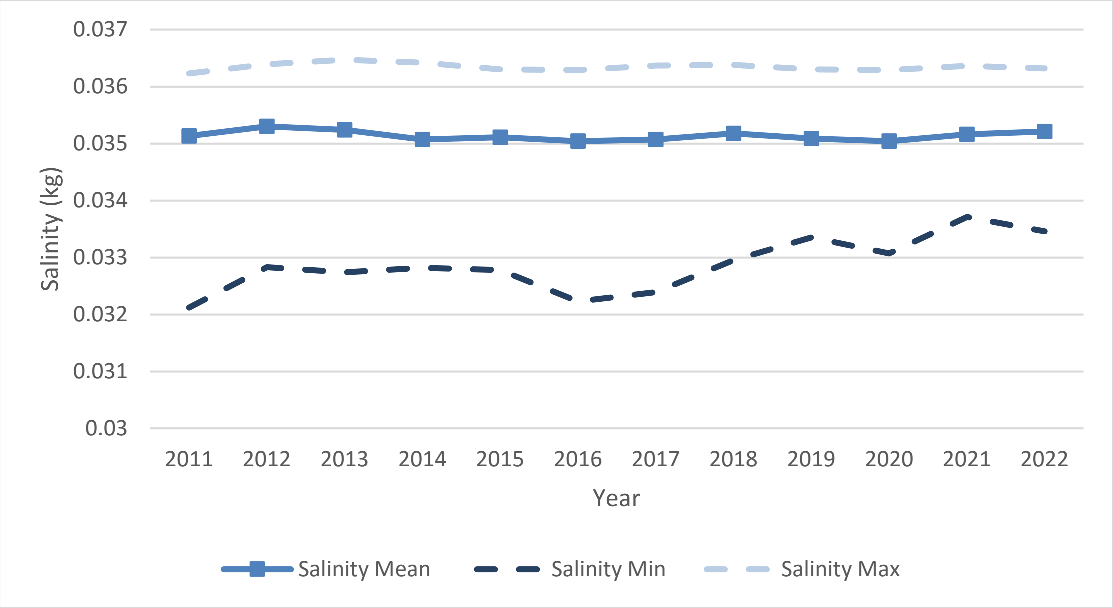

Figure 7 Annual salinity: mean, minimum and maximum values for the Eastern Tropical Atlantic. Mann-Kendall Test Statistic for Salinity Mean is -0.480; p-value 0.631; Sen's Slope -5×10^{-6}*; Mann-Kendall Test Statistic for Salinity Min is 2.537; p-value 0.0112; Sen's Slope* 9.75×10^{-5}*; Mann-Kendall Test Statistic for Salinity Max is -0.617; p-value 0.537; Sen's Slope* -3.67×10^{-6}*).*

NAO: Johns et al. (2020) identified that the NAO anomaly of 2009-2010 exported sargassum from the Sargasso Sea to the Tropical Atlantic. The NAO is an oscillation of sea-level pressure between the Icelandic Low and Azores High, resulting in changes in pressure which impacts the location of the Jet Stream and therefore ocean surface currents and wind fields. In positive phases, there are stronger trade winds, a northerly shift of the westerlies, and milder winters; in negative phases there are weaker trade winds, more southern westerlies, and cooler and wetter winters (Johns et al., 2020). Given the established connection between NAO and the initial movement of sargassum blooms in 2011, the NAO between 2011 and 2022 was considered to determine any potential continued influence on the movement of sargassum in the Eastern Tropical Atlantic region (figure 8). It can be observed that there were major negative NAO events (below -2) in June 2012, October 2012, July 2015, May 2019, and October 2021. There were major positive events (above 2) in April 2011, December 2011, December 2015, May 2018, and November 2020. There appears to be *limited co-variance* with the extreme NAO positive phases, however there is some overlap with the minor peaks and negative NAO; July 2015 (south), May 2019 (south), May 2019 (north) were months with minor peaks, but this pattern is not consistently observed. To attempt to account for delays or subsequent blooms, this can also be evaluated at an annual level; years with major negative peaks (2012, 2015, 2019, 2021) appear to have *no co-variance* with wet biomass estimates for either study area, similarly years with positive peaks (2011, 2015, 2018, 2020) don't appear to co-vary with sargassum biomass in the Eastern Tropical Atlantic. The trend statistics calculated (Mann-Kendall and Sen's Slope) indicated no statistically significant trends across the time period. Given the lack of apparent co-variance, we suggest that NAO positive and negative phases are likely not a causal pathway of sargassum biomass occurrence in the Eastern Tropical Atlantic.

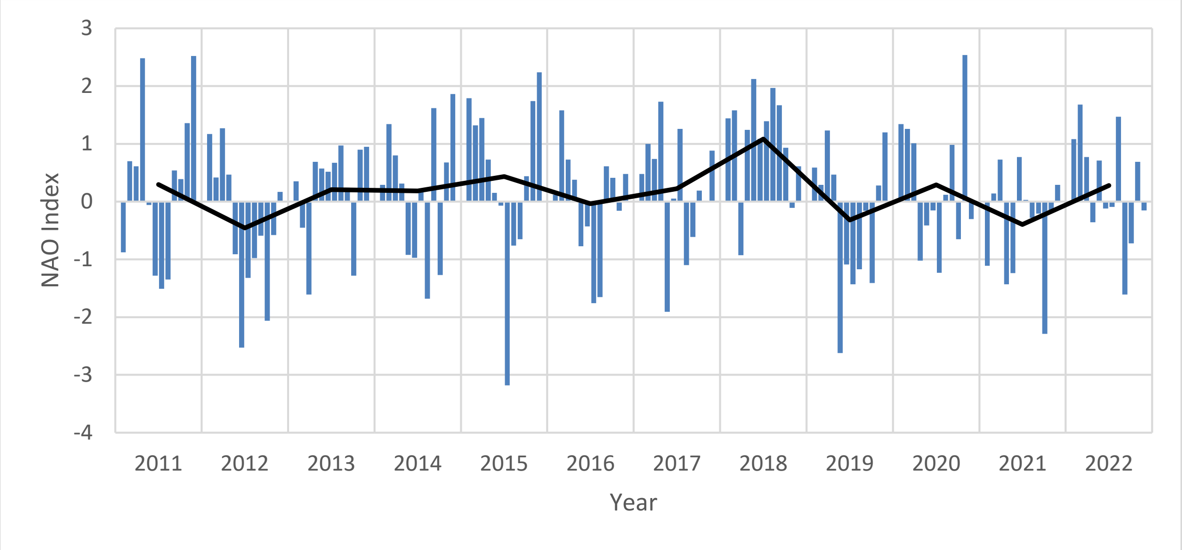

Figure 8 Monthly NAO index 2011-2022 (monthly values in blue, annual average shown in black). Mann-Kendall Test Statistic for monthly NAO is -0.1485; p-value 0.8819; Sen's Slope -0.0004).

Volcanic eruptions: Iron is an important external input for primary production in surface water areas as it is a limiting factor of algae growth in a wide range of aquatic environments, examples of external inputs include mineral dust and volcanic ash (Langmann et al., 2010; Natsuike et al., 2020). In the North Atlantic, a decrease in surface water dissolved iron with an increase in latitude has been observed due to declining atmospheric inputs, and this has been associated with iron stress (Wu and Boyle, 2002; Achterberg et al., 2018). In the Atlantic region since 2010 there have been five volcanic eruptions with a volcanic explosivity index >2. These were in 2010, 2011, 2014, and two in 2021 (see historical timeline in supplementary materials). It is hypothesised that these eruptions contribute a nutrient source, particularly supplying iron, and the effects of this on sargassum biomass may not be immediate and could be delayed, for example we see biomass peaks in 2011, 2015 and 2017, after eruptions.

AMOC: The AMOC is a transport mechanism moving heat from low to high latitudes in the Atlantic Ocean, where there is a northward flow of warm water and a colder deeper southward return flow. Multiple reports have shown that Atlantic circulation is likely to change in a warming climate including the 2001 Intergovernmental Panel on Climate Change (IPCC) report showing that AMOC could weaken. Srokosz and Bryden (2015) showed that there was a low AMOC event in 2009-10 where it declined 30%, followed by a general weakening over the next decade. The decline in AMOC was associated with changes in the heat content of the ocean and weather. Sargassum blooms appeared shortly after this decline and have propagated, therefore there could be *co-variance of sargassum biomass increasing as AMOC declines*. However, it is challenging to distinguish the effect of AMOC from other ocean and atmospheric factors such as sea surface temperature, currents, and wind.

ENSO: The impact of ENSO cycles on sargassum bloom seasons has been established in the Gulf of Mexico, where it has been shown that cold ENSO events supported an increase in the seasonal presence of sargassum, transporting them to the Gulf of Mexico and maintaining them (Sanchez-Rubio et al., 2018). However, the effect of ENSO on the Eastern Tropical Atlantic has not been established. The southern oscillation index (figure 9) shows El Nino phases (negative) and La Nina phases (positive); the statistical tests indicate a weak increasing trend suggesting positive La Nina phases are increasing, however it is not statistically significant. Despite this, it can be argued that there is potential for co-variance with sargassum biomass, as the biomass for the Southern study area shares these trend results, and the p-value is 0.07 which is close to the threshold for significance. Particularly strong El Nino phases can be observed in the latter part of 2015 and early 2016, some co-variation can be seen with the North study area where 2015 was a high biomass year, however there is *no co-variation* with the South study area. Strong positive phases can be observed in early 2011 and the end of 2020 into early 2021; 2020 was also a high biomass year for the North study region where it reached its maximum peak. It appears that there is *no direct co-variation* with ENSO and sargassum biomass in the Eastern Tropical Atlantic, however studies have suggested that ENSO has a role in the monsoon season in West Africa and that there is a Pacific-Atlantic relationship (Joly and Voldoire, 2009). The data *does not show a consistent or clear co-variance* for ENSO and sargassum biomass in the Eastern Tropical Atlantic.

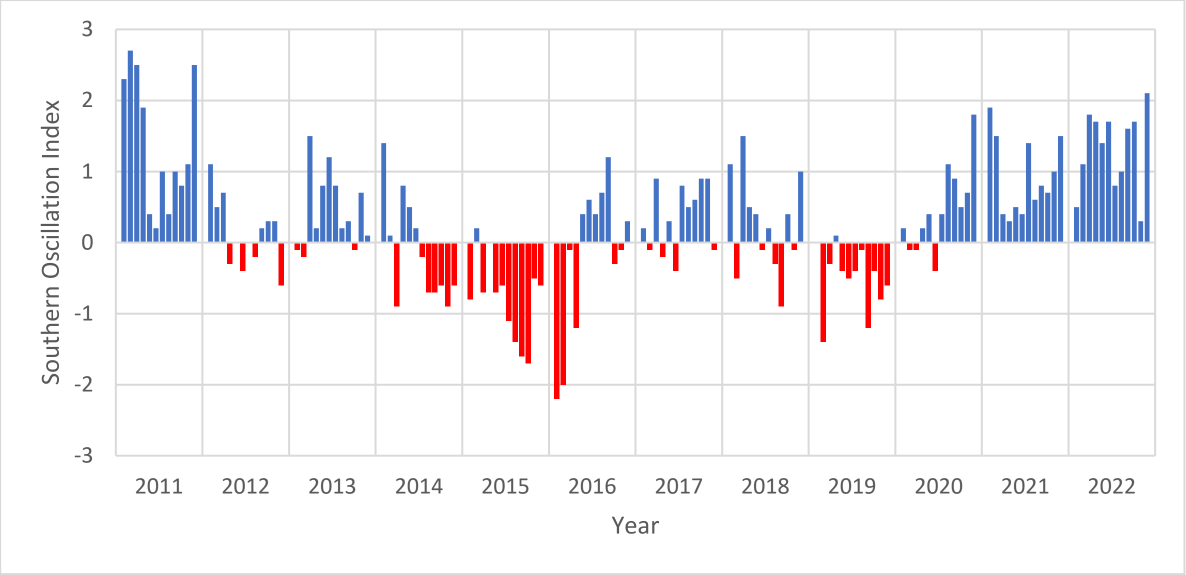

Figure 9 Monthly Southern Oscillation Index for 2011-2022 El Nino phases (negative, red) and La Nina phases (positive, blue). Mann-Kendall Test Statistic for monthly SOI is 1.814; p-value 0.070; Sen's Slope 0.00328).

Oil spills: Almeda et al. (2018) demonstrated a connection between oil spills and harmful algal blooms in the Gulf of Mexico, where they found that bloom-forming algae increased in concentration and grazers of phytoplankton decreased. They suggest that oil spills and dispersants disrupt predator-prey controls in plankton food webs creating ‘loopholes’ in the system for other species to thrive. Powers et al. (2013) note that a pool of oil from the Deepwater Horizon spill in the Gulf of Mexico came into contact with large floating sargassum mats causing impacts in three ways: it exposed organisms living in sargassum to high concentrations of oil and contaminants; application of dispersant caused sargassum to sink causing oil and dispersant to transport vertically; and it created a low-oxygen environment around the mat potentially impacting and stressing animals using the mat as a habitat. These publications indicate that there are two potential scenarios for sargassum: that they could thrive due to ecosystem alterations where there is a ‘loophole’ after an oil spill, or that they are sunk and removed from the surface due to oil spills. It is possible for both scenarios to co-exist. The Gulf of Guinea is a very active area for oil and gas exploration and in the historical timeline established (supplementary material) shows three significant oil spills in 2010, and others in Nigeria in 2011 and 2014. The coincidence of oil spills, commencement of oil extraction from a new oil field in Ghana, and the appearance of sargassum at around the same time has led communities in Ghana to believe they are connected, but there is no evidence base for this (Atiglo et al., *in review*). Many oil spills are unreported in West Africa, as shown by (Najoui et al., 2022), hindering our capacity to assess co-variance and establish a holistic timeline. As there is limited evidence for co-variance of oil spills and sargassum, a causal pathway for it cannot be confidently identified. Instead, we propose an additional pathway, as sargassum mats have been shown to sink and move vertically, there is the potential for oil spills to impact ‘transport within a consolidation region’. More research is needed to understand the impact of oil spills on sargassum growth and transport.

Co-variation discussion summary: Nine different factors were assessed for co-variance with sargassum biomass through using numerical qualitative data and descriptive reasoning. The factors were also investigated for their causal pathway based on the UNEP typology (UNEP, 2021), this along with the outcome of the co-variation assessment is summarised in table 3.

From this initial work, it is likely that salinity and AMOC experience co-variance with sargassum biomass in the Eastern Tropical Atlantic. As no co-variance, and no causal pathway could be established for NAO, the results suggest that it is not a driver of sargassum for the Eastern Atlantic Region, but its role in triggering the initial entry to the system is acknowledged (as shown by Johns et al., 2020). There is the possibility that salinity, Saharan dust, volcanic eruptions, AMOC, ENSO and water quality / river pollution are supporting the proliferation or transport of sargassum within the East Atlantic region. More work is needed to explore the nature of these relationships to either confirm its presence and to better understand the functional mechanisms, or to resolutely confirm it is not relevant. This is particularly true where variables are contentious notably water quality / river pollution and oil spills. As oceanic events, atmospheric events, and policy are intertwined and co-exist in the same space and time it is challenging to distinguish their effects from each other. This furthers the need for more exploration on drivers, specifically in the Eastern Tropical Atlantic including: more comprehensive detection of oil spills; exploration of the connectivity between oceanic and atmospheric events and rainfall with sargassum biomass; and water pollution monitoring with biochemical analysis to determine sargassum uptake of nutrients and pollutant metals.

Table 3 Summary of factors explored for co-variance with sargassum biomass in the Eastern Tropical Atlantic. Confidence in co-variance was established quantitively where possible and qualitatively based on the evidence explored (including regression analysis and existing literature); 'L' indicates low confidence; 'H' indicates high confidence. 'N.O/U' or 'N.D/U' indicates the driver has no observed/determined co-variance/pathway or is unknown.
Drivers listed in italics indicate exploration based on quantitative data observations with qualitative judgements, drivers listed in standard font were explored through reanalysing data from literature and qualitative assessments; water quality / river pollution uses both.

	Co-Variance			Causal Pathway			
Driver	Temporal co-variance	Temporal delay	None observed / unknown	Persistence / proliferation	Transfer to new	Transport within	None determined / unknown
Sea surface temperature	H	H					N.D/U
Salinity	H			H			
NAO			N.O/U				N.D/U
Saharan Dust	L			H			
Volcanic eruptions		L		H			
AMOC	H			L	L	L	
ENSO			N.O/U	L	L		
Oil Spills			N.O/U			H	
Water quality / river pollution	L	L		L			

3.4 Conclusions

For the first time, this paper characterises the seasonal and annual trends of sargassum bloom influxes in West Africa. We have shown that there is a statistically significant increasing trend of sargassum biomass in the North Eastern Atlantic Region, and a non-statistically significant trend in the South Eastern Atlantic region. We have also shown that the North and South regions have varying peak seasons, with the North typically in September and the South most commonly in July or August. Both regions also experience a second smaller peak, which varies in the South but is usually in March-May for the North. For the North region, 2017 had highest biomass accumulation and in the South 2019 (with 2017 second). However, we also highlight that there are challenges with this detection method, particularly associated with cloud cover in the Inter-tropical Convergence Zone. To enable effective management of sargassum blooms, there is a need for alternative methods to overcome the challenge that cloud cover presents and to address the gaps in the dataset.

Also for the first time, this paper has undertaken novel exploratory work generating hypotheses about the drivers of movement and proliferation of sargassum in Eastern Tropical Atlantic. This research shows that a variety of atmospheric and oceanic events co-vary with sargassum biomass. This does not prove causal relationships, but it highlights potential areas for future research into the drivers of movement and proliferation of sargassum biomass. We theorise that there is not a single dominating driver or causal pathway of sargassum, but there are many contributing factors and simultaneous events occurring within the system that have created the opportunity for sargassum to be transported across the region and proliferate. This work shows that a forward looking research agenda to better understand the drivers of movement and proliferation of sargassum should ideally include activities that explore the relative roles of (1) sea surface temperature, (2) sea salinity, and (3) nutrient inputs from natural and anthropogenic sources.

Acknowledgements for Chapter 3

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Author Contribution Statement for Chapter 3

YF: investigation, conceptualisation, methodology, data curation, formal analysis, visualisation, writing – original draft
JD: supervision, conceptualisation, writing – review and editing
DYA: writing – review and editing
PNJQ: writing – review and editing
KAA: writing – review and editing
WS: writing – review and editing
ET: supervision, conceptualisation, writing – review and editing

Supplementary Material to Chapter 3

SM3.1 Historical Timeline

SM3.1.1 Introduction to timeline method:

A historical timeline was established to collate events to explore their co-variance with sargassum biomass. An event was considered to be an occurrence or a change from the baseline, including long-term or short-term changes, as well as bounded individual events. The events were categorised into oceanic (relating to the ocean), atmospheric (relating to the atmosphere) and policy (relating to legislation). The decision to include events was based on previous literature which indicated a potential relationship with sargassum blooms for the wider or Western Tropical Atlantic region. If no time period was specified in literature, then data for 2010-2022 was included. The sources of data are noted in section 2.3 Assessing Co-variance, table 1 of the main text. The year and description of events were included. For the factors with continuous monthly or annual measurements, the extreme years were included as events in the historical timeline. To support visual assessment, oceanic events were categorised in blue, volcanic in red, atmospheric in green, policy in grey.

SM3.1.2 Historical timeline

Table 1 Historical Timeline of Oceanic, Atmospheric and Policy Events. Where entries are categorised by colour: blue represents oceanic events, red volcanic, yellow oil, green atmospheric, grey policy.
VEI: Volcanic Explosivity Index
SOI: Southern Oscillation Index
NAO: North Atlantic Oscillation

Title	Year	Description
Low AMOC (Atlantic Meridional Overturning Circulation) event	2009	Low AMOC event in 2009-10, followed by general weakening over the next decade.
Volcanic eruption: Pacaya, Guatemala	2010	May 27th 2010, explosive eruption with debris and ash columns (VEI:2)
Commercial Oil Pumping Begins in Ghana	2010	Offshore oil pumping begins in Ghana's Jubilee Field
Oil spill (Nigeria)	2010	ExxonMobil pipeline supplying crude to Qua Iboe Export Terminal, Ibeno, Akwa Ibom State coastline ruptured and spilled an estimated 33,565 barrels of oil into the Atlantic Ocean, Delta Rivers, coastal settlements ground and surface waters, fishing grounds and farmland.

Title	**Year**	**Description**
Oil spill (Gulf of Mexico)	2010	Deepwater Horizon, oil spill in the Gulf of Mexico caused by Wellhead blowout, estimated 3.19 million barrels
La Niña	2011	Cooler than average sea surface temperature (SOI greater than 2).
Sea Salinity Low	2011	Low sea salinity minimum (0.0321 kg).
Oil spill (Nigeria)	2011	Shell Nigeria Petroleum Company Bonga Oilfield spilled 40,000 barrels into the Atlantic Ocean, coastal settlements ground and surface waters, fishing grounds, mangroves and farmlands.
Volcanic eruption: Tagoro, Canary Islands	2011	October 2011 - March 2012, underwater eruption (VEI:2)
NAO Index Low	2012	Low annual NAO Index (0.45).
Sea Surface temperature Low	2012	Lowest average annual sea surface temperature (299.8 K).
Nigeria: Water Resources Master Plan	2013	Assesses water resources supply and demand from 2010 to 2030 and defines basin development priorities and risks.
Low aerosol optic depth (indicative of Saharan dust)	2013	High AOD in the Eastern Tropical Atlantic (reaching 0.37 in the North study area and 0.42 in the South)
Oil spill (Nigeria)	2014	Oil spill in Akwa Ibom State due to equipment failure, estimated 300,000 barrels into inland waters.
Volcanic eruption: Pico de Fogo, Cape Verde	2014	November 2014 - February 2015, fissure eruption, with lava and volcanic clouds (VEI:3).
High aerosol optic depth (indicative of Saharan dust)	2015	High AOD in the Eastern Tropical Atlantic (reaching an annual average of >0.5).
El Niño	2015	Warming of sea surface temperature (SOI greater than -1).
El Niño	2016	Warming of sea surface temperature (SOI greater than -2).
Nigeria: National Water Resources Policy	2016	Originally drafted in 2004, the National Water Policy was approved in 2016. The policy establishes that all water is a national asset and defines planning and development through an integrated water resources management framework (point 95 on pollution prevention).
NAO Index High	2018	High annual NAO Index (1.08).
El Niño	2019	Warming of sea surface temperature (SOI greater than -1).

Title	Year	Description
La Niña	2020	Warming of sea surface temperature (SOI greater than 1).
Ocean Salinity	2020	Annual Ocean salinity increase in the Eastern Tropical Atlantic (increase in annual minimum to 0.0331 kg).
Sea Surface temperature High	2020	Peak in average annual sea surface temperature (301.6 K).
La Niña	2021	Cooler than average sea surface temperature (SOI greater than 1).
Volcanic eruption: Saint Vincent and the Grenadines	2021	December 2020 - April 2021, effusive eruption, ash cloud and material produced. (VEI:4)
Volcanic eruption: Cumbre Vieja, Canary Islands	2021	September - December, Strombolian fissure eruption with lava, volcanic ash and material (VEI:2, increased in November to 3)
Ocean Salinity	2020	Annual Ocean salinity increase in the Eastern Tropical Atlantic (increase in annual minimum to 0.0337 kg).
La Niña	2022	Cooler than average sea surface temperature (SOI greater than 2).

SM3.1.3 Historical timeline analysis

The historical timeline allows visualisation of types of events, clustering, regularity, and patterns. It shows that oceanic events are the most commonly occurring type of event across the time period, and policy is the least commonly occurring event. The colour-coded timeline allows observation of clustering of events; in 2010 there was a cluster of oil related events, and in 2018-2022 all but two events are oceanic. From 2015 onwards the events become less mixed and more oceanic.

The historical timeline also enables long term interpretations of all the drivers collectively to be made. From the time-series analysis of biomass (main text, section 3.2 How much floating sargassum is there in the Gulf of Guinea, and what is the seasonal and annual variability?), it was observed that since 2011, the sargassum biomass has been increasing over time particularly in the North study region of the Eastern Tropical Atlantic. The preliminary observation can be made that both sargassum biomass and oceanic events have increased over this time period, which is indicative that there could be a connection between increasingly frequent ocean changes and sargassum. Whilst the historical timeline offers this overview and insight into potential patterns, it is also important to note that it is a coarse and potentially incomplete dataset which limits the capacity for deeper or fine scale analysis.

2. Sargassum biomass of North and South study area s combined together

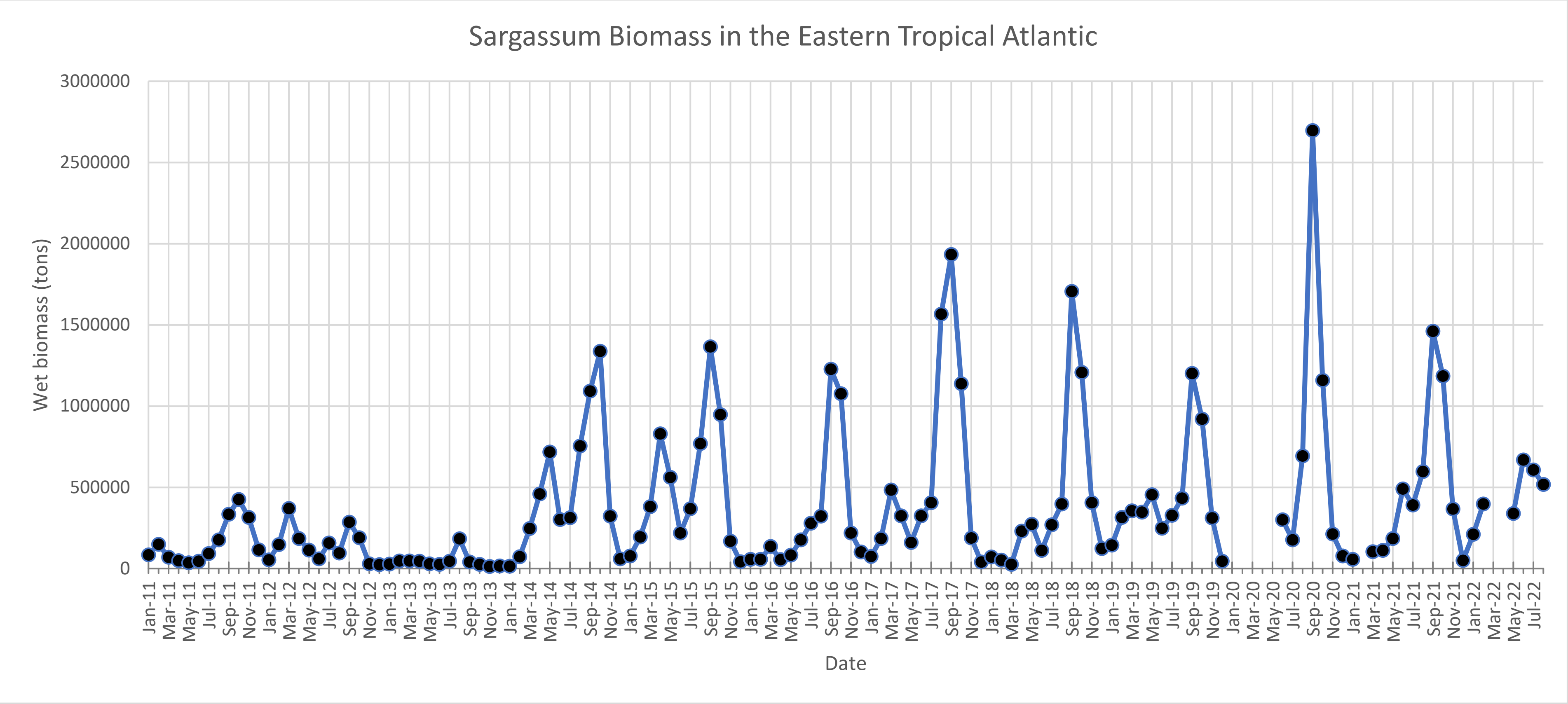

Figure 1 Time-series of monthly wet sargassum biomass (in tons) for the Eastern Tropical Atlantic, combination of the North and South study areas together.

Preamble to Chapter 4

In the second analysis chapter, two of the main research gaps identified in the systematic review are addressed. I assess both the characteristics of floating sargassum (shape, speed of movement, phenology, amount), and the transport pathways. This work uses a novel tracking method for monitoring sargassum to address objective 4 [TRANSPORT]. GPS trackers, with bespoke housing were designed and deployed in the Caribbean Sea on sargassum rafts and tracked using satellite imagery. Strides are made towards understanding the life cycle of floating mats and their aggregation, separation and decomposition patterns.

This chapter takes steps towards a better understanding of the life cycle of floating mats and their aggregation, separation, and decomposition patterns. Information about the nature of floating sargassum and its transport pathways can improve sargassum forecasting. The method developed by Yanna Fidai as part of this PhD has now been used for forecasting purposes – see Marsh et al., 2022. An underlying assumption of this thesis is that sargassum forecasts can be used to deliver interruptions to the cycle of cascading and interconnected risks loops to reduce vulnerability and increase resilience to blooms (see figure 1 in Chapter 6 section 6.3). This method in this chapter was designed to be low cost and accessible to community members, fishers, local government, to support widespread and extensive GPS tracker deployment across sargassum affected areas. I show in this chapter the importance of extended and expanding tracking opportunities to gather monitoring data in areas where satellite imagery is not available.

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Chapter 4 Tracking and detecting sargassum pathways across the Tropical Atlantic

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Abstract

Pelagic sargassum (S. *fluitans* and S. *natans*) algal blooms and beach landings have become a regular occurrence in the Tropical Atlantic Basin since 2011; they have a variety of impacts on the marine ecosystem and blue economy. To reduce the impacts and enable effective management, forecasting and monitoring of the blooms are essential. Challenges associated with use of satellite imagery for sargassum detection in the Tropical Atlantic are spatial resolution and cloud cover, which is particularly dense in this region due to the inter-tropical convergence zone, tropical storms and hurricanes. Successful models of forecasting and prediction of pelagic sargassum are hindered by unreliable satellite data, uncertainty around windage and as well as growth and mortality. In the longer term, we aim to improve the forecast models of pelagic sargassum mat movements in open oceans by introducing evidence of the speed of travel, changing mat morphology, and size and health status of sargassum mats. To achieve this, we deployed eight trackers on floating sargassum mats in the Western Tropical Atlantic. In addition, we explore the coincidence of surface currents, wind stress and sea surface temperature as a parameter for growth on the tracker pathways. When used in conjunction with both remote sensing methods and climate data (wind, current and sea temperature), we find that GPS tracker data can facilitate more reliable monitoring of sargassum transport pathways, helps to overcome satellite-based challenges as well as model based uncertainties, and may improve the accuracy and general utility of sargassum early warning systems.

4.1 Introduction

Pelagic sargassum (*S. fluitans* and *S. natans,* henceforth sargassum) blooms have become a regular occurrence in the Tropical Atlantic region, resulting in sargassum deposits across the region's shorelines. In 2018 it was estimated that there was over 20 million metric tons of sargassum biomass covering an area of almost 3000 km^2, subsequently coined the 'Great Atlantic Sargassum Belt' (Wang et al., 2019). There is uncertainty in both the initial trigger of blooms in 2011 and the subsequent drivers of bloom proliferation in subsequent years (Marsh et al. 2023). Regarding the latter, hypotheses invoke roles for ocean-surface circulation patterns, wind associated with the inter-tropical convergence zone, and nutrient enrichment (Johns et al., 2020; Lapointe et al. 2021; Skliris et al. 2022). Sargassum inundation events have the potential to disrupt social, economic and ecosystem functioning, and to negatively impact human health (Chavez et al., 2020; Fidai et al. 2020; Ramlogan et al., 2017; Sissini et al., 2017; Solarin et al., 2014; van Tussenbroek et al., 2017), and have been described as an emerging environmental hazard to coastal communities across the Wider Caribbean region and countries of West Africa (UNEP-CEP, 2021).These impacts have led to growing demand for methods to detect, track and forecast the sargassum.

Remote sensing has been widely used to detect and monitor sargassum in the open-ocean at different scales (Wang and Hu, 2016; Arellano-Verdejo et al., 2019; Wang and Hu, 2020; Laval et al., 2023; Marsh et al., 2023). Most satellite based monitoring of floating sargassum is done at the basin-scale using optical data collected by Moderate Resolution Imaging Spectroradiometer (MODIS), Sentinel-3 Ocean and Land Colour Instrument (OLCI), Visible Infrared Imaging Radiometer Suite (VIIRS) and Medium Resolution Imaging Spectrometer (MERIS) at spatial resolutions of 250 - 1 km. Optical satellite data collected at higher spatial resolution satellite of 0.5 m – 30 m tend to be used to fill in 'gaps' on local to near-shore scales (Marsh et al., 2023). Forecasting models that integrate satellite-derived sargassum data products have also been developed, see examples including Maréchal et al. (2017), Johnson et al (2020) and Marsh et al. (2021). Across scales, however, cloud prevents optical sensors from viewing the ocean surface. This is particularly acute in the East Atlantic region and in the inter-tropical convergence zone, making satellite data acquisition and, by extension, model detection and forecasting less reliable across the Tropical Atlantic Basin (Marsh et al., 2022).

A number of studies have trialled the use of drifters and trackers to contribute to understanding sargassum transport pathways. To develop transport models, Van Sebille et al. (2021) used sophisticated Stokes drifters, Surface Velocity Program drifters, and GPS trackers to simulate surface currents; Johnson et al. (2020) used drifters from the Global Drifter Program to identify ocean currents; Franks et al. (2016) utilised drifting buoys as part of the World Ocean Circulation Experiment for surface drift data; Putman et al. (2020) combined ocean circulation models and wind velocities with the use of oceanographic drifters and GPS trackers on sargassum mats to improve transport prediction models. However, these models are limited in their capacity to track individual mats. Van Sebille et al. (2021) highlighted a need for further improvements to hydrodynamic models to better forecast sargassum. Whilst models used for forecasting are useful, they are largely reliant on current and wind data to predict where sargassum ‘pixels’ detected from satellite imagery will travel. Additionally, a major uncertainty in model predictions of sargassum drift is the extent of ‘windage’, the fractional influence of winds on sargassum mats (Marsh et al., 2022). Further, there are limited data on the speed that individual mats travel, and on whether changes in size and morphology of mats are primarily due to growth and mortality/sinking of sargassum thalli, or simply the coalescence or fragmentation of sargassum mats along their transport pathway. Ody et al. (2019) use ship deck and satellite observations to typify the shape of mats, however, they also acknowledge the challenge of high cloud cover to observe the mats with remote sensing. Identifying speed of travel and changing mat morphology requires very high spatial and temporal resolution remote sensing and/or time at sea following and observing individual mats. Both of these approaches would be difficult and costly, constraining attempts to address this data gap.

Improvements in satellite technology and design, combined with more satellites, have resulted in cheaper tracking options that are more widely accessible to the science community and are therefore now being used for many different applications. For example, data from GPS trackers and satellites have been combined and used for a variety of purposes in marine environments including to track wildlife and marine fauna such as turtles (Hays and Hawkes, 2018). These data have also been used to track the transport pathways of individual pieces of litter in both ocean and riverine systems (Duncan et al., 2022). In New Zealand, GPS trackers in plastic bottles were used to determine the influence of wind and tides on dispersal of detached algae (Hawes et al., 2017). In a hazard management context, radio frequency identification and GPS trackers were used to track tree log transport movements during flood events (Ravazzolo et al., 2015). They have also been used for monitoring surface currents, and technological developments in tracking have facilitated bespoke design and development of drifters and buoys at lower cost than pre-made options (see examples: Herbers et al., 2012; Mansor et al., 2016).

4.1.1 Aims

We aim to develop a framework that would provide quantitative evidence on speed of travel, changing mat morphology, and health of sargassum mats which in turn would improve the forecast models of pelagic sargassum mat movements in open oceans. These empirical dataset fill the gaps created by cloud cover, and the temporal and spatial coverage of satellite imagery. To achieve this, the following sub-aims were undertaken: i) to design a tracker that can track pelagic sargassum in open ocean for weeks-months (including selection of tracker, design and testing of suitable GPS housing); ii) to detect sargassum transport pathways, and describe their coincidence with current speed, wind stress, and sea surface temperature, and determine the speed of travel of individual mats; and iii) to document the morphological and size and health condition changes of the sargassum mats during the lifespan of the trackers.

4.2 Methods

4.2.1 Tracker selection, housing design and deployment

The GPS tracker and housing were selected and developed to be as cheap as possible and made from readily available, non-specialist items such that the method is widely accessible and simple to set-up for replication by anyone from researchers to local government personnel, fishers and community members. Additionally, for supporting improved forecasting and monitoring in the future, the number of deployed trackers will need to be expanded. Keeping costs as low as possible should ensure that future upscaling of this method is not prohibitively expensive. The GPS tracker had to also satisfy the minimum requirements of being able to track off-shore in a marine environment, with coverage of the study area, and send multiple location updates per day to maximise potential pairing with satellite imagery. Other considerations in the design specification included operating temperature range and duration of power supply. The trackers that were researched and considered are discussed in more depth in the supplementary material.

Once the tracker was selected, the housing was designed. Trials were undertaken in pre-made cases but were found to have limitations (see supplementary material), as such we designed a bespoke housing from widely accessible materials. The housing was tested in a controlled environment and then in the near-shore at Southbourne Beach in the UK, before being deployed in sargassum mats in the Caribbean Sea. This was to ensure that the tracker and housing floated with minimal structure above the surface of the water and had a similar buoyancy to seawater (around 1022 kg/m^3), that it floated upright and did not overturn in high waves, and that it could tangle with the sargassum to successfully travel with the mat.

Once assembled, a label with contact details and project information was attached and the trackers and housing were deployed off the coast of Jamaica and Barbados, by researchers or fishers, on mats of sargassum that were classified as type 3 (windrows with small patches, a few metres in diameter), 4 (windrows dominated by large patches a few meters to a few tens of metres in diameter) or 5 (large quasi-circular patches that can reach hundreds of meters in diameter) (as typified by Ody et al., 2019) between August and October 2021.

4.2.2 Analysing the tracker pathways

The tracker pathways were downloaded from the Globalstar web service in '.csv' format. The tracker datasets were reformatted in Microsoft Excel to remove text formatting, empty/null cells, and non-location recordings of status updates such as power on and low battery alerts sent by the device. The data were then processed in 'ArcGIS Pro 3.0.0' software where the duration, distance and speed of travel were calculated using geoprocessing data management tools.

4.2.3 Tracking with satellite imagery

Optical data collected by the Sentinel-2 Multi-Spectral Instrument (MSI) have been previously used to detect sargassum (Wang and Hu, 2020; Leon-Perez et al., 2023). This dataset offers freely available high resolution data at 10 m resolution (Qi and Hu, 2021), where sargassum mats smaller than 10 m^2 can be identified, allowing detection of mat types 3, 4 and 5. In this study, we first used 'Sentinel Hub EO Browser' (EO Browser, https://apps.sentinel-hub.com/eo-browser/, Sinergise Ltd.) to explore the Sentinel-2 Level-2A data archive imagery and identify cloud-free images which overlapped spatially and temporally with the tracker positions. In a radius around the coordinates sargassum mats that could be associated with the tracker were searched for, with the radius size proportional to the amount of time that had elapsed between the time of image acquisition and the time associated with the tracker position. Average speeds of travel were calculated in section 3.2 to determine the radius. Sentinel-2 level-2A images were downloaded directly from the ‘Sentinel Hub EO Browser’ and further analysis was completed in ‘ArcGIS Pro 3.0.0’ software.

False colour imaging was used to highlight sargassum floating on the ocean surface, pixels with vegetation within the search radius were digitised as polygons. To determine the health status or ‘greenness’ of the floating vegetation the Normalised Difference Vegetation Index (NDVI) was applied using Sentinel Hub EO Browser. NDVI was selected as it is has been used successfully to discriminate sargassum and other floating vegetation in satellite imagery (see examples Hu, 2009; Dierssen et al., 2015; Hu et al., 2015); it also offers an indication of the health of the sargassum mat as values closer to 1 are indicative of ‘greenness’. The polygons and NDVI were then used to explore the morphology, size and health status of the mats.

It was not possible to use Sentinel-2 imagery for all trackers as some had substantial cloud interference, obscuring the view of the sargassum mats and tracker path. In the observation period, between August and December 2021, there were nine tropical storms (Fred, Kate, Julian, Mindy, Odette, Peter, Rose, Victor, Wanda) and six hurricanes (Grace, Henri, Ida, Larry, Nicholas, Sam) in the Western and Central Tropical Atlantic regions (National Hurricane Centre, 2023). These meteorological events made tracking with Sentinel-2 optical data challenging. As such we applied a method for sargassum detection using Sentinel-1 Synthetic Aperture Radar (SAR) developed by Biermann et al. (unpublished). SAR has a wide range of applications, including measuring vegetation biomass; it utilises microwave wavelengths and as such has all-weather day and night capability, meaning it provides ground observations regardless of clouds, storms and hurricanes and time of day (Malenovský et al., 2012; Torres et al., 2012).

Operational implementation of this automated method involved two main steps: preparing the data using a processing chain for Sentinel-1 SAR data, and detecting Sargassum (Biermann et al., unpublished). The SAR processing chain is composed of several steps. These include the downloading of Ground Range Detected High-resolution (GRDH) Interferometric Wide (IW) swath mode data from the NASA Alaska Satellite Facility (ASF) Distributed Active Archive Centres (DAAC); application of orbit file for accurate positioning; removal of thermal noise and GDR border noise; masking of land with 2-pixel extension of the shoreline; calibration for calculation of backscatter coefficient measurements for VV and VH; and calculation of the SARgassum Index (see supplementary material) to improve positive contrast between sargassum and water. Sargassum patches of at least 400 m^2 in size were detected using a two-stage approach described in Kurekin et al. (2018). In the first stage, a constant false alarm (CFAR) detector was applied to calculate target-to-clutter ratios (TCR) and discriminate pixels containing sargassum. Detected pixels with TCR values below 1.6 were masked as water, and TCR values above 3.0 were masked as vessels. In the second stage of automation, bright pixels with TCR values between 1.6 and 3.0 that met 8-pixel connectivity were grouped as sargassum patches, and a contouring algorithm was applied (Biermann et al., unpublished). Due to large numbers of false detections arising from strong atmospheric disturbances, an additional manual step was done to mask storms. Resulting output shape files were then explored and analysed in Arc Pro 3.0.0 software.

4.3 Results

4.3.1 GPS tracker and housing

The GlobalStar SPOT TRACE was selected as the most appropriate GPS tracking device as it gave hourly location updates in near-real time via the GlobalStar satellite network, had an browser-based interface or alternative mobile phone application, was relatively low cost, had a long battery life, and its compact size allowed it to be accommodated in small waterproofed housing easily. It had also been previously used in ocean environments in surface drift experiments (Novelli et al., 2017) and been found to have >2.5m accuracy for 95% of recordings (Meyerjurgens et al., 2019).

Through trialling different materials and combinations to make to GPS housing, it was established that the density required to float was approximately 1000 kg m^{-3}, slightly lower than Tropical seawater. Table 1 shows the various combinations of weight (plasticine) as a proportion of the container that were trialled in the basin and their outcomes. To create the heavy stable base, it was found that plasticine, homemade dough and sand gave identical results as they are similarly dense materials when packed as a base weight. However, it was found that using rocks caused the housing to float at an angle or horizontally due to air gaps between them. The housed tracker needed to have a low centre of gravity (dense material in the base) to ensure upright attitude.

Table 1Combinations of material proportions trialled for GPS housing. The percentage is a representative proportion of 1 L plastic bottle, excluding the space occupied at the top by the tracker.

Trial number	**Weight**	**Silica Beads**	**Foam**	**Outcome (plasticine/sand/dough weight material)**
1	0%	70%	30%	Floated horizontally on the surface
2	20%	40%	40%	Floated diagonally
3	30%	40%	30%	Floated diagonally
4	40%	40%	20%	Floated nearly upright with a portion of the bottle above the water surface
5	50%	40%	10%	Floated upright with the lid just above the surface
6	60%	30%	10%	Floated upright with the lid at the surface
7	70%	20%	10%	Sunk

Combinations 5 and 6 (table 1) were tested in the near-shore coast at Southbourne beach, UK. They both withstood the 2 hour test, however the height above water for combination 6 (figure 1) was thought to be more appropriate as the profile appeared to more closely match the seaweed floating on the surface.

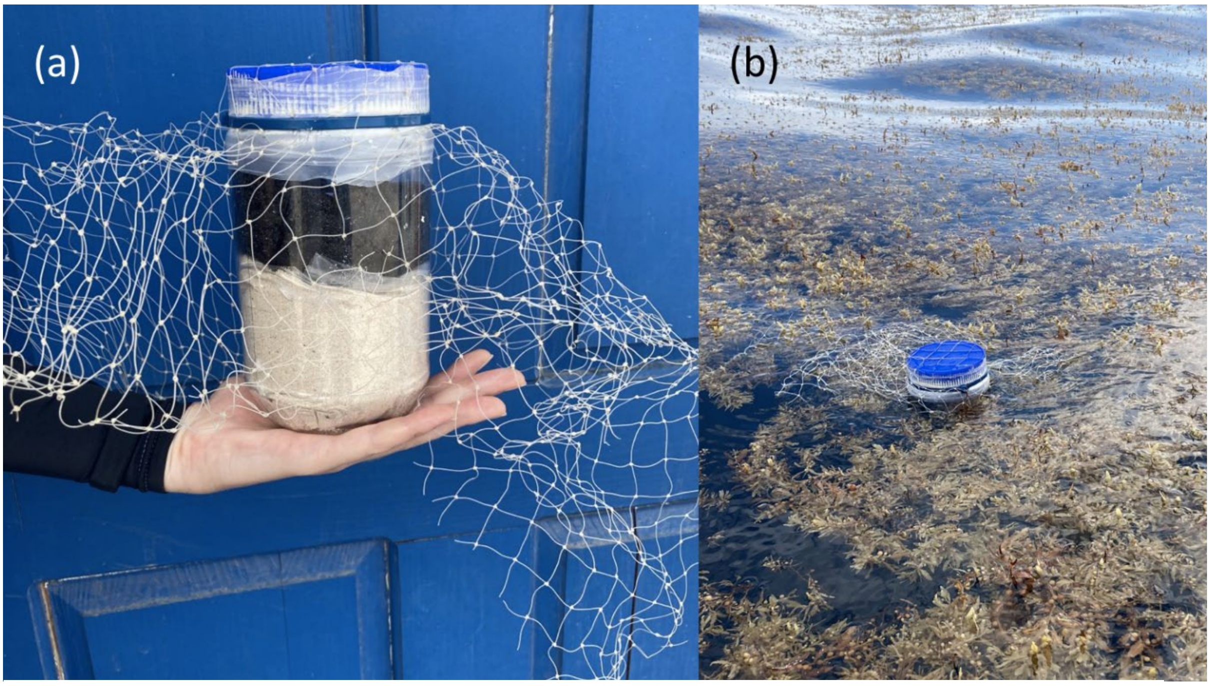


Figure 1 The successful GPS housing design, (a) prepared for deployment and (b) deployed onto sargassum mat. From bottom to top: a dense weight (sand) at the base in a plastic bag, a layer of packing foam above this, then the GPS tracker flush against the screw-top lid of the bottle, with gill netting secured by a zip tie.

After exploration, the housing GPS ‘recipe’ included: 1L plastic jar/bottle, sand or plasticine to act as a dense weight at the bottom, packing foam, optional silica beads to absorb moisture that may enter (can be replaced with extra foam), and the SPOT tracker sitting at the top against the lid which was sealed with silicone and parafilm and had gillnetting (or similar material such as chicken wire) (approx. size 60 x 60 cm) wrapped around to tangle with the sargassum (figure 1). Through the tests and exploring of different materials, we expect that users of this method could substitute most materials for alternatives that are found locally.

4.3.2 What was the journey taken by the trackers?

Five trackers (numbered 1, 3, 6, 7, and 8) were deployed off the coast of Barbados and two off the coast of Jamaica (4, 5) (figure 2, table 3). These locations were selected as they experience regular sargassum influxes and were accessible by researchers and fishers for deployment. All trackers, regardless of their starting point moved across the Caribbean Sea in a similar overall direction, where the final location recordings for them were in a north-westerly direction from where they began (figure 2). Tracker 7 is the exception where it appeared to have been picked up by a boat based in St. Lucia as we watched it make regular trips out to sea and back to shore, where it remained stationary for long periods of time. Tracker 8 landed on the east coast of St. Lucia within 7 days of being deployed. Both the trackers deployed off the east coast of Jamaica travelled north around the island through complex local eddies and currents. Tracker 5 was initially deployed 02/10 but it returned to shore with sargassum on the same day and was redeployed. The last recorded location of tracker 5 was on the Caribbean coastline of Mexico’s Yucatan Peninsula, and tracker 4 travelled into the Gulf of Mexico.

Tracker 4, followed by tracker 1, recorded the most location updates, but did not last the longest number of days (table 2). Tracker 7 recorded location updates for the longest number of days, however as it was picked up by a boat the data were not useful for tracking sargassum (and as such is henceforth discounted from average calculations). Tracker 5 lasted one day less than tracker 1, but recorded significantly fewer location positions, a number of potential reasons are hypothesised for this, including: battery, poor connection with the satellite due to wave action, and water entering the housing. We hypothesise the same potential explanations for the shorter lifespans of trackers 3 and 6.

Figure 2 Tracker pathways depicted as lines, dates and speed of trackers in table 2.

Table 2 Tracker pathway analysis, including duration, distance, and speed. Average speed was calculated using position geometry, recorded speed is the mean speed as recorded by the tracker converted from mph to cm/s. Tracker 7 is discounted from the summary statistics at the bottom of the table as it was not tracking sargassum for most of its lifespan (results are rounded to 2dp, and mean is used to calculate the average speed).

Tracker	Dates	Time (Days)	Time (Hours)	Number Of Positions Recorded	Distance (Km)	Average Speed (mean) (cm/s)	Average Recorded Speed (mean) (cm/s)
1	09/08/21 – 05/11/21	88	1397.90	932	1622.30	32.22	25.28
2	No data due to battery failure						
3	09/09/21 - 24/09/21	15	360.26	311	430.93	33.33	24.17
4	01/10/21 - 15/12/21	65	1810.76	1043	2434.16	37.22	27.22
5	02/10/21 - 28/12/21	87	2100.59	84	2092.54	27.78	19.72
6	25/09/21 - 16/10/21	21	509.42	239	653.79	35.56	35.56
7	31/08/21 - 25/12/21	116	2781.37	314	1022.62	01.28	35.00
8	28/09/21 - 05/10/21	7	168.60	95	180.60	29.72	21.94
Average		47.17	1057.92	450.67	1235.72	32.78	25.56
Minimum		7	168.60	84	180.60	27.78	19.72
Maximum		88	2100.59	1043	2434.16	37.22	35.56

Trackers 4, 5 and 1 travelled the furthest distances across the Caribbean Sea (table 2). The average speed calculated from the distance and number of hours between the first location recording at deployment and last recording, shows that the tracker speed ranges from 27.78 to 37.22 cm/s, averaging 32.64 cm/s (discounting tracker 7). The tracker itself records the speed of movement at the same time the position is recorded; the average tracker-recorded speed was 25.56 cm/s, which is 6.94 cm/s lower than the average speed calculated from the data. In the Atlantic region, the predominant ocean surface current speed is 5-15 cm/s, but near more energetic eddies and major currents, the predominant speed is 20-40 cm/s (University of Miami, 2013). This supports that the observed movements are influenced by surface current speeds, for example, tracker 4 is the fastest moving tracker and it can be observed that it is transported through eddies around the Jamaican coast.

Figure 3 shows the tracker positions overlaid with monthly-mean surface currents from a high-resolution ocean model hindcast (Megann et al., 2022). The currents are highly variable in both space and time, with the strongest flows (exceeding 100 cm/s in places) found near the western boundary, where the North Brazil Current transitions to the Guiana Current and the Caribbean Current, progressing from southeast to northwest. Figure 3 highlights that the GPS trackers largely stay in the slower flows (0.2 – 10 cm/s), with the exception of tracker 4, following the swift Caribbean Current (over 50 cm/s) that exits the Yucatan Strait in December.

In Figure 4, the effect of wind on the trackers is considered, with monthly means of the wind stress used to force the hindcast. The trade winds that dominate the study region are predominantly blowing westward throughout the deployment period, with peak strength in the Caribbean, weakening from August to October before strengthening to December. Westward blowing winds aid tracker drift in this general direction. Tracker 4 travels through the Yucatan Strait in the opposite direction to wind, suggesting that strong currents play a significant role in GPS tracker movement. Tracker 1 likewise drifts across the prevailing winds through the Mona Passage, where the current also dominates tracker drift. In conclusion, the transport direction of the trackers is not consistently congruent with wind stress direction, suggesting that current is more significant than wind for transporting sargassum.

To further explore the size and health of sargassum mats, the hindcast sea surface temperature is considered in Figure 5. The trackers deployed in August, September and October were deployed in relatively warm waters, between 28 and 29.5 °C, and the trackers generally stay in areas between these temperatures, with the exception of trackers 4 and 5. In December, tracker 4 experiences lower temperatures, down to 26 °C, and tracker 5 down to 27 °C. Marsh et al. (2023) suggest that sargassum grows optimally at 26 °C and that mortality increases above 28 °C, suggesting that the waters in which the trackers drift through August, September and October are too warm for maximum sargassum growth. However, it has been shown that different sargassum morphotypes have different growth rates in different temperatures (Corbin and Oxenford, 2023; Magana-Gallegos et al., 2023). These studies suggest that S. *fluitans* III has a maximum growth at 28°C, whilst S. *natans* VIII, and S. *natans* I appear to prefer lower temperatures (22-25°C), all three experience decreased growth at 31°C (Magana-Gallegos et al., 2023). This suggest that in the months of August to October that S. *fluitans* III in particular could be thriving, which is further supported by the work of Corbin and Oxenford (2023) who shows that S. *fluitans* III grew significantly faster than the other morphotypes over a temperature range of 27 - 30 °C.

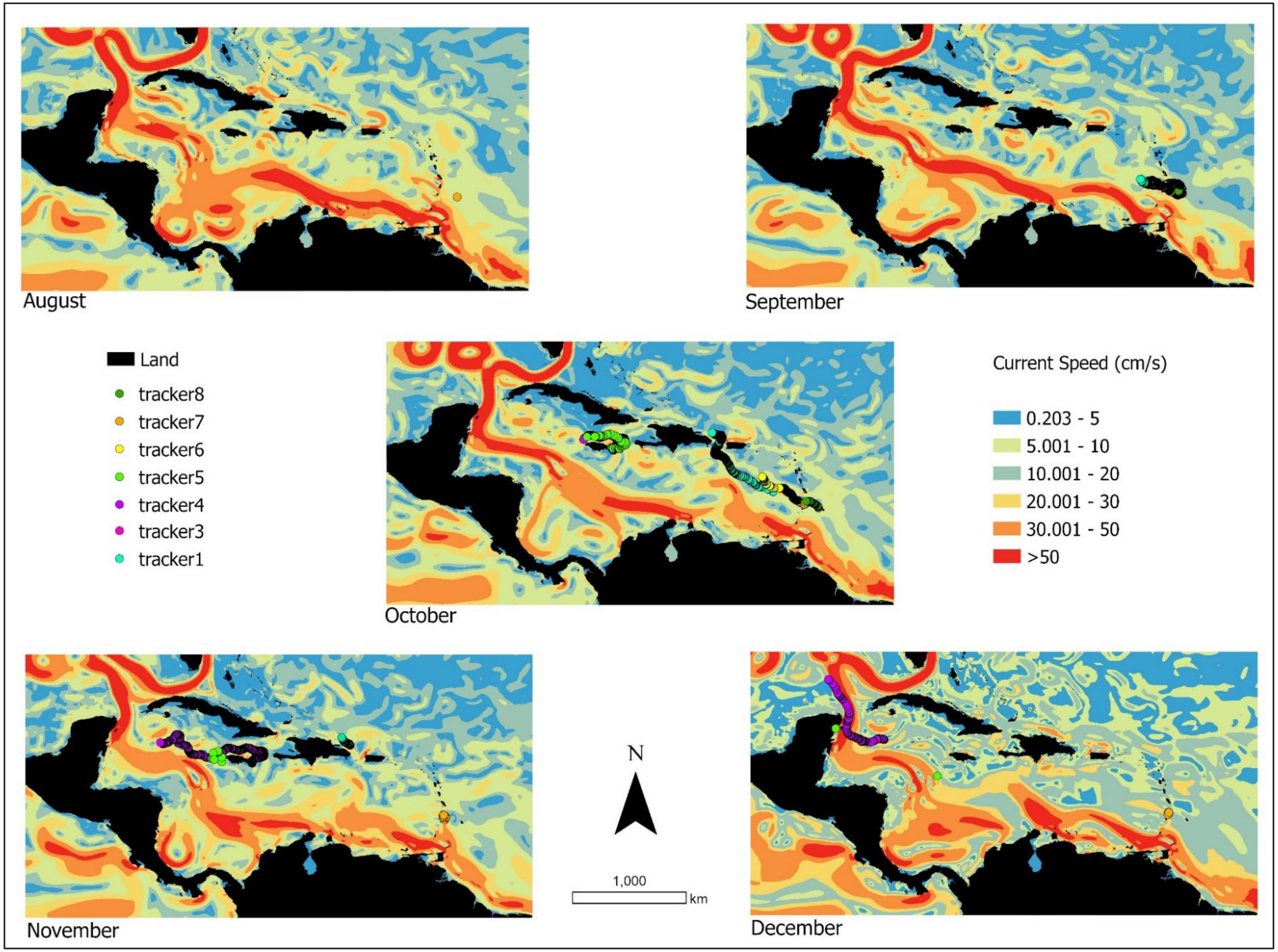


Figure 3 Hindcast surface currents for the duration of tracker data acquisition, obtained with ORCA12 version of NEMO ocean model (Megann et al., 2022).

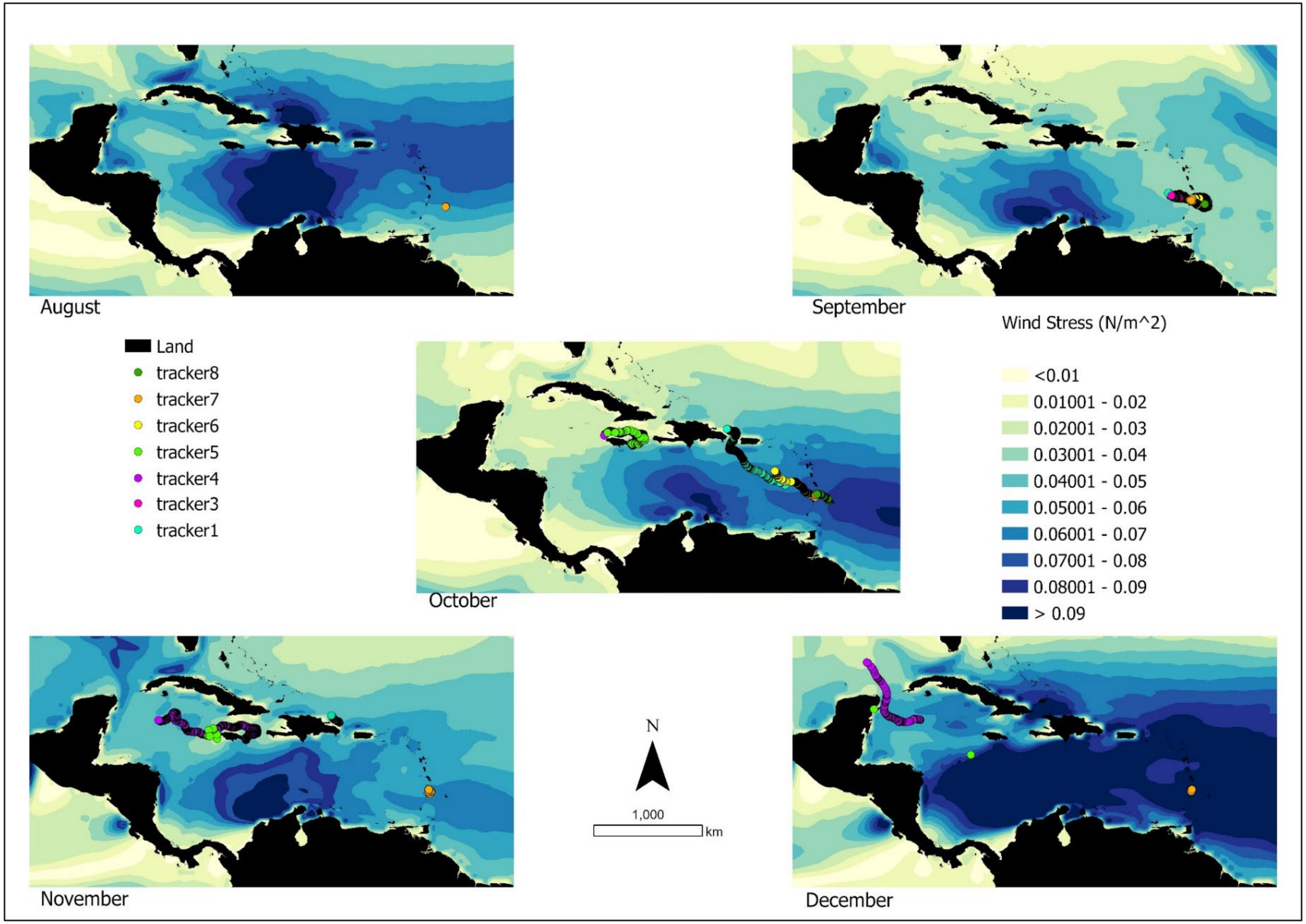
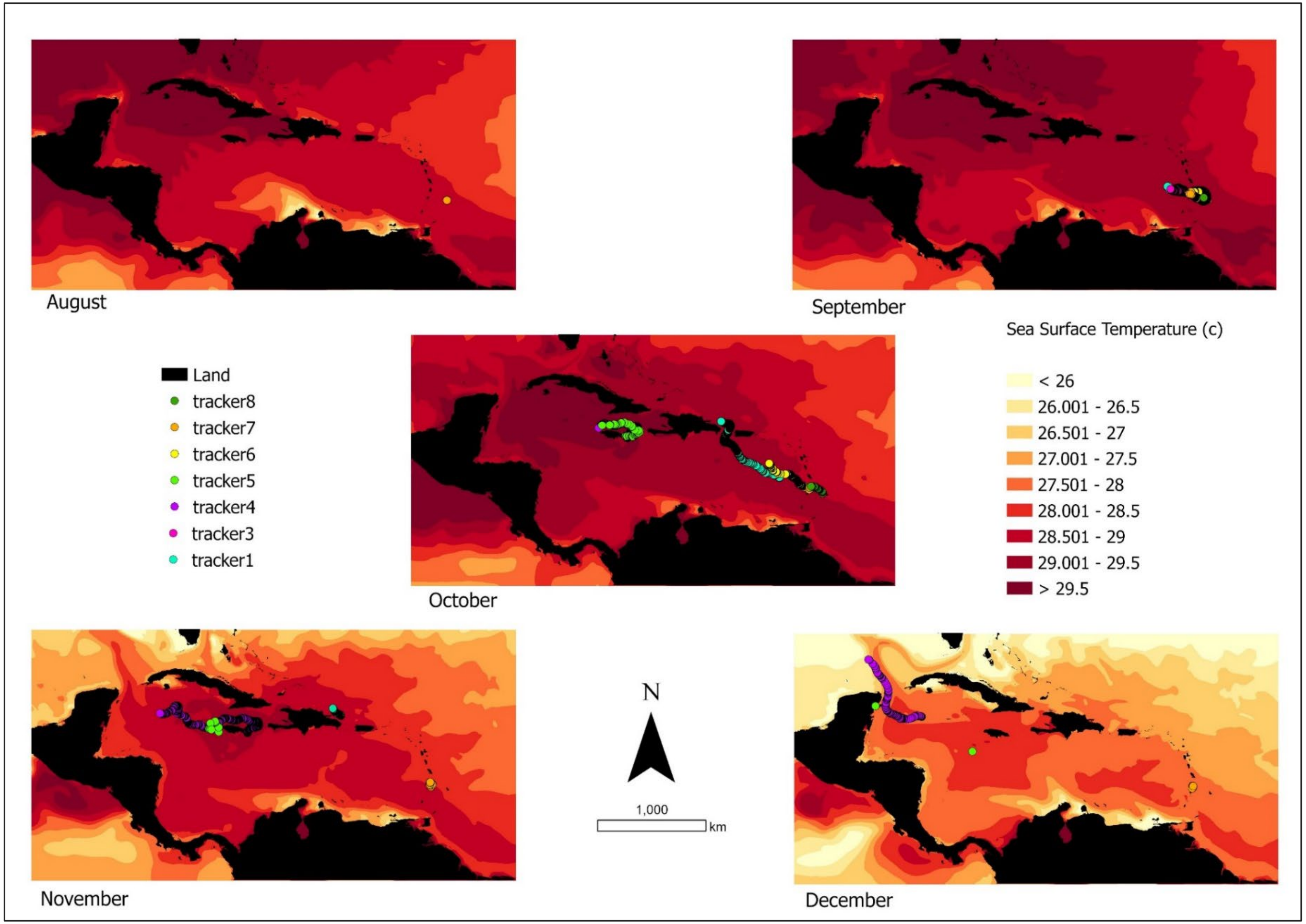


Figure 4 Monthly wind stress (in Newtons per square metre) for 2021 overlayed with tracker positions (wind stress data obtained from with ORCA12 version of NEMO ocean model (Megann et al., 2022)). In the Caribbean Sea, in August, November and December the wind direction is southwest from the Lesser Antilles towards Venezuela and Columbia, and in a south-westerly direction into Central America (Panama/Costa Rica). In September and October the wind ravels in a Westward direction from the Lesser Antilles, and then Southwest into Central America. Between Mexico and Cuba, in August, September, and October the wind travels in a Westerly direction (from Cuba/Jamaica to Mexico), and in November and December in a South/Southwest direction (from Cuba to Mexico).

Figure 5 Monthly Sea surface temperature overlayed with GPS tracker positions for data acquisition months. Sea surface temperature data obtained from with ORCA12 version of NEMO ocean model (Megann et al., 2022).



4.3.3 What can we understand about the change in size and health of the tracked sargassum mats?

The following section draws on Trackers 1 and 4 as they had the highest position frequency and longer tracked pathways.

Using the average speed calculated above to determine the search area, five images in sentinel-2 imagery were found that overlapped with the transport pathway of tracker 1. Three of these images contained sargassum (Figure 6).

In the first image (10/09/21) the sargassum raft appears more faintly with a vegetation signal across a few pixels, two aggregations within the search radius can be observed signalling that its morphology was type 4. The NDVI ranged between 0.50 and 0.70. From the imagery, a minimum area of 1200 m^2 was estimated for the mats combined, with a total perimeter of over 120 m. Nearby pixels in the image with moderate NDVI values (0.2-0.5) could be observed, indicating mixed pixels, where sargassum rafts were likely present but less than 10 m supporting that type 4 windrows were present and suggesting that the sargassum presence is higher than detected.

In the second image (06/10/21) with the main aggregation morphed in a tear-drop shape and smaller patches formed to the east, indicating multiple type 5 mats had formed, with one very large one. The area estimated for the largest patch was 16,280 m^2 with a perimeter of nearly 780 m. The total area estimated for the sargassum within the search radius of the tracker was over 27,600 m^2 (equivalent of nearly 4 football pitches) and the total perimeter was nearly 2900 m. The orientation of the aggregation indicates that it travels with the largest patch at the forward end and the smaller patches at the tail. The sargassum is likely to have grown between the images, Corbin and Oxenford (2023) indicate that sargassum doubles in biomass between 13 and 31 days depending on the species morphotype and temperature. Given that there are 26 days between the images, it is likely that the biomass grew as well as was aggregated with other mats by wind and currents to form this larger mat. Furthermore, the NDVI ranged between 0.6 and 0.9, indicating a stronger ‘green’ signal than the first image. This indicates that the sargassum mat was showing new growth. The increase in greenness (higher NDVI value) could also be due to mortality and sinking of ‘browner’ sargassum (lower NDVI values) between images.

The third image (19/10/21), shows fragmentation of the large aggregation where the total area estimated is close to 9000 m^2 and total perimeter of the aggregations is close to 1600 m. The NDVI ranged between 0.3 and 0.9, the wider range indicated that there was a weaker ‘green’ signal in some areas of the mat than previous images, which was indicative of the sargassum ageing (becoming more brown). Two images at the end of October and start of November did not contain any visible sargassum, within the search radius or beyond. As the aggregation appears to grow and peak in size and then fragment and become smaller overtime, it was hypothesised that the sargassum continued to fragment and was formed as type 1 or 2 mats, which cannot be detected easily by Sentinel-2 due to its resolution. Additionally, given the declining NDVI it was further hypothesised that the sargassum may have continued to age, loosing gas bladders, and ultimately sunk. It can be observed in figure 5 that throughout its journey in September and October this tracker stays in water that is 29 – 29.5 °C, and in November 28.5 - 29 °C. Following Marsh et al. (2023) this would suggest that sargassum is experiencing a growth factor close to 90% of peak in September and October, and close to peak in November. Where the aggregation grows in early September, we must consider that there are other variables supporting its growth, such as nutrients, or that a specific morphotype is growing faster (as shown by Magana-Gallegos et al., 2023). Alternatively, wind causing sargassum to coalesce could also be a factor of apparent mat growth especially where temperature may not be optimal for growth, the wind stress at the maximum area of the tracked sargassum is moderately high at 0.06-0.07 N/m^2 (figure 4).

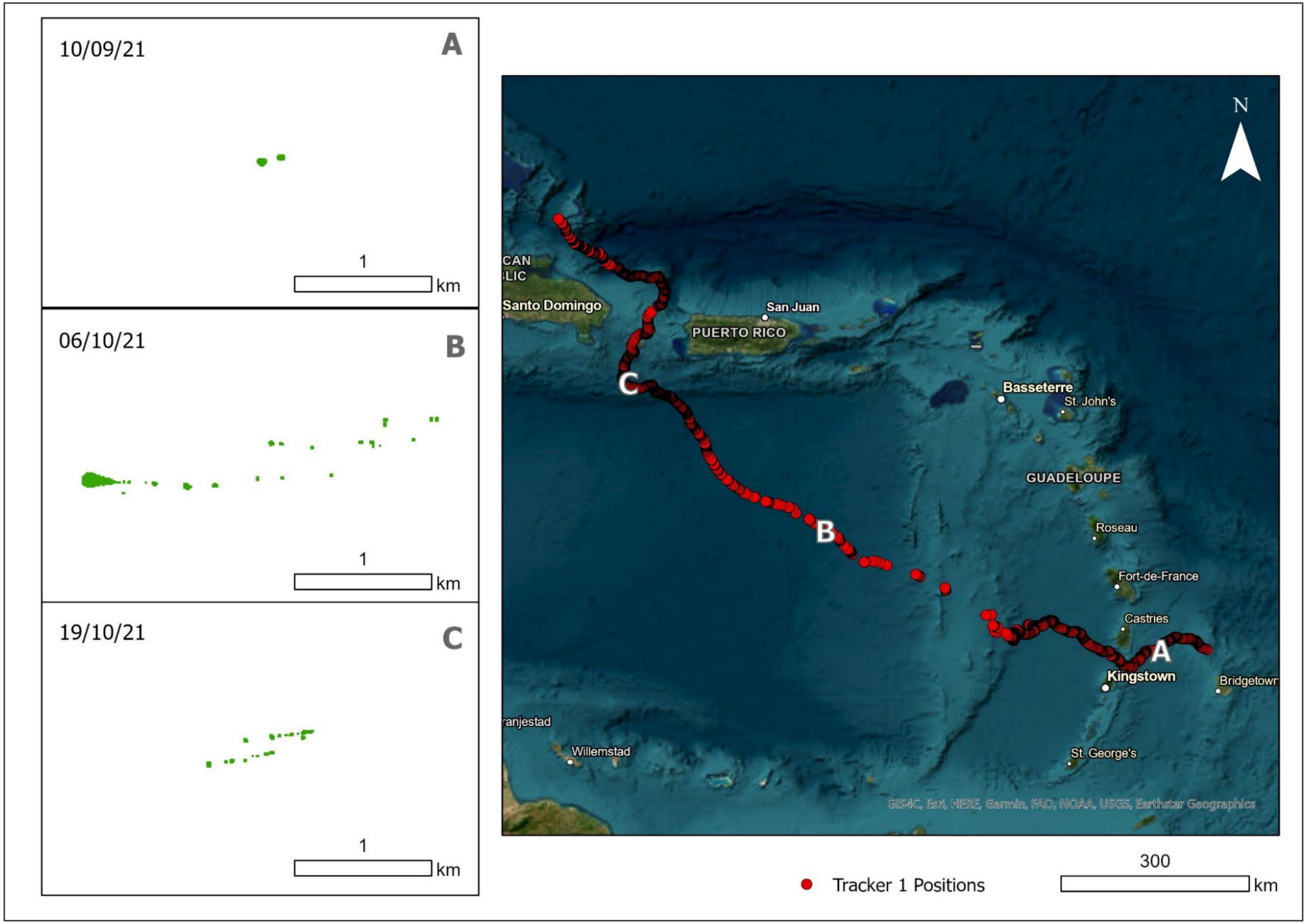


Figure 6 The morphological changes of the sargassum mat tracked identified using sentinel-2 imagery. The left panels (A-C) show the pixels identified as floating vegetation and the change in morphology across the journey can be observed, the position and pathway of the tracker and detected mats are indicated on the right.

As the positions for tracker 4 were heavily obscured by dense cloud and storm cover it was not possible to identify the sargassum mats associated with the tracker using Sentinel-2 imagery. Therefore, to detect sargassum along the tracker pathway, an alternative method using sentinel-1 SAR data was applied. A total of eleven scenes which overlapped spatially and temporally with the tracker pathway were identified and processed for sargassum detection. After this, the average speed calculated above was used to determine the search area to identify the sargassum mat associated with the tracker. Four polygon aggregations were identified from four scenes (presented in figure 7).

In the first scene (02/10/21), a single large polygon was identified with an area of 17,162 m^2. In the second scene (07/10/21), two medium polygons with a total area of 21,517 m^2 were identified within the search radius. The third scene (15/10/21) had the smallest polygon with an area of 609 m^2, and the fourth scene (12/12/21) a single polygon with an area of 1,830 m^2. The progression shows that the sargassum aggregation grew by over 3000 m^2, before significantly shrinking, indicating a similar pattern to tracker 1. However, there is a significant temporal gap in the tracking using SAR between the third and fourth detections of over one month. Whilst four scenes were available in this time gap, none of them contained detections within the search radius of the tracker, the nearest sargassum detection was over 4 km from the tracker pathway. Given that sargassum was detected towards the end of the tracker path (D), it is theorised that during this time gap the sargassum mat formation was too small to be detected using this method. However, separation of the tracker and sargassum mats is also a possibility.

The size and orientation of the polygons indicate that they are type 5 aggregations detected. The rectangular morphology and orientation suggests they are similarly positioned to image B of tracker 1 (figure 6) as the long-side of the rectangles are usually perpendicular to the direction of travel. Image B (figure 7) is an exception to this where the south polygon is orientated with the short-side (111 m) parallel rather than the long-side (120 m), this detection is nearly square which indicates it is not a false flag such as a ship. A possible explanation for this shape and orientation is that there are adjacent type 5 aggregations beside each other which have been grouped together by the automated detection method. Due to the resolution of the detections, it is not possible to determine if there are smaller windrows or aggregations adjacent to the large mats detected. Using SAR for detecting mats is limited by challenges in calculating NDVI and therefore understanding the health status of sargassum is not possible from this detection method.

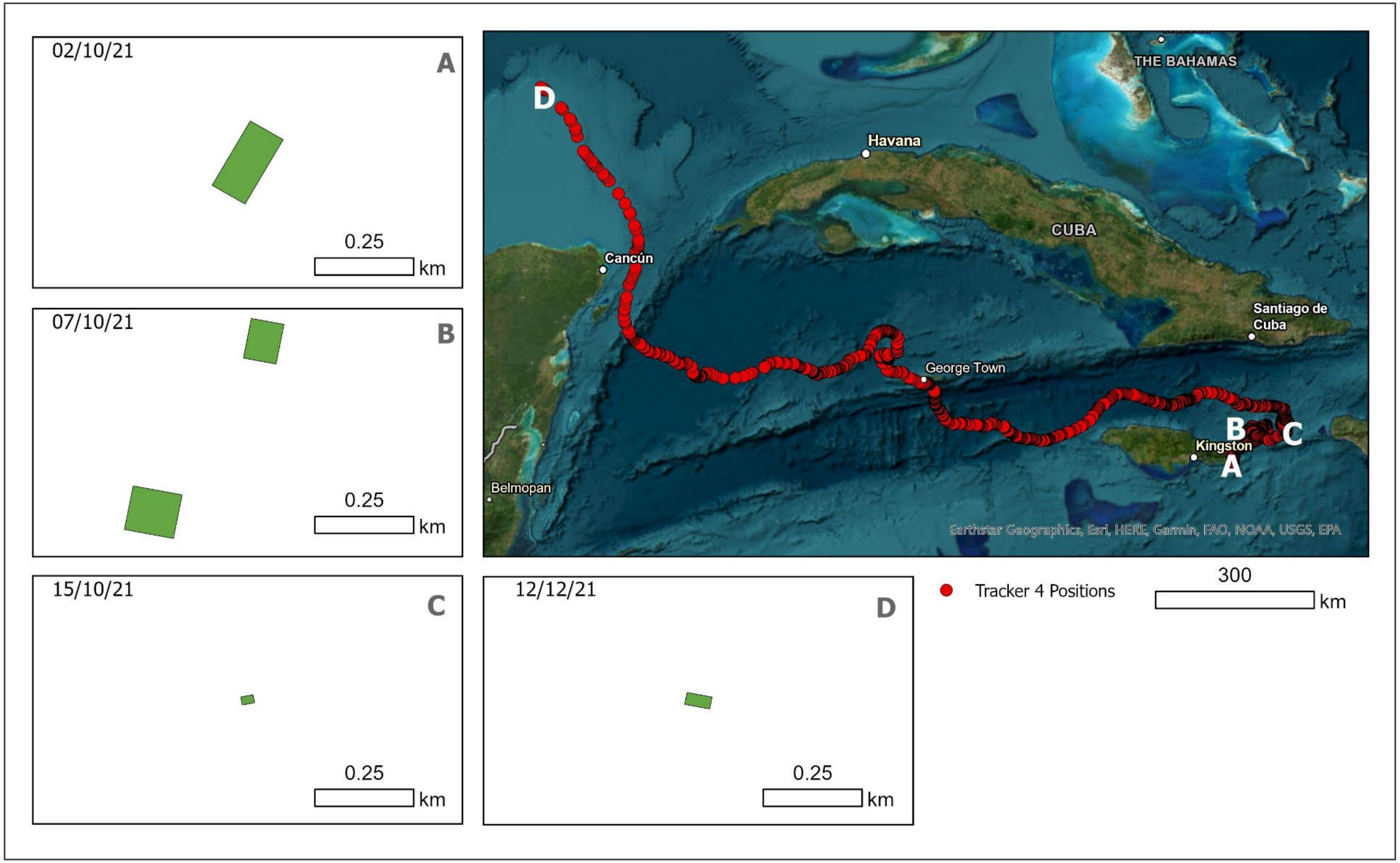


Figure 7 The morphological changes of the sargassum mat tracked identified using sentinel-1 data. The panels (A-D) show the pixels identified as floating sargassum mats and the change in morphology across the journey can be observed, the position and pathway of the tracker and detected mats are indicated in the top right box.

4.4 Discussion

By using GPS trackers, continuous data can be collected to observe the full pathway of an individual mat, using this method enables the temporal and spatial data gaps between remote sensing to be filled. The GPS trackers show that sargassum mats generally move in a north-westerly direction (from both Barbados and Jamaica) across the Caribbean Sea and towards Mexico and the Gulf of Mexico. Even where multiple trackers were deployed at similar starting points, it was observed that different paths were taken, for example tracker 8 landed on the coast of St. Lucia, whereas tracker 1 travelled up through the Mona Passage; similarly off Jamaica, tracker 5 arrived at the Yucatan Peninsula, whereas tracker 4 travelled through the Yucatan strait into the Gulf of Mexico.

The trackers predominantly reveal sargassum pathways through the interior of the Caribbean. Away from broad western boundary flows, Caribbean currents are fine-structured, comprising jets only a few km wide. These jets may be highly chaotic, shedding eddies with diameter 10s of km that typically drift west across the Caribbean in the slower background flow (e.g., Centurioni and Niiler, 2003). Of the seven trackers, only tracker 4 was entrained into the western boundary current, just east of the Yucatan peninsula. From a fix in the mid Yucatan Straits (86.23°W, 21.64°N at 1354 on 12 December) to a final fix in the Gulf of Mexico (87.89°W, 24.26°N at 2216 on 15 December), tracker 4 moved progressively to the northwest at an impressive average speed of 116 cm s^{-1}. However, most sargassum reaching the Caribbean is seen outside of the boundary current system. To understand this distribution and the influence of strong boundary flows, we need to appreciate the upstream provenance of Caribbean-bound sargassum in spring and early summer. Previous studies (e.g., Marsh et al. 2021) show that sargassum originally in the North Brazil Current is gradually drifting to the north, out of the boundary current and towards the central/northern Caribbean.

Further examination of pathways and drift has been undertaken with virtual particles and simulated (ocean model) currents – see Supplementary Material. Forward trajectories from Barbados and Jamaica (Fig. S2) confirm that trackers drift pathways are within a wide range of possibilities. Backward tracking of large ensembles of virtual particles from east of Jamaica (Fig. S3) likewise confirms that the western boundary current conveys sargassum towards the Caribbean, subject some northward drift which is a likely consequence of prevailing easterly trade winds that drive surface Ekman drift oriented at 45° to the right of wind direction. Our observed tracker trajectories are of course highly subject to starting location and time, but from a broader perspective these trajectories confirm that sargassum tends to accumulate in the central and northern Caribbean, only rejoining the western boundary current via drift westward of Jamaica.

These observations further compliment reports evidence from remote sensing that sargassum migrates north then west across the Caribbean, moving north through passages Windward, Mona and Anegada, and then west to the Gulf of Mexico (Frazier et al., 2013). However, it has also been suggested that sargassum likely takes different routes in different months due to variable winds and currents (Oxenford et al., 2021). Whilst these data suggests that currents are more significant than wind in transporting sargassum mats, by deploying GPS trackers more widely across the Tropical Atlantic and in different months, the uncertainty of windage and currents can be reduced as transport pathways can be established by continuously monitoring mat positions with *in situ* data from trackers.

From the remote sensing data paired with GPS tracker positions the size of the mat can be quantified, it was observed that an individual mat can rapidly grow and shrink. Using this combined method of tracking individual mats has also provided information on the orientation of the mats to the direction of travel. The NDVI indicated that in the growth phase the sargassum bloom was ‘greener’ and when it was smaller it was ‘browner’ which demonstrates the capacity to detect growth and mortality phases of an individual mat using these combined datasets. Through using these observations alongside sea surface temperature and existing knowledge on the effect of temperature on sargassum growth (by Marsh et al., 2023; Corbin and Oxenford, 2023; Magana-Gallegos et al., 2023) we could observe the growth and mortality of an individual mat.

There are a variety of forecast methods including automated satellite imagery detection, statistical methods and models undertaken at different scales, as well as a variety of input data including surface currents, winds and waves (Marsh et al. 2022; Marsh et al., 2023). By combining these models with *in situ* ground truth data of tracked sargassum mats more accurate and more reliable sargassum forecasts can be established. This is possible because: (1) the GPS trackers continue to collect high resolution position data regardless of cloud cover, which is a barrier to date in effective detection of sargassum mats (as noted by multiple sargassum detection studies including: Wang and Hu, 2016; Maréchal et al., 2017; Ody et al., 2019; Marsh et al. 2022). (2) the combination of datasets enables tracking the change in area of an individual sargassum mat which means that not only can arrivals be forecast but the amount could also be quantified. This is vital from a management perspective as different quantities arriving on shore demand different responses. (3) Tracking sargassum that is also remotely sensed, in an environment for which we know the currents, winds and sea surface temperature provides the opportunity for better defining the windage of sargassum mat transport, and the growth and mortality rates. Putman et al. (2020) state that windage coefficient estimates differs depending on wind and currents and the local ocean region and more work is needed to represent wind in forecasting models. This work is a step towards this goal as using *in situ* trackers can provide the opportunity for constraining windage parameters in forecast models.

This work presents a case study for a methodology that can be scaled and expanded in the future. To enable transport pathways to be established across the region and effectively support forecasting for the region, GPS trackers should be released on sargassum mats across different months of the year and from multiple starting points, including the Eastern Tropical Atlantic, South Caribbean, Gulf of Mexico and Central America. To support this aim, the data will be made openly accessible on Zenodo at point of publication. To reduce the potential for the trackers to detach from sargassum, a shallower design which may be more fluid and flexible to closer match the profile of floating sargassum is suggested. Additionally, to extend the battery life a battery pack can be included (but the change in density must be accounted for). A remaining challenge is detecting small (type 1 and 2) mats of sargassum using satellite imagery, for which there is a need for open-access high resolution imagery in open-ocean areas.

4.5 Conclusions

This work has demonstrated the potential for tracking sargassum mats using GPS trackers to determine the transport pathways, and when combined with satellite imagery, the capacity to determine changes in morphology, size and health status. The GPS trackers provide high temporal and spatial resolution *in situ* ground truth data to support remotely sensing methods. The GPS trackers not only enable the temporal and spatial gaps of satellite imagery (and those caused by cloud cover) to be filled for continuous tracking of individual mats, but they also facilitate exploration of the growth and mortality of the mats, especially when combined with wind, current and sea surface temperature parameters. This has significant value for improving forecasting and sargassum population dynamics (growth and mortality of sargassum mats), as whilst they provide information about the physical and biological drivers of sargassum, using GPS trackers and remote sensing reduces uncertainty in key processes such as windage.

Acknowledgements for Chapter 4

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Author Contribution Statement for Chapter 4

YF: conceptualisation, investigation, methodology, formal analysis, visualisation, writing – original draft
JD: supervision, methodology, review
RM: Funding acquisition (MONISARG PI), methodology, writing – review and editing
HO: methodology, data collection, writing – review and editing
LB: SAR data services and management, writing – review and editing
NM: SAR data processing
ET: Funding acquisition (SARTRAC PI), supervision, methodology, writing – review and editing

Supplementary Material to Chapter 4

SM4.1 Tracker selection, housing design and deployment

Table 1 indicates the drifters and trackers that were researched and considered. Asset trackers were found to be more affordable, however a common barrier to including many of the brands was that they only had terrestrial telemetry coverage or were limited in the Atlantic Region, it was common for the Gulf of Guinea and the Eastern side of the Tropical Atlantic Basin to not have telemetry coverage, to enable applicability of using the design/technology across the entire affected region they could not be considered as potential options.

Table 1 Drifters and Trackers explored which satisfied the minimum requirements to be considered for tracking sargassum.

Tracker Model (Company / provider)	Cost Region (GBP)	Transmittance Frequency	Battery Life	Coverage	Extra Features / Data Collected	Additional Housing Required	Telemetry System	Data Access
CODE/DAVIS Drifter (Met Ocean / RS Aqua)	>£1000	Variable	3 -12 months	Worldwide	Sea surface Temperature	No	Iridium or Argos PTT	Web access
CARTHE Drifter (Pacific Gyre)	>£1000	Every 5 minutes	Up to 3 months	Nearly global	80% biodegradable material	No	Globalstar Simplex	Web access, API download interface
Reef Drifter (Pacific Gyre)	>£1000	10 minutes to 24 hrs	5000-7000 transmits (equal to a maximum of 48.6 days at 10 minute transmission intervals)	Worldwide	Environmental sensors can be added (additional cost)	No	Iridium	Web access
SPOT Trace (Global Telesat Communications)	<£100	2.5 – 60 minutes	Minimum 60 days	Nearly global	Movement tracking, status updates	Yes	Globalstar	Real-time Mapping via app and web browser

Between February and July 2021 various housing options were first tested in a controlled environment using a large basin, which was 40 cm deep, 160 cm long and 60 cm wide. The first tests were undertaken using small cases. In the basin environment the cases performed well and floated in the basin. As such, three of these were then trialled off the coast of Barbados (supplementary material) and it was found that the cases were larger than needed and had higher windage than sargassum, they overturned in wave action and consequently the transmittance signal from the trackers was interrupted. Additionally, the cases floated around 2 inches above water level which meant there were likely to be differently influenced by wind and currents compared with sargassum, and the nature of the case meant they could not tangle with the mats and as such appeared to drift away independently from the mats. Additionally, they were picked up by fishers presumably because they are highly attractive to boaters.

Figure 1 shows the transport pathways collected from trialling pre-made cases as GPS housing. It was observed that the tracked pathways were shorter and more intermittent. As no low battery messages were received when position updates stopped, it was determined that the tracker casing was preventing reliable tracking. This is possibly because it was too thick or that it overturned due to a lack of heavy base weight preventing connection with the satellite system to be maintained. There was also no mesh to entangle the tracker with the sargassum, increasing the changes of separation. However, they do support the westerly movement identified by subsequent trackers. From this outputs, a need for alternative housing was identified.

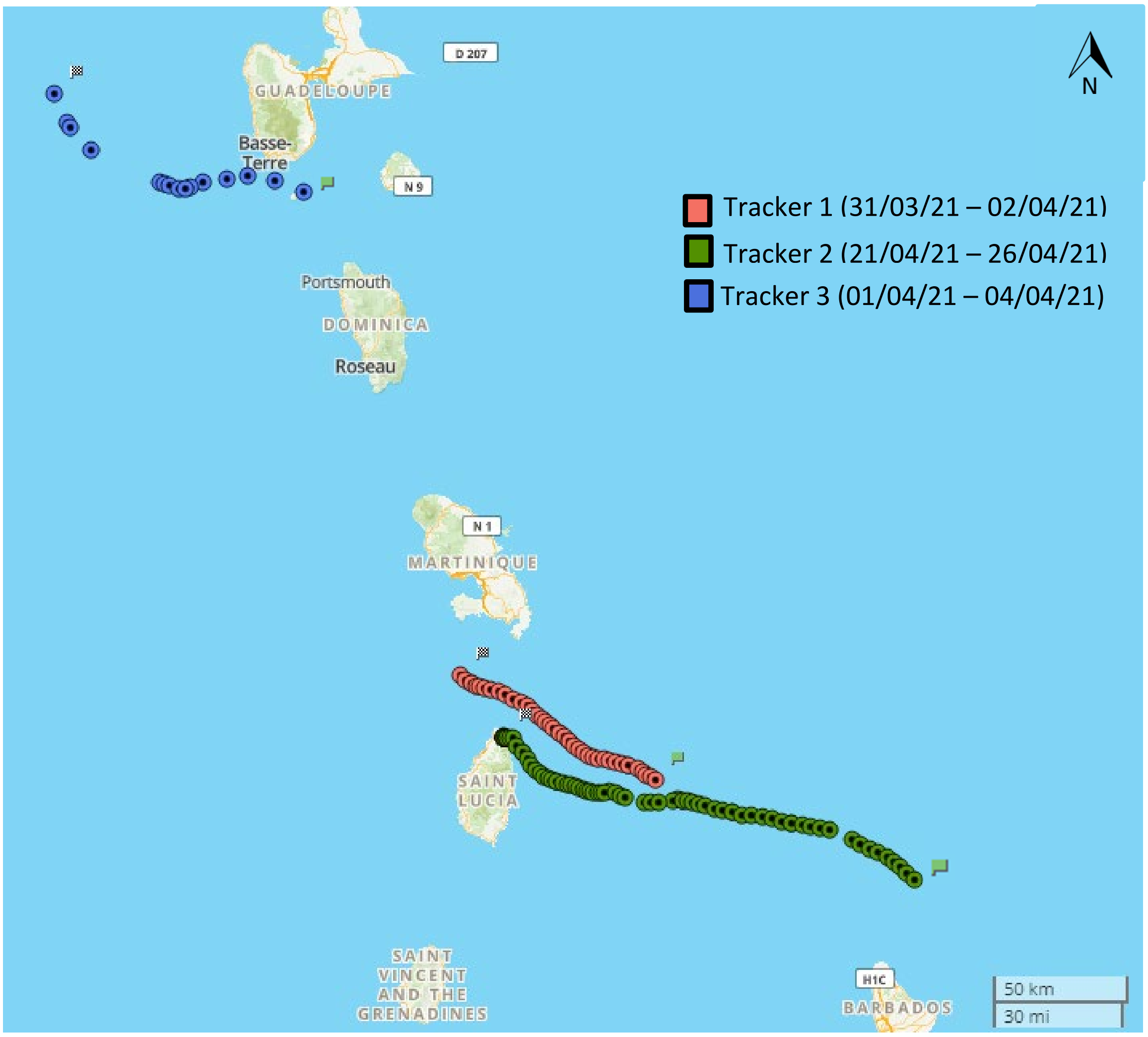

Figure 1 Map showing three tracker paths, as tracked using a pre-made case.

Due to these challenges with pre-made cases, we tested alternative housing, with the additional criteria that: i) the GPS tracker and housing floated with minimal structure above the surface of the water and had a similar buoyancy to tropical sea water (around 1022 kg/m^3); ii) that it floated upright and did not overturn in high waves; iii) that it could tangle with the sargassum to successfully travel with the mat.

This was achieved by testing housing options with varying proportions of materials until the requirements were met, first in the controlled basin environment and then in the near-shore coast at Southbourne beach, UK, and ultimately off the beach in Barbados. Materials trialled included: carious wide-necked bottles/jars as the container; sand, plasticine, homemade dough or stones as the stabilising weight; packing foam to prevent dislodgement of the GPS tracker and provide stabilising buoyancy; silica beads for removing moisture; and various mesh types to entangle with sargassum.

In the near-shore coast at Southbourne beach, UK, the two combinations that were most successful in the basin were tested. They were entangled in local varieties of floating detached seaweed to mimic sargassum mats and long strings were attached for retrieval purposes. The designs were tested in the sea for 2 hours to ensure they stayed tangled and were robust. Further modification and testing was undertaken in the sea by local researchers in Barbados and Jamaica to use locally freely available components.

SM2. SARgassum Index using Sentinel-1 Synthetic Aperture Radar

To reduce noise, increase reflectance strength, and improve positive contrast between Sargassum and water, Biermann et al. (unpublished) developed the SARgassum band index:

$$SARgassum\ (SG) = (\sigma_{VV}^{0} \times 0.1) + (\sigma_{VH}^{0} \times 3) \qquad (1)$$

where σ_VV^0 is backscatter in the sigma0_VV band and σ_VH^0 is backscatter in the sigma0_VH band. Values derived from the SARgassum index were saved as a third band alongside σ_VV^0 and σ_VH^0 (hereafter VV, VH, and SG, respectively).

SM3. Simulating sargassum drift with virtual particles

Given only a limited number of trackers, we put these observations into context with a much larger number of virtual ‘particles’, which are subject to the winds and ocean currents of an eddy-resolving ocean model hindcast. This hindcast dataset comprises 5-day averages of surface winds and currents from a hindcast spanning 1988-2010, obtained with the Nucleus for European Modelling of the Ocean (NEMO) ocean model (Madec, 2008) in eddy-resolving global configuration (ORCA12), henceforth NEMO-ORCA12. The ORCA12 configuration of NEMO has a horizontal resolution at the Equator of 1/12º, or 9.277 km, similar to that used in previous sargassum drift calculations (Putman et al., 2018; Brooks et al., 2018; Johns et al., 2020), and essential to best represent the swift and narrow boundary currents that dominate the region.

To complement GPS tracking, particles are released hourly for 5 days at selected locations (amounting to 120 virtual trackers), with subsequent positions recorded at daily intervals for 90 days. The particle trajectories are calculated using the off-line Lagrangian ARIANE mass-preserving algorithm (Blanke and Raynaud, 1997) in 'qualitative mode', with the 5-day mean horizontal velocity fields of NEMO-ORCA12. ARIANE is based on an analytical solution for curvilinear particle trajectories across model grid cells. In this study, particles are constrained to drift with surface currents and the trajectories are hence 2-dimensional in the latitude-longitude plane. Similar to previous studies of sargassum drift (Johns et al., 2020; Johnson et al., 2020; Putman et al., 2020; Berline et al., 2020), the surface-drifting particles are also subject to 'windage', here specified as 1%.

We release particles from the launch sites of our trackers, for comparison with observed tracks. Extending this approach to back-track particles for up to 120 days from offshore the Jamaican survey beaches, we assess the extent to which sargassum beaching in east Jamaica may be monitored with trackers deployed near Barbados. For forward and backward tracking experiments, particle data are statistically analysed on a grid of resolution 0.5º x 0.5º for fractional presence (number of particle transitions through a grid cell divided by total number of transitions) and mean age (days adrift, since the experiment started). We run the experiment for 23 hindcast years spanning 1988-2010, to account for interannual variability in winds and currents.

In Figure S2, we present 'grand ensemble' statistics of particle dispersal from Barbados and Jamaica. Fig. S2A and S2C show the fractional presence of particles, while Fig. S2B and S2D show the mean age, the number of days elapsed since deployment. Following relatively high values of fractional presence, most likely pathways are revealed. From Barbados, a broad westward drift is evident, including a northward branch into the subtropics (Fig. S2A). From Jamaica, drift is westward through the Yucatan Channel, with onward flow via the Loop Current of the Gulf of Mexica, and through the Florida Straits with the Gulf Stream (Fig. S2B). Drift timescales between Barbados and east Jamaica are of order 80 days (Fig. S2C), while particles released from east Jamaica do not leave the vicinity of the island for around a month (Fig. S2D). These pathways and timescales are broadly consistent with the GPS tracker observations, encouraging us that additional trackers will add value to the seasonal monitoring of sargassum, while simulations such as these are sufficiently realistic to provide useful forecasts at seasonal timescale.

Back-tracking particles from east of Jamaica, we obtain the statistics shown in Figure S3. The distribution of fractional presence in Fig. S3A clearly reveals a primary pathway via the western boundary current system, from the equatorial Atlantic. The drift timescale from Barbados is around 100 days, considering the upstream flow located at or south of Barbados (see Fig. S3B). We further note high fractional presence to the north of Jamaica, associated with mean ages of up to 30 days, indicating that some of the particles (hence sargassum) arriving off east Jamaica may arrive via a longer and hence slower clockwise round-island flow. These particles drift westward to the south of Jamaica, almost reaching the Yucatan Channel before returning to the east.

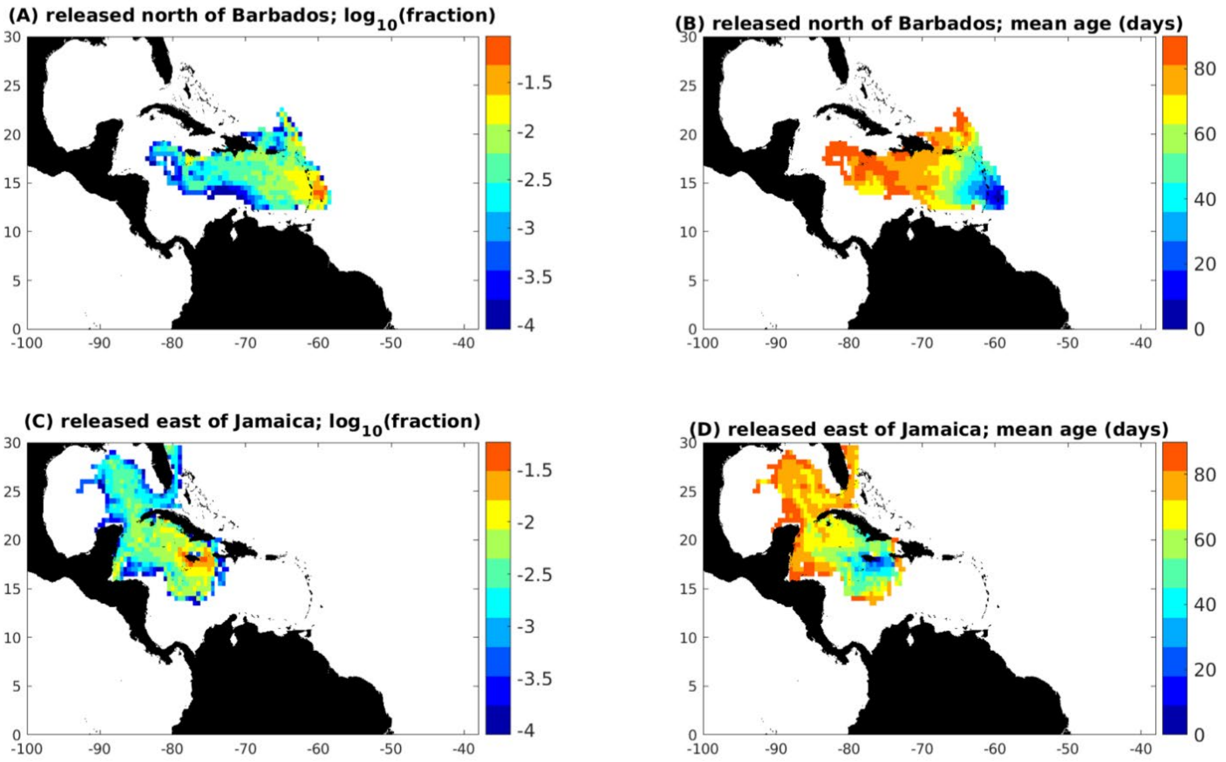

Figure 2 Statistics of SARTRAC-EFS forward trajectories over 90 days, for August releases from the two locations of SPOT tracker deployment: (A), (C) fractional presence and (B), (D) mean age for Barbados releases (A, B) and Jamaica releases (C, D).

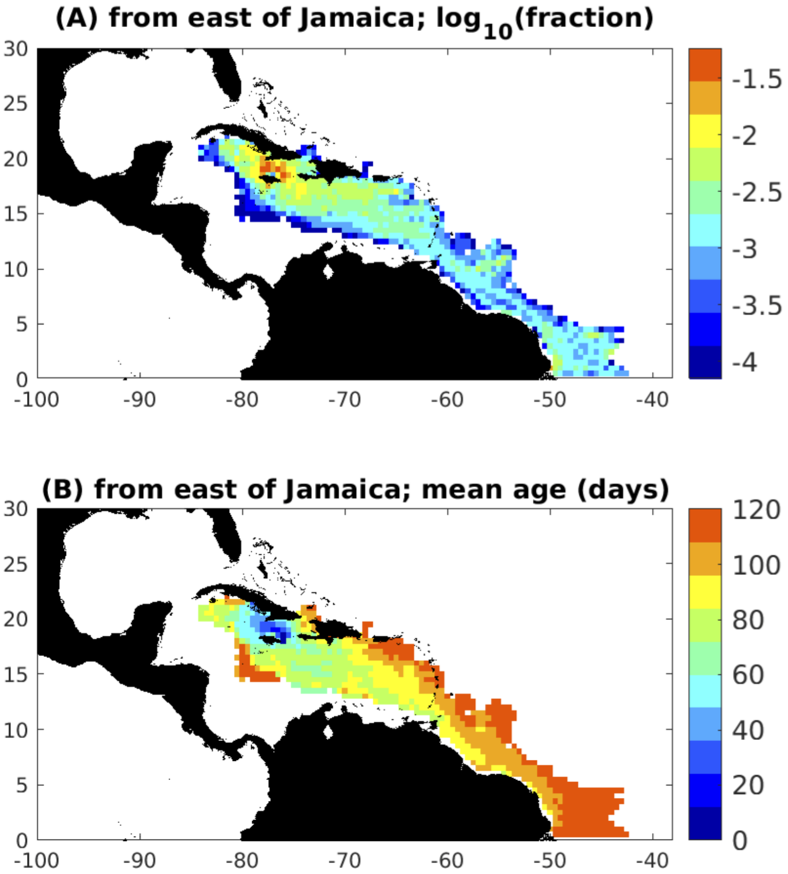

Figure 3 Statistics of simulated 120-day backward trajectories for August releases over 1988-2010 from the location of SPOT tracker deployment off east Jamaica: (A) fractional presence; (B) mean age (days before arrival off Jamaica).

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Preamble to Chapter 5

In the final analysis chapter, chapter 5 introduces detection and monitoring of beached pelagic sargassum, addressing objectives 5 [BEACHING] and 6 [PROPERTIES]. An operational framework is developed to detect beached sargassum using ground and airborne datasets, directly addressing the research gaps identified in the systematic review by: focusing on sargassum beaching events; collecting data in both West Africa and the Caribbean; identifying the species/morphotypes; and utilising remote sensing techniques combined with *in situ* data. This chapter addresses the thesis research question: iii) What opportunities exist to improve beach detection and monitoring in cloud covered regions?

By focusing on beached sargassum and using drone imagery and ground measurements this chapter explores sargassum at a high spatial resolution, it employs an interdisciplinary approach and integrates aspects of remote sensing and biology to achieve the overarching goal. In doing so, it offers an innovative spectral assessment of sargassum, generating insights into the biochemical composition and physical properties. The findings in this chapter contribute to improved management of sargassum through targeting two parts of the disaster risk management cycle: the 'response' through better understanding of beaching events, and 'rehabilitation and recovery' by taking steps towards making valorisation of sargassum possible.

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Chapter 5 Innovative spectral characterisation of beached pelagic sargassum towards remote estimation of biochemical and phenotypic properties

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Abstract

In recent years, pelagic sargassum (*S. fluitans* and *S. natans*) – henceforth sargassum, macroalgae blooms have become more frequent and larger with higher biomass in the Tropical Atlantic region. They have environmental and socio-economic impacts, particularly on coastal ecosystems, tourism, fisheries and aquaculture industries, and on public health. Despite these challenges, sargassum biomass has the potential to offer commercial opportunities in the blue economy, although, it is reliant on key chemical and physical characteristics of the sargassum for specific use. In this study, we aim to utilise remotely sensed spectral profiles to determine species/morphotypes at different decomposition stages and their biochemical composition to support monitoring and valorisation of sargassum. For this, we undertook dedicated field campaigns in Barbados and Ghana to collect, for the first time, *in situ* spectral measurements between 350 and 2500 nm using a Spectra Vista Corp (SVC) HR-1024i field spectrometer of pelagic sargassum stranded biomass. The spectral measurements were complemented by uncrewed aerial system surveys using a DJI Phantom 4 drone and a DJI P4 multispectral instrument. Using the ground and airborne datasets this research developed an operational framework for remote detection of beached sargassum; and created

spectral profiles of species/morphotypes and decomposition maps to infer biochemical composition. We were able to identify some key spectral regions, including a consistent absorption feature (920 – 1080 nm) found in all of the sargassum morphotype spectral profiles; we also observed distinction between fresh and recently beached sargassum particularly around 900 – 1000 nm. This work can support pelagic sargassum management and contribute to effective utilisation of the sargassum biomass to ultimately alleviate some of the socio-economic impacts associated with this emerging environmental challenge.

5.1 Introduction

Pelagic sargassum[2] algal blooms and associated beach depositions are an emerging environmental challenge affecting the entire tropical Atlantic region, including the Caribbean Sea, Gulf of Mexico, and Gulf of Guinea since 2011.

These blooms and beaching events (as defined by Fidai et al., 2020) have a variety of impacts on social aspects and economic activities and industries such as tourism, fisheries and aquaculture, as well as public health (Chavez et al., 2020; Solarin et al., 2014; Ramlogan et al., 2017; ANSES 2017; Resiere et al., 2018). They also have detrimental environmental effects on coastal ecosystems, water quality and beach stability (McGlathery, 2011; Maurer et al., 2015; van Tussenbroek et al., 2017). The impact on these sectors is further exacerbated by accumulated sargassum that decomposes after a couple of days on the beach and produces gas, leachates and organic matter which interact with wave action, resulting in hypoxic conditions and deterioration of water quality as far as 480 m from the shore (Chavez et al., 2020; Rodriguez-Martinez et al., 2019). Rodriguez-Martinez et al. (2019) estimated that 78 faunal species died as a result of accumulated and decaying sargassum in the nearshore marine environment in Mexico in 2018, including fish, crustaceans, molluscs,

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[2] *S. fluitans* and *S. natans* species are referred to in shorthand as ‘sargassum’ (following Fidai et al., 2020).

echinoderms and polychaetes. Similarly, van Tussenbroek et al. (2017) found that it resulted in mortality of near-shore seagrasses and associated fauna and corals in Mexico.

To enable the region, especially small islands and lower income countries, to manage the challenges of pelagic sargassum events, there is a demand to identify ways of using the biomass and develop strategies to reduce their impacts. Researchers are already suggesting that the seaweed biomass has the potential to be used for: construction blocks, biofuel, fertiliser, cosmetics and more (Desrochers et al., 2022). There are two recognised species of pelagic sargassum: S. *fluitans* and S. *natans* (Taylor 1972; Guiry and Guiry 2023), and several morphotypes for each species: S. *fluitans* III and X; S. *natans* I, II, VIII, and IX (Parr, 1939). Schell et al. (2015) showed that *S. natans* I, *S. natans* VIII and *S. fluitans* III were found across the Sargasso Sea, Antilles Current, Eastern Caribbean and Western Tropical Atlantic in varying proportions at each location. To reduce the negative impacts of sargassum and by utilising it as a natural resource there is a need to: i) determine if there is any variation in physical characteristics between species morphotypes and subsequent impacts of this on potential uses; ii) understand how decomposition in a beach environment affects its properties for use; iii) develop an *in situ* method of assessing the quality and quantity of sargassum for harvesting. To address some of these gaps, remote sensing techniques, particularly space-borne satellite imagery, have been used to monitor pelagic sargassum, typically in the open ocean at a coarse basin scale resolution. For example, Wang et al. (2019) considered the 'Great Atlantic Sargassum Belt' stretching across the Tropical Atlantic. Similarly, Gower and King (2011) examined the distribution across the Gulf of Mexico and North Atlantic. Other studies looked at smaller but still substantial regions of the Atlantic such as Sutton et al. (2019) and Ped et al. (2016) who focussed on the Caribbean area. Detection algorithms such as ERISNet for Yucatan Peninsula in Mexico (Arellano-Verdejo et al., 2019) and Sargassum Early Advisory System (SEAS) for the Texas Gulf Coast (Webster and Linton, 2013) have also been established using coarse resolution space-borne remote sensing methods for specific regions. In addition, some studies have detected sargassum at finer resolutions. Hu et al. (2015) used measurements from various multi-spectral satellite sensors (Moderate Resolution Imaging Spectroradiometer or MODIS, Landsat, WorldView-2) with spatial resolutions varying between 0.02 m and 1000 m. Similarly, Ody et al. (2019) utilised a variety of satellite sensors with spatial resolutions ranging from 10 m to 1000 m. However, Fidai et al. (2020) noted that the majority of publications focus on general monitoring of floating sargassum at low resolution and very few on sargassum beaching events. So far, remote sensing methods have not been commonly used in beach environments to monitor sargassum, with most undertaking surveys and laboratory analysis. An example of a study that used remote sensing to monitor the beach environment is Valentini and Baloiun (2020) who used photography from smart phones and image classification methods to monitor the coast of Martinique and detect sargassum. Leon-Perez et al. (2023) detected fresh and decomposing sargassum along the shoreline and near-shore waters of Puerto Rico using space-borne Sentinel-2 imagery supported by drone photographs. Development in access to uncrewed aerial systems (UASs) provides an opportunity for monitoring sargassum. They have been used in parallel fields such as for monitoring harmful algal blooms (Wu et al., 2019) and other beached macroalgae such as *Rugolopteryx* (Roca et al., 2022), which demonstrates there is the potential to utilise them for sargassum.

Field spectroscopy has been used to distinguish vegetation at higher resolutions. Szekielda et al. (2010) used an airborne portable hyperspectral imager to measure floating windrows. Similarly, Dierssen et al. (2015) utilised an airborne imaging spectrometer to distinguish a mass of floating sargassum and seagrass at 1 m resolution. Airborne hyperspectral and thermal infrared imagery has also been used to generate spectra of floating aggregations of submerged sargassum (Marmorino et al., 2011). This high spectral resolution monitoring and mapping technique is commonly used to characterise the reflectance of natural surfaces in a variety of environments such as forest canopies for species identification (for example, Malenovsky et al., 2019; Asner et al, 2015), and agriculture for crop health and type (for example Bian et al., 2013; Su, 2020). It has been used to discriminate benthic, subtidal, and intertidal macroalgal species as well (Casal et al., 2013; Olmedo-Masat 2020). Spectroscopy is also often used for scaling-up measurements from small areas to scenes, and even satellite sensors, as achieved by Gamon et al. (2006) on linking leaf measurements to canopy data. Applying this technique to beached sargassum deposits has the potential to contribute towards addressing current research gaps in understanding the spectral properties of sargassum and their implications for valorisation, and ultimately enhancing monitoring capacity from freely available satellite data to facilitate more appropriate management of this resource.

In this context, the focus of this research was to develop an operational framework for remote detection of beached pelagic sargassum to improve valorisation potential with the specific aims of: i) evaluating the potential of spectral reflectance data to differentiate between species/morphotypes of pelagic sargassum (*S. fluitans* III, *S. natans* I and *S. natans* VIII); ii) exploring spectral variation in sargassum species across levels of decomposition (freshly deposited (<1 day) and recently deposited

(<3 days)); iii) exploring the potential of detecting species/morphotypes and decomposition levels using ‘off-the-shelf’ UASs; and iv) inferring biochemical composition of sargassum species/morphotypes from spectral profiles.

5.2 Methods

5.2.1 Field data collection methods

5.2.1.1 Study sites

Beach surveys were undertaken at Consett Bay, a small cove in Barbados, and at Sanzule village, a long straight open beach, in the Ellembelle District of Ghana’s Western Region (figure 1). In Barbados, sargassum was accumulated and densely stacked on the beach with the different morphotypes tangled together, and there was a clear difference between the freshly deposited and the decomposing sargassum (more recently termed fresh gold and old gold (Small et al., 2022)). In contrast, at Sanzule, the samples were scattered across the beach as individual thalli and not tangled together. These locations were selected as they have both experienced regular pelagic sargassum deposits on their coastlines over the past decade and these beaches support the daily employment and livelihoods of communities particularly through fishing and tourism.

Figure 1 Maps showing location of data collection sites and images of beached sargassum sampled. Basemap sources: Esri, FAO (Food and Agriculture Organization of the United Nations), USGS (United States Geological Survey), and Earthstar Geographics.

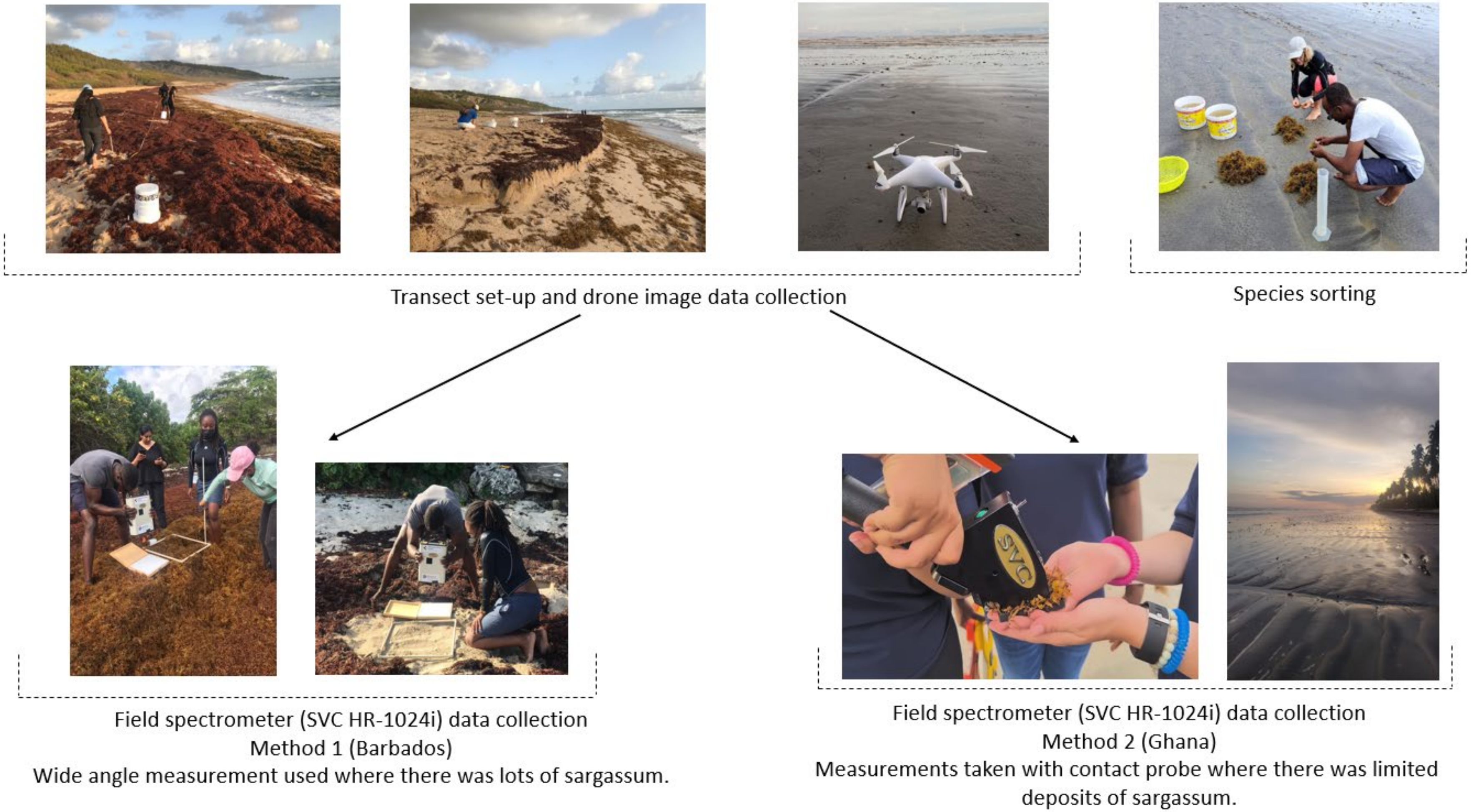
A field spectrometer (SVC HR-1044i) was used at both sites to collect ground spectral measurements. The SVC HR-1044i is a high-performance single-beam field spectroradiometer measuring over the visible to short-wave infrared wavelength range (350 - 2500 nm) with internal GPS and wireless communication capabilities. It can be used with the integrated lens held above the sample (Consett Bay), or with a contact probe (with its own light source) placed directly on the sample (Sanzule).

5.2.1.2 Sampling framework

In Barbados, beach surveys were undertaken in March 2022, and in Ghana in June 2022. Two differing methods of data collection were used to accommodate for the time of day, weather, and volume of fresh sargassum deposited on each of the beaches (illustrated in figure 2).

Consett Bay beach was covered with accumulated layers of sargassum morphotypes mixed together. The survey was undertaken at low tide, shortly after sunrise, as these conditions allowed for the field spectrometer to be used directly over the samples (method 1). A longshore transect was set up and white ground markers were placed every 5 m to distinguish boundaries of fresh golden and recent brown deposits of sargassum and to identify sample points to support UAS imagery processing. The field spectrometer was held at 0.15 m directly above the target, which gave a field of view with a diameter of 0.40 m. The instrument was calibrated with a white panel at each sample site, each sample was measured five times and averaged to reduce the impact of atmospheric noise and user movement on the final results. Additional calibrations were made if there were any noticeable changes to sun/cloud cover between measurements. As the sargassum beach deposits in Barbados were entangled, the thalli were sorted by morphotype to fill a quadrat (0.40 m diameter) and measured with the field spectrometer as above to obtain profiles for each morphotype found (*S. natans* I, *S. natans* VIII and *S. fluitans* III). The DJI Phantom 4 UAS with integrated RGB camera was flown at 45 m height with 75% front and 65% side overlap to give 0.012 m image resolution, over a 70 m extent using the ‘corridor’ flight plan outlined in Baldwin et al. (2022).

In Sanzule, low tide took place close to sunset and the weather conditions were cloudy; this, combined with a scattering of sargassum deposits across the beach, meant it was most appropriate to use a contact probe in conjunction with the field spectrometer (method 2). Flags and ground markers were laid out at 5 m intervals across a longshore transect (similar to protocol at Consett Bay). The thallus deposited nearest to each marker was sampled by placing it in a specimen tray and measuring directly onto the sample with the contact probe; 20 measurements were taken and averaged for each sample. Older deposits were observed on the beach, but these were likely to have been deposited >3 days previously and were not measured as they were decomposing and not ‘intact’ to allow sampling. Morphotype sorting was not required in Sanzule as the thalli were mostly not entangled and were measured individually along the transect, *S. fluitans* III and *S. natans* VIII were identified.



igure 2 Flow chart and images illustrating the field conditions and the two different methods used to collect ground measurements.

5.2.2 Data processing

5.2.2.1 Spectral data

Spectral profiles of pelagic sargassum morphotypes S. *natans* I, S. *natans* VIII, and S. *fluitans* III were created by using a combination of software packages including ‘SpectraGryph 1.2.16d’, ‘Microsoft Excel’ and ‘R version 4.2.2’ (R Development Core Team, 2021) to process and analyse spectral beach survey data collected using the field spectrometer. The SVC HR-1044i model can collect each reading and via Bluetooth share it to a mobile phone to store it as a ‘.sig’ file. This feature was used to store the data in a cloud location instantly. Later, the ‘.sig’ files were uploaded to the SpectraGryph software, where the curves of multiple readings were averaged and exported to a ‘.csv’ file. Next, MS Excel and R version 4.2.2 were used to explore patterns and plot the data. To evaluate the potential of ground spectral data to distinguish between species/morphotypes of pelagic sargassum (first aim of our study), and to explore spectral variation in sargassum species across levels of decomposition (second aim), two approaches were used: first, the full spectra were examined and statistical tests were performed, and second, indices were utilised to explore classification and upscaling potential. The spectral data were first explored by applying a two-way analysis of variance (ANOVA) statistical test. This was to assess the interaction effects between the reflectance of the spectral profiles grouped into 10.0 nm wavelength intervals (response variable), the three species/morphotypes and the two decomposition levels (categorical variables). The Tukey multiple comparisons of means was used to establish if the categorical variables (three species/morphotypes and the two decomposition levels) had statistically different spectral profiles by determining whether there was a difference in the means of all the possible pairs of wavelengths. This contributed to establishing whether or not they could be confidently mapped and upscaled.

The potential for biochemical estimation (fourth aim of our study) was explored by considering that the spectra were reflectance curves and the inverse of absorbance curves, and thus Curran’s (1989) work on foliar biochemistry could be applied to the spectra to determine which regions of the curve are indicative of different compounds. This was supplemented with research on chemicals we expect to find in brown algae such as sulfates and fucoidans. Wavelengths of identified compounds were included in creation of figure 10 as an indication of dominant absorption features (Machado et al., 2022; Agatonovic-Kustrin et al. 2020). Similarly, knowledge of various chemicals not expected to be seen in sargassum such as those found exclusively in red algae were also researched and the regions of the spectra where we expected to see them were explored (Shalev et al., 2022).

Once spectral differences were established, indices were selected and applied to the data, the reflectance values of the central wavelengths and the wavelengths ±10 were averaged to reduce any potential noise or errors (blue 450 nm, green 550 nm, red 650 nm, near-infrared (NIR) 800 nm). The indices selected were the normalised difference vegetation index (NDVI) (1) and the normalised green-red difference index (NGRDI) (2). NDVI was selected as it is popular for monitoring vegetation and algae, and it has been used at coarser resolutions to monitor sargassum (Dierssen et al., 2015; Hodgkins et al., 2017; Hu, 2009; Hu et al., 2015). NGRDI was chosen for two reasons. Firstly, it has been used with drone imagery to detect algae with success (Xu et al., 2018; Gao et al., 2018); secondly, it utilises only the visible bands of the electromagnetic spectrum, allowing it to be applied to both the ground spectral measurements and the UAS imagery data collected.

$$NDVI = \frac{NIR - Red}{NIR + Red} \qquad (1)$$

$$NGRDI = \frac{Green - Red}{Green + Red} \qquad (2)$$

In addition to the spectral indices, the absorption band depth (ABD) of the identified feature was established. To do this, the band depth relative to the continuum was calculated following the methods developed by Kokaly and Clark (1999). As illustrated in figure 3, first the continuum line was established through applying a linear interpolation between the peaks surrounding the feature (92 - 1080 nm). Then the band depth of each point in the absorption feature was calculated by

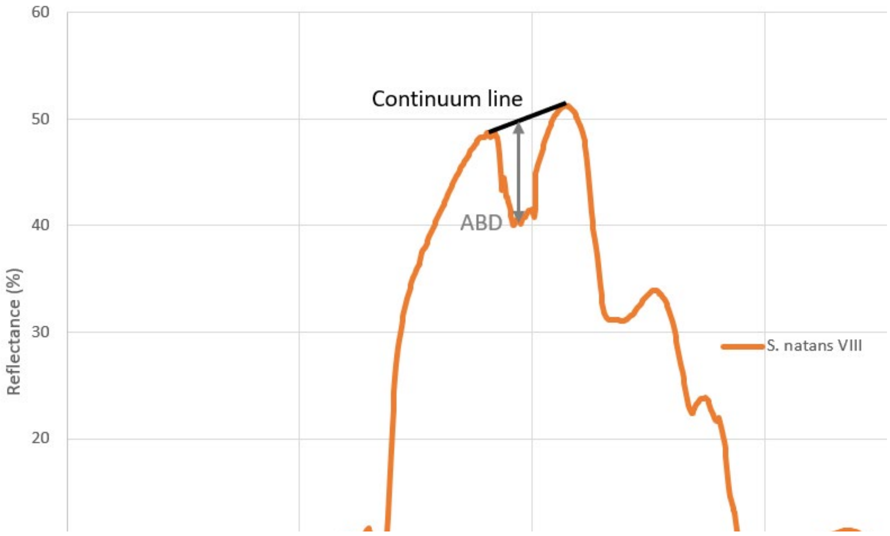


Figure 3 Illustration of how the absorption band depth (ABD) was calculated. First, the continuum line was created via application of a linear interpolation between the two peaks, and then the depth was determined by calculating the difference between the reflectance measured at each wavelength on the curve and the value on the contimuum line; the band depths for all points in the feature were then averaged to give a final value.

subtracting the reflectance of the actual wavelength from the linear interpolation, and then the average of the band depths was calculated to generate a final value for ABD for each spectrum.

To establish if the indices and ABD results were statistically significantly different for each species/morphotype and decomposition level, *k*-means cluster analysis was undertaken for the species and the decomposition levels. This unsupervised classification method showed if the data converged around the centroid of the cluster, meaning that the results for each of the indices were consistent for all classification categories, or if there was no statistically consistent pattern in the indices calculations.

5.2.2.2 UAS data

To explore the potential of detecting and distinguishing species/morphotypes and decomposition levels using an ‘off-the-shelf’ UAS (third aim of our study), the images captured were processed using the ‘Structure from Motion’ (SfM) and ‘Multi-view Stereo’ (MVS) algorithms implemented in DroneDeploy (Barbados) and Agisoft Metashape (Ghana). Both applications have been reported to yield comparable results (Kloc et al., 2021; Blach et al., 2019). The SfM analyses involved, first, the alignment of the images that includes detection and matching of features, to develop the basic image structure (Mancini et al., 2013). Second, a pixel-based dense stereo reconstruction was carried out using the aligned data, and finally, orthomosaics were produced and used for further analysis. For the Ghana dataset, the geometric accuracy for the airborne image was 0.2 m root-mean-square error (RMSE), while Barbados had an RMSE of 0.3 m, both being in the acceptable range as outlined by Baldwin et al. (2022). Supervised classification was carried out on the orthomosaic using the Semi-Automatic Classification Plugin (SCP) (Congedo, 2021) in QGIS (version 3.10 A Coruña) software. Regions of interest (ROI) covering the same 0.40 m diameter sampling locations that the field spectrometer measured in Consett Bay were digitised (identifiable by ground markers in the imagery) and the spectral profiles for each class (i.e., fresh gold and recent brown deposits) were calculated. To establish if there was a statistical difference between the classes the pairwise Bray-Curtis Dissimilarity Index was calculated between the digitised ROI plots using the SCP in QGIS. This index returns a percentage between 0 and 100 where 0 indicates identical data and 100 indicates complete dissimilarity and is often used to examine dissimilarity between vegetation plots (for example Feret and Asner, 2014). Next, the regions of interest were expanded to include measurements from across the image to determine the impact of shade and other variations, and the Bray-Curtis Dissimilarity Index was re-calculated. If the Bray-Curtis Dissimilarity Index were above 90% it was considered that the profiles were statistically different, and a supervised classification could be applied to the whole image; if it were below 90% then they were considered not statistically distinct. The minimum distance method for supervised classification was applied as it has been used successfully to identify macroalgae (Olmedo-Masat 2020) and was considered simpler to implement for this dataset. Next, the NGRDI was applied to the image and the range of NGRDI for each field in the classification was calculated.

5.3 Results and Discussion

5.3.1 Spectral profiles

In figure 4 the spectral response of fresh sargassum is presented. In the visible electromagnetic range (400 - 700 nm) we observe that there is higher reflectance in the green region (500 - 600 nm), and there is more absorption in the red region (600 –700 nm). This is important as variation in the red portion is widely used as an indicator of chlorophyll abundance which can be indicative of plant health and phenological stage (Myeni et al., 1995). Along the red edge (sharp increase between red and near-infrared reflectance), there is a sharp increase in reflectance to the near-infrared region (>700 nm). The water absorption region (970 nm) is distinct where sargassum has a dip in reflectance to below 31%. The spectral profile of sargassum is largely similar to what we expect to see in typical terrestrial vegetation, indicating that existing terrestrial vegetation detection and monitoring methods are transferable for use with beached sargassum. Variation in reflectance of wavelengths can be attributed to numerous bonds characteristic of various chemical compounds as explored later (section 3.4).

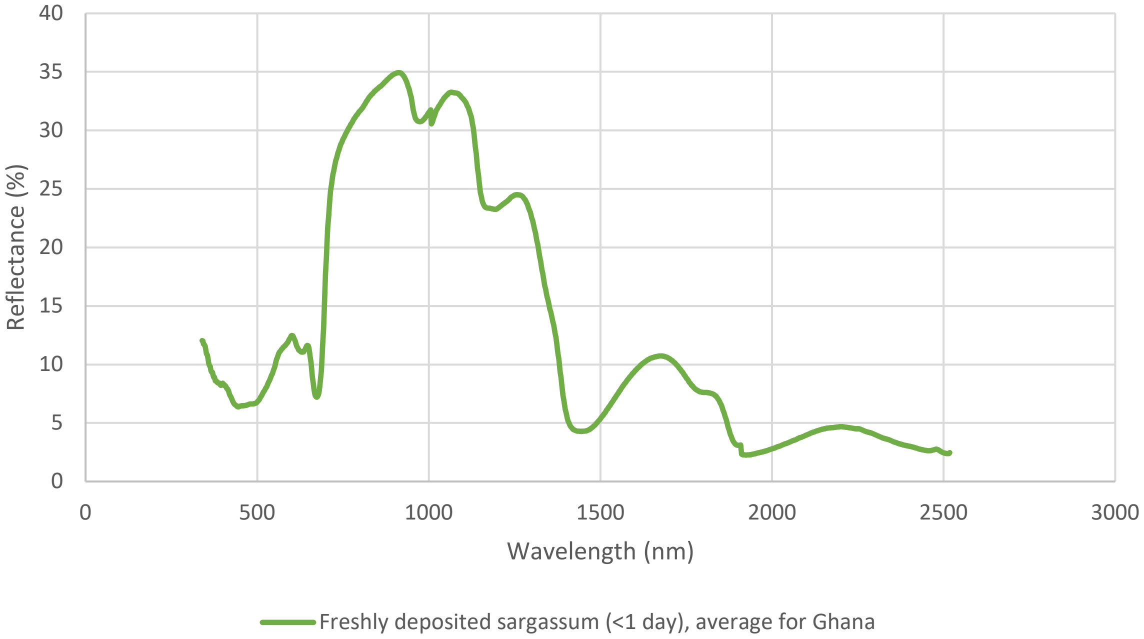


Figure 4 Spectral profiles of mixed sargassum species/morphotypes (measured using method 2).

In Barbados, three morphotypes were found (*S. fluitans* III, *S. natans* I and VIII) and in Ghana, two morphotypes were found (*S. natans* VIII and *S. fluitans* III). The spectral profiles of morphotypes found in Barbados and Ghana (figure 5) have some distinctions. In the blue (400 - 500 nm) and green (500 - 600 nm) regions, all three morphotypes are alike, but in the red region *S. natans* I has a wider spectral feature than the other morphotypes. All three species show an increase in reflectance along the red-edge, but *S. natans* I increases less sharply. A consistent feature observed in all the spectra was a deeper absorbance profile between 920 nm and 1080 nm, and as such, this was used to calculate the ABD. Variation in water absorption (~970 nm) can be observed in the spectral profiles between all morphotypes. In both locations *S. natans* VIII consistently has a lower reflectance (at ~970 nm), indicating increased water absorption compared to the other morphotypes. Whilst the morphotype profiles (especially *S. fluitans* III and *S. natans* VIII) are closely aligned, we theorise that the variation in absorption is a consequence of differences in biochemical composition (further explored in 3.4). We also observe that the spectral profiles from Ghana have generally lower reflectance peaks and smoother curve than Barbados above 1800 nm, and suggest that this is likely due to variation of instrument used (i.e., contact probe use versus integrated lens) and the associated atmospheric interactions with method 1.

When two-way ANOVA and Tukey multiple comparisons of means was performed on the species spectra, the Barbados dataset shows there was a statistical difference ($F_{2, 218} = 9094.64$, $p \leq 0.001$) in the reflectance values of *S. natans* I when compared to the *S. natans* VIII and *S. fluitans* III ($p < 0.001$), but *S. natans* VIII and *S. fluitans* III were not statistically different ($p = 0.87$). In Sanzule, the ANOVA analysis shows that there was statistical difference between S. *natans* VIII and S. *fluitans* III ($F_{1, 218} = 11585.86$, $p = 0.001$) indicating that the variance between species curves was not consistently statistically distinct across both locations; multiple factors such as chemical composition, thallus age, epiphyte load, extent of sun-drying on the beach, and/or atmospheric interaction (particularly for method 1), could contribute to this observed variation.

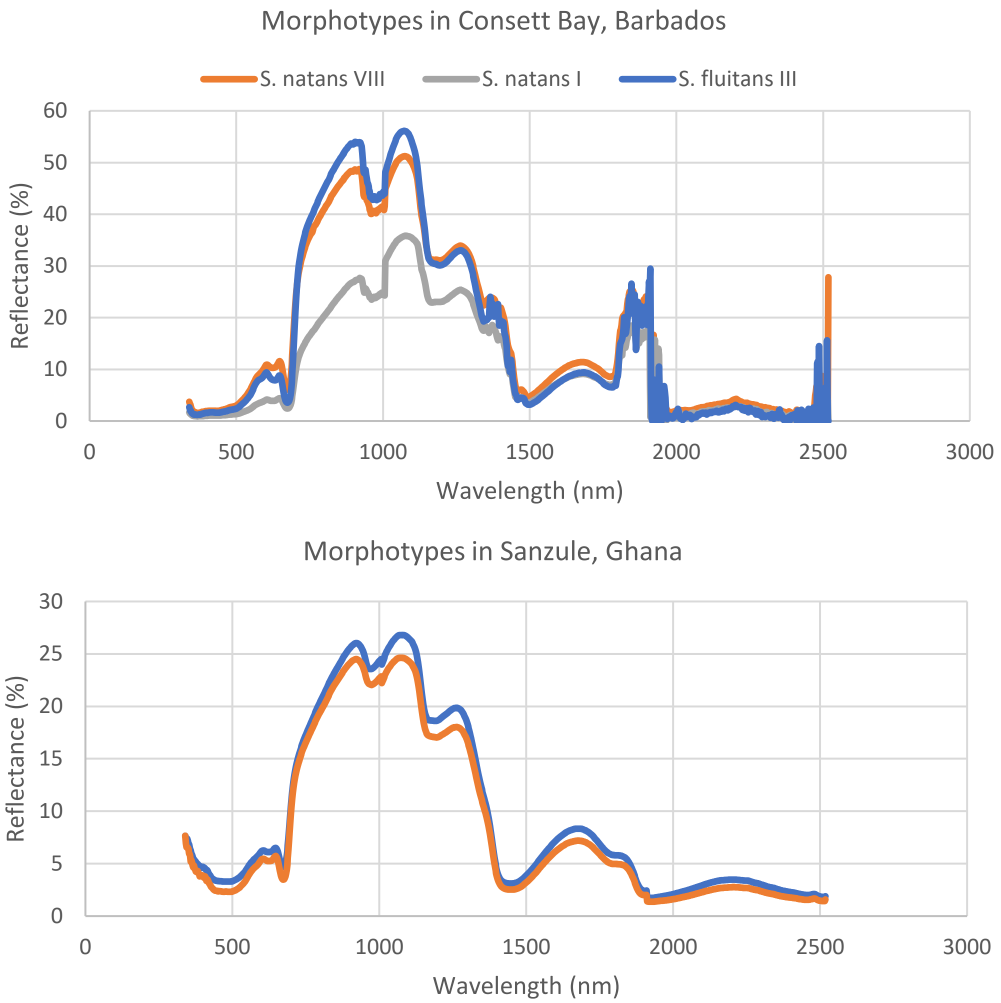


Figure 5 Spectral profiles of sargassum morphotypes (S. natans VIII, S. natans I, S. fluitans III) found at both beach survey locations (Top: Consett Bay, Barbados; Bottom: Sanzule, Ghana).

Freshly deposited and recently deposited sargassum spectral profiles display some distinct features (figure 6). In the green wavelength region (500 - 600 nm), fresh sargassum has higher reflectance, and in the red wavelength region (600 – 700 nm), fresh deposits have a narrower and deeper profile than recent deposits. Both sharply increase along the red edge. The water absorption region (970 nm) is also varied where freshly deposited sargassum has a stronger absorbance (deeper profile) than recently deposited sargassum, indicating that the recent deposits have less water and are drying on the beach, which supports our *in situ* observations. When comparing the decomposition spectra, the two-way ANOVA analysis confirmed that fresh and recent deposits have distinct spectral profiles (($F_{1, 218} = 20461.30$, $p \leq 0.001$). Changes in illumination might have affected reflectance, however, care was taken to remove the effects of changes in illumination by using a reference panel between measurements to normalise the spectral response and by removing the effect of solar radiation. Additionally, a standard protocol was followed for each measurement to ensure that the top canopy of beached sargassum was measured, and the accumulation was not disturbed to prevent collecting measurements from within the pile which may have been differently affected by sun drying.

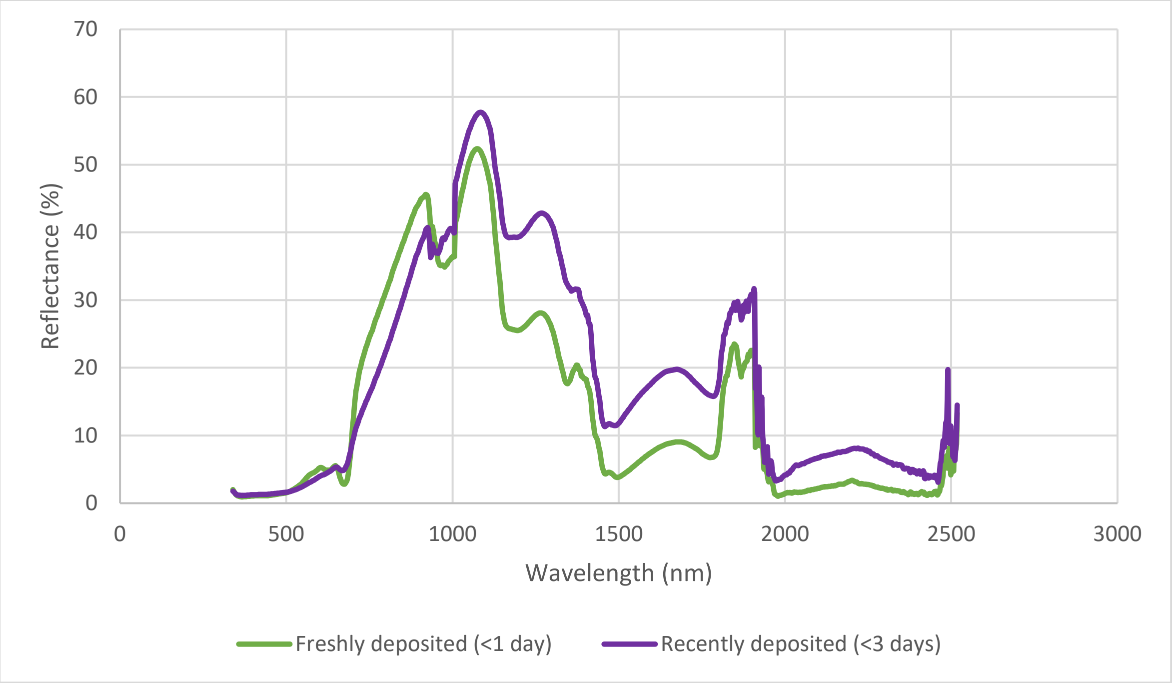


Figure 6 Spectral profiles of fresh (<1 day) and recent (<3 day) beach deposits of sargassum measured using method 1 at Consett Bay (Barbados).

5.3.2 Spectral indices and clustering analysis

The NDVI and NGRDI, along with the ABD, were calculated for each spectral profile. As shown in table 1, recently deposited sargassum has slightly lower NDVI values than freshly deposited, which supports that they were older samples which have started to dry or decay on the beach and are less green. The ABD average values showed that there is a difference, indicating that recently deposited sargassum has a less trough between 920 and 1080 nm. Similar to NDVI, the NGRDI results show that whilst there is some overlap, the recently deposited sargassum has lower NGRDI values than freshly deposited. The results in table 1 are congruent with the results of the ANOVA analysis.

Table 1 Values for NDVI, NGRDI and ABD indices applied to fresh (<1 day) and recent (<3 day) beach deposits of sargassum.

		Freshly Deposited	**Recently Deposited**
NDVI	Min	0.67	0.55
	Max	0.76	0.72
	Mean	0.72	0.62
ABD	Min	4.21	1.68
	Max	9.63	6.45
	Mean	6.39	3.60
NGRDI	Min	-0.22	-0.25
	Max	-0.29	-0.45
	Mean	-0.25	-0.36

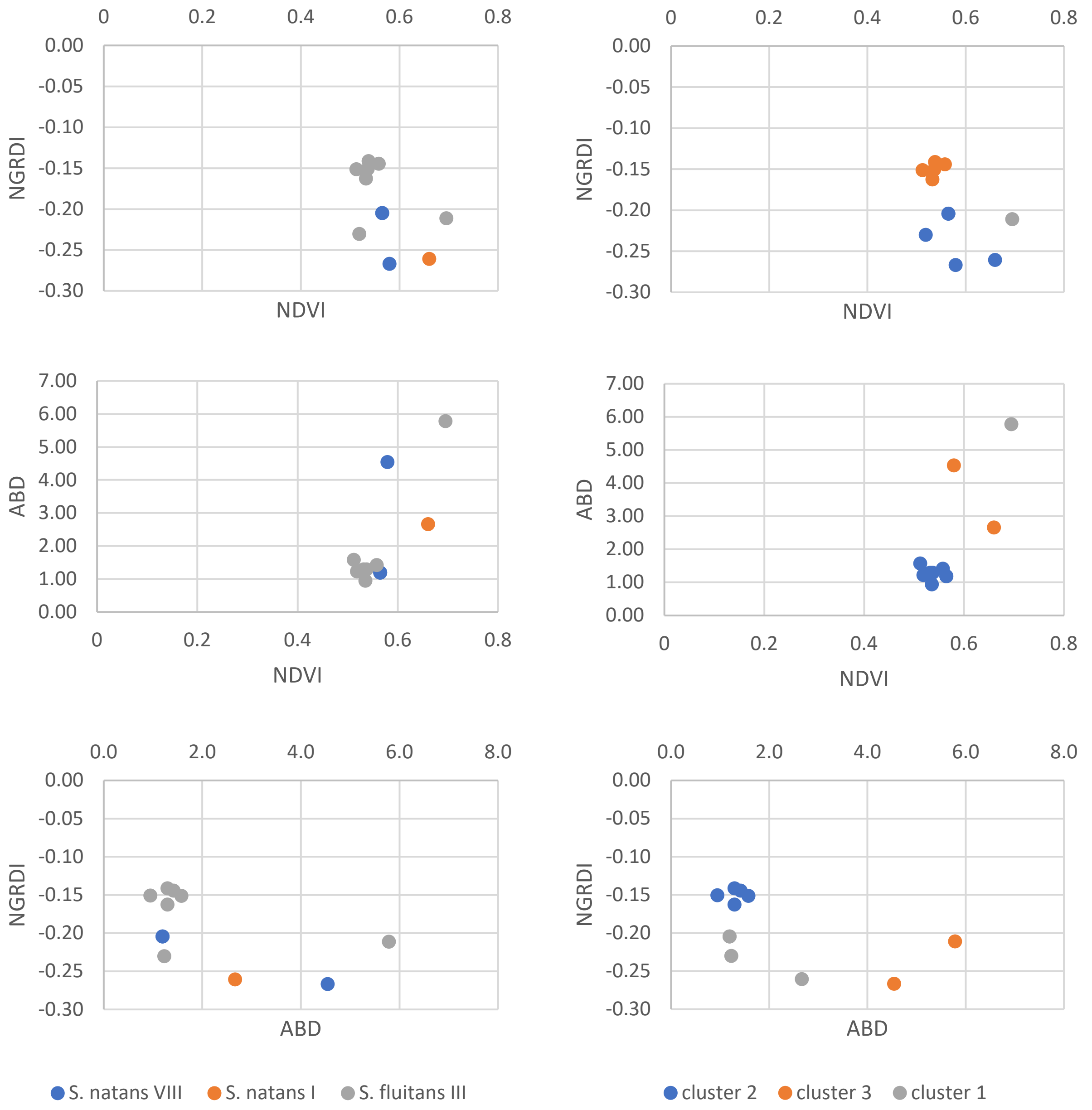


Figure 7 Cluster analysis graphs showing potential for species differentiation for both locations (Barbados and Ghana) together, with the species clusters on the left (each point represents the indices calculated from each spectra) and the k-means cluster result on the right.

After the NGRDI and NDVI were plotted, *k*-means cluster analysis was undertaken. The morphotypes (for both locations) did not converge as 27% of the points were not statistically close to their cluster (figure 7); it was observed that S. *fluitans* III was most consistent with fewest samples falling outside the cluster. There is of course a notable difference in the number of samples of each morphotype, *S. fluitans* III appeared to be most common on the beach, whereas *S. natans* I was least common and was not sampled in Sanzule. In 100% of the cluster calculations, S. *natans* I was not independently clustered. The cluster analysis for both indices and the ABD indicated 18% of the samples did not converge. There is an uneven number of samples for each morphotype and additional samples, especially for *S. natans* I, would be beneficial in establishing more confident clusters. Other factors including thallus tissue condition, age and epiphyte load could also contribute to variation in the spectral profile and resultant clusters. *S. fluitans* III was the most sampled morphotype, indicating that it was the most abundant morphotype in the sargassum beaching event in Sanzule. *S. fluitans* III has been identified as the dominant morphotype in other sargassum events in the Tropical Atlantic as well, such as in Jamaica (Machado et al., 2022; Davis et al., 2021), in Barbados (Alleyne et al., 2023), and in Mexico (Garcia-Sanchez et al., 2020).

The results for the different decomposition levels showed they were more distinct with less than 17% not converging with their cluster (figure 8). When the ABD was plotted with both NDVI and NGRDI, and the *k*-means cluster analysis was applied to both combinations, both indices did not have converging clusters and in both cases 25% of sample points did not converge with their cluster. Thus, it was inferred that the decomposition clusters where more distinct than the species but maintain some overlap.

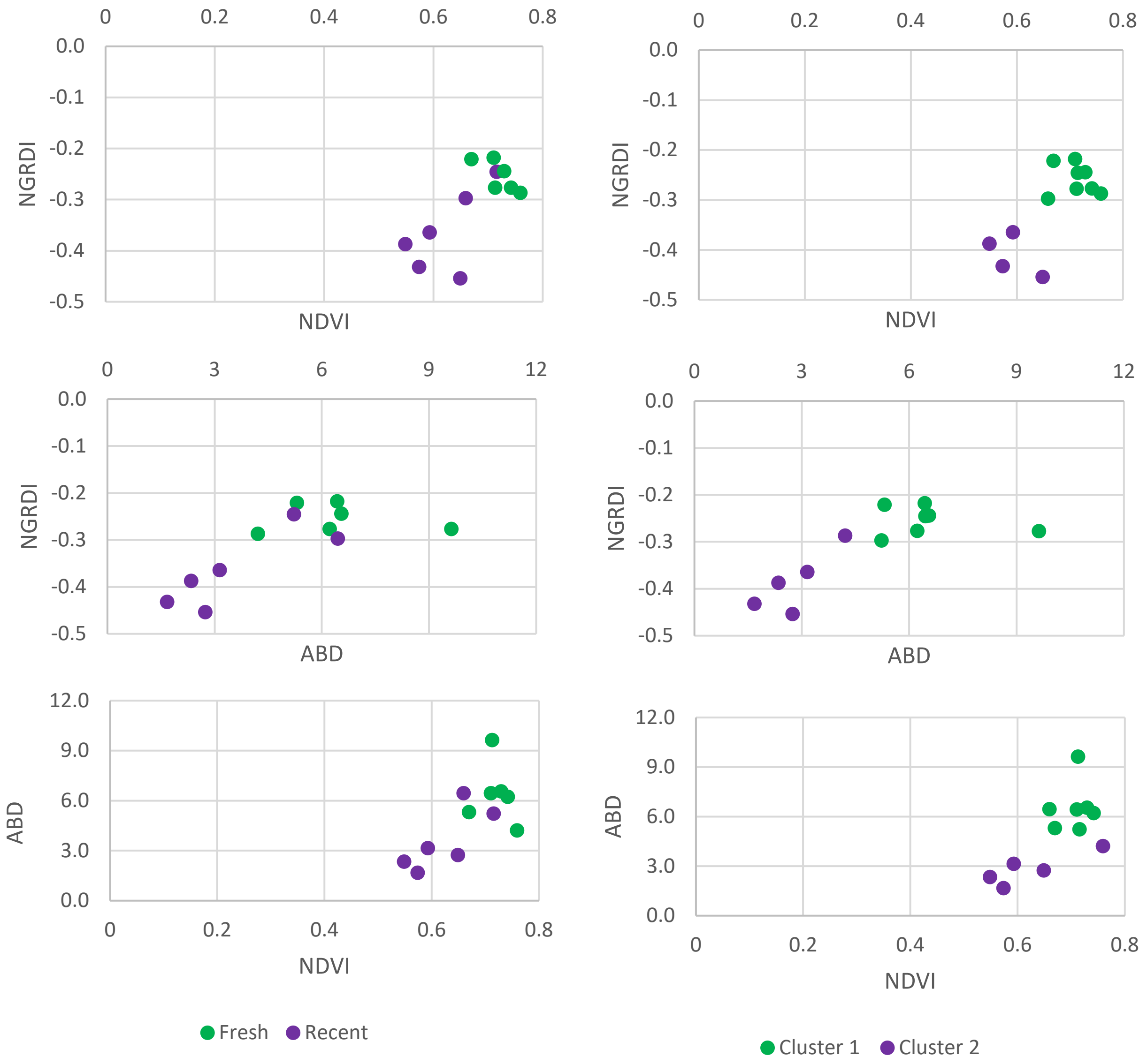


Figure 8 Cluster analysis graphs showing decomposition differentiation of mixed species in Barbados, with the decomposition clusters on the left (each point represents the calculated indices from the spectra) and the k-means cluster results on the right.

We theorised that some of the decomposition samples did not cluster as the measurements may have been affected by variation in sunlight due to cloud passing overhead, or by shade/shadows from vegetation along the beach. Additionally, method 1, compared to method 2, provides more opportunity for atmospheric interference as well as user error and variation. More specifically, a distance of 0.15 m to the target was measured at each sampling point to record spectra for 0.40 m sample diameter. However, over multiple recordings, the user could, due to different reasons including tiredness and/or wind, move the spectrometer closer or further from the target, changing the size of the measured area and potentially including adjacent seaweed that was outside the sample category, and this would result in erroneous data. It was not possible to use a tripod for consistency due to a lack of access to equipment that could enable measurement as low as 0.15 m height from the ground in these field conditions. For these reasons, we recommend method 2 over method 1 for measuring beached sargassum samples. Putman et al. (2023) demonstrate the success of using citizen science in monitoring coastal inundations, there is also an opportunity to use this here to expand the number of samples collected and further explore the spectral properties, for example, low-cost sensors or photography could be an accessible method of data collection to distinguish sargassum decomposition levels.

5.3.3 UAS mapping

As the ANOVA statistical tests, supported by the *k*-means cluster analysis, indicated that there was variance in decomposition spectra from Consett Bay (Barbados), the potential of differentiating these in drone imagery was explored. The supervised classification of the drone imagery was achieved by digitising the same 0.40 m sample regions that were measured *in situ* with the field spectrometer as regions of interest for classification training data. The spectral signatures were calculated (supplementary material figure 1) and it was observed that the red region had lower reflectance values than the green, which is different to what was found in the ground measurements. As such the Bray-Curtis dissimilarity index was calculated to determine if the digitised ROIs for recent and fresh deposits were differentiated. The Bray-Curtis result was 95.66%, indicating that they were statistically distinct, but the confusion matrix indicated an overall accuracy of 62% (supplementary material table 2) indicating that the classification accuracy was low. After classification of the images, it was observed that there were some errors in classifying sargassum shaded by vegetation, which likely contributed to the low overall accuracy. As such, the supervised classification was repeated, separating fresh deposits, recent deposits, fresh deposits with shadow/shade, and recent deposits with shadow/shade. The Bray-Curtis dissimilarity index was calculated again, and the results showed a statistical difference between fresh and recent deposits of 91.73% and the confusion matrix showed a higher and improved overall accuracy of 83.55%. It also enabled the classification map (figure 9) to closer match the identified boundary markers (white discs).

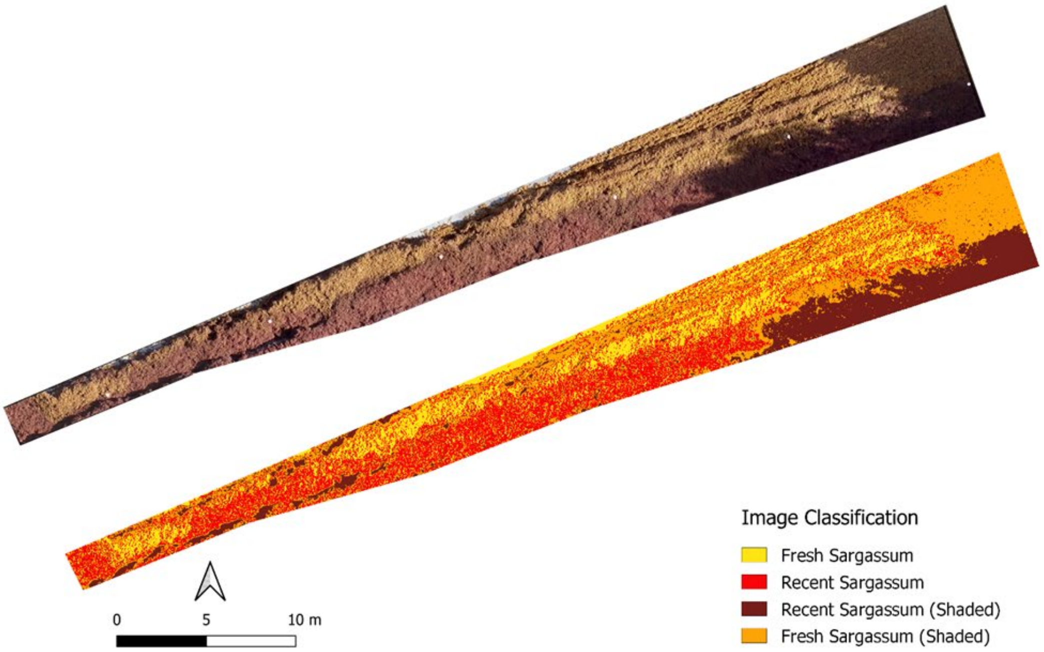


Figure 9 Supervised classification of UAS imagery. True colour RGB (top) and classification differentiating freshly and recently deposited sargassum, and shaded regions (bottom).

In the classification image, we observed that fresh sargassum was closer to the water and recently deposited sargassum was further from the shore, which aligned with our *in situ* observations. Although the overall accuracy was 83.55%, some errors distinguishing between fresh shaded and recent shaded deposits remained, particularly where sargassum was deeper, creating shade over more shallow areas.

The NGRDI values were calculated (table 2), and it was observed that there was some overlap in the range of NGRDI for fresh and recently deposited sargassum but there were distinct averages. From these results it is evident that there is the potential for fresh and recent deposits of sargassum to be distinguished in drone imagery, and to further this analysis it would be useful to obtain drone imagery at midday to reduce the impact of shade/shadow to enable a more robust classification and confident NGRDI identification range.

Table 2 NGRDI values calculated from drone imagery classification.

	Freshly Deposited NGRDI	Recently Deposited NGRDI
Drone Imagery Supervised Classification	Min: -0.30 Max: 0.96 Mean: 0.19	Min: -0.58 Max: 0.97 Mean: 0.17

A potential extension of the operational framework would be to connect the ground based and airborne measurements. Due to various logistical reasons, including access to equipment and weather conditions, it was not possible for this to be explored (supplementary materials 1).

Remote sensing, in particular UASs, are being increasingly used to map coastal agriculture, vegetation, and habitats. For example, Nurdin et al. (2023) used drone imagery to map the spatial distribution of seaweed farming, and Diruit et al. (2022) have mapped macroalgal habitats using hyperspectral imagery. In a sargassum context, methods for high resolution coastal monitoring are being established. For example, de la Barreda-Bautista et al. (2023) have explored high spatial resolution (3 m) monitoring in Mexico. However, application in this context is new and this work contributes to its progress. Indeed, Lazcano-Hernandez et al. (2023) and Fidai et al. (2020) have highlighted the need to increase near-shore and beach monitoring of sargassum where communities experience significant impacts and prediction and management measures are needed, considering that most research to date has focussed on floating blooms.

5.3.4 Biochemical analysis

The biochemical analysis of sargassum (figure 10) highlights relevant chemical signals and allows us to compare decomposition and species variation. Where there is a trough, we assumed that there was an increased presence of a chemical. The region of the curve that ABD was calculated from (92-1080 nm) is also inclusive of the region where water content can be observed. The variation in depth between spectra could be explained by a difference in water content; recently deposited sargassum had been exposed to the sun and wind on the beach, begun to dry out, change colour, and its ABD was lower when compared to freshly deposited sargassum.

The interpretation of the figure is supported by biochemical analyses of Ghanaian (Rhein-Knudsen et al., 2017) and Jamaican sargassum (Machado et al., 2022), who used laboratory analytical procedures to establish the biochemical content of fresh and dried samples. Analysis of the pelagic sargassum biochemical composition showed presence of compounds such as proteins and monosaccharides, which can also be estimated from the figure. For example, we could identify various protein signals in the regions of 910 nm, 1020 nm, 1510 nm, 1690 nm, 1940 nm, 1980 nm, 2060 nm, 2130 nm, 2180 nm, 2240 nm, 2300 nm, 2350 nm; sugar signals (possibly monosaccharides) were present at 1445 nm, 1490 nm, 1580 nm, 1780 nm, 1960 nm, 2080 nm, 2270 nm. Hu et al. (2015) noted that sargassum has a distinctive curvature at ~630 nm due to its chlorophyll c pigments, which we also observed.

From the earlier statistical analysis, it was found that the species/morphotypes were not consistently statistically different in Barbados and Ghana, therefore we can infer that their biochemical composition is also similar. Davis et al. (2021) observed that qualitative composition of Jamaican sargassum samples was homogeneous, with differences in quantities of certain compounds between morphotypes. Using this evidence, we can suggest that the variation in spectra could also be attributed to difference in the quantities of biochemical compounds, in addition to the potential methodological and atmospheric impacts to the data collection previously mentioned.

Analysis of reflectance of pelagic sargassum could be potentially useful for compounds specific to brown algae such as mannitol, laminarin, phenolics, alginate and fucose containing sulfated polysaccharides. These chemicals are supporting the use of brown algae in a number of industrial applications and are therefore of interest for the valorisation of sargassum. From initial desk-based research, the peaks and manufacturer supplied spectra of these chemical compounds fall beyond the range of the field spectrometer used in our study, therefore a wider range of wavelength data would be required to enable reflectance detection of these chemicals. Importantly, whilst there is a goal to valorise sargassum and understanding the biochemical composition works towards this, there are constraints and challenges associated with valorisation. These are summarised by Oxenford et al. (2021) who note that the supply of sargassum is unpredictable and variable; the chemical composition is variable and can have micro-pollutants; and there are difficulties surrounding harvesting, transport and storage of sargassum.

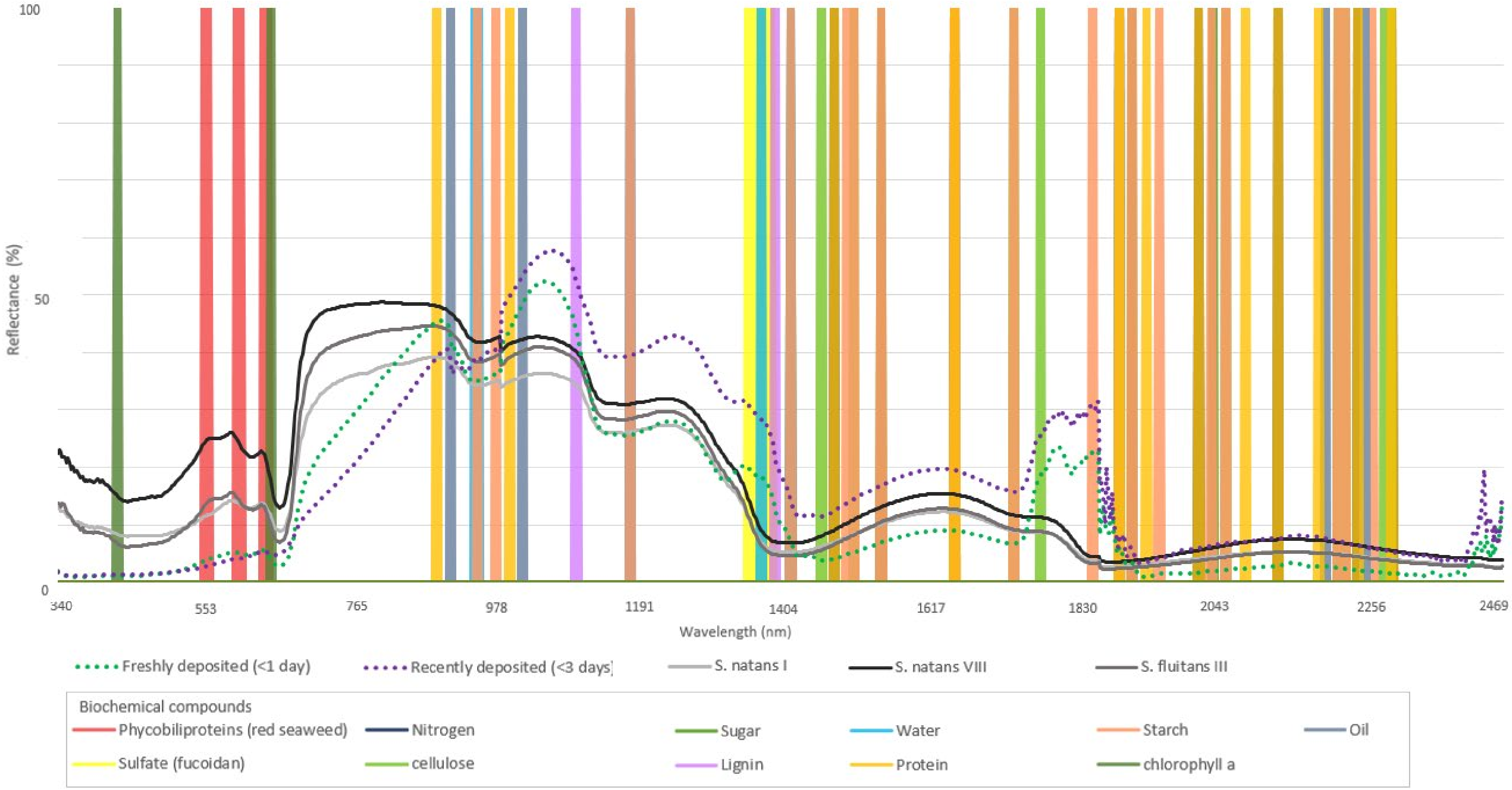


Figure 10 Biochemical analysis. The species and decomposition are plotted with wavelength regions where we can expect to observe specific chemicals. The wavelengths that indicate biochemical compounds were established from literature including Curran (1989), Machado et al. (2022), Agatonovi-Krustin et al. (2020) and Shalev et al. (2022).

Conclusions

Utilising ground and airborne datasets, we have developed an operational framework for quantifying spectral measurements of pelagic sargassum alongside generating spectral profiles of species/morphotypes, creating decomposition maps, and inferring biochemical composition. In the short term, this preliminary research contributes to understanding the spectral properties of sargassum morphotypes and decomposition levels. We presented the first *in situ* remote assessment of pelagic sargassum on beaches and found that fresh gold and recent brown sargassum are spectrally distinct; sargassum profiles have a distinct absorption feature between 920 nm and 1080 nm; signals for water and other chemical compounds suggest that different morphotypes and decomposition levels contain differing quantities which has implications for use. The method developed could be used to easily determine the quality of beached sargassum to inform harvesting and processing of the biomass and could replace the current costly requirement of collecting, drying, and transporting samples to a laboratory to determine their value. In the longer term, we expect utilising remote sensing and spectroscopy capabilities in combination with biochemical techniques to allow for better monitoring of pelagic sargassum from air and space borne methods, as well as the opportunity for quality assessments for commercial harvesting and valorisation. This would support management of this environmental challenge by providing crucial information for utilising pelagic sargassum.

In areas where sargassum cannot be monitored remotely due to weather and cloud cover conditions, this approach to data collection issues could provide simpler methods of sargassum quality and quantity assessment. While any *in situ* monitoring requires people to undertake the monitoring, there are emerging approaches to gather such data. Some of the outstanding challenges could be addressed through utilising citizen science methods and engaging communities affected by sargassum in research. Reflectance analysis could be used to explore seasonal and annual variation as well. In line with this, we noted a variation in spectral profiles collected at each location, and we attributed this to the field conditions and consequent variation in methods we employed. However, in future research, it would be valuable to explore if variation in biochemical composition also contributed to the differing spectra. Integrating interdisciplinary methods from biology and remote sensing would facilitate impactful research to advance knowledge on detection, migration, and biology of pelagic sargassum.

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Author Contribution Statement for Chapter 5

YF: data curation, formal analysis, investigation, methodology, visualisation, writing – original draft
CM: formal analysis (biochemical analysis), writing – review/editing
VDA: formal analysis (ANOVA statistical analysis), writing – review/editing
HO: data curation (Barbados fieldwork campaign), writing – review/editing
PNJQ: data curation (Ghana fieldwork campaign), writing – review/editing
TT: data curation (Ghana fieldwork campaign), supervision, writing – review/editing
JD: conceptualisation, data curation (Ghana fieldwork campaign), supervision, writing – review/editing

Supplementary Material to Chapter 5

SM5.1 Connecting Ground and Air Measurements

Attempts were made to upscale the ground measurements to drone imagery by resampling the ground based NGRDI calculations for decomposition levels to the drone camera band ranges and identifying the pixels in the image that fall in each decomposition category. When the resampled ground spectral NGRDI results were applied to the drone image, it was found that they are not representative of all sargassum in the image. Less than 0.3% of the pixels in the study area were classified as sargassum in both classes and this is not plausible based on *in situ* observations. As there is some distinction in NGRDI for recently and freshly deposited sargassum, we are confident that if the data and calibration methods were altered the ground-based measurements would be transferable to the UAS imagery. Due to various logistical reasons, including access to equipment and weather conditions, it was not possible for us to explore this.

Table 1 NGRDI calculated range and average for ground measurements resampled to the drone camera bands and for the supervised classification.

	Freshly Deposited NGRDI		**Recently Deposited NGRDI**	
Ground Spectral Measurements	Min: -0.22 Max: -0.29 Mean: -0.25		Min: -0.25 Max: -0.45 Mean: -0.36	
Resampled Ground Spectral Measurements	Min: -0.34 Max: -0.37 Mean: -0.35	0.03% of pixels	Min:-0.23 Max: -0.35 Mean: -0.29	0.23% of pixels
Drone Imagery Supervised Classification	Min: -0.30 Max: 0.96 Mean: 0.19		Min: -0.58 Max: 0.97 Mean: 0.17	

SM5.2 Classification Spectra

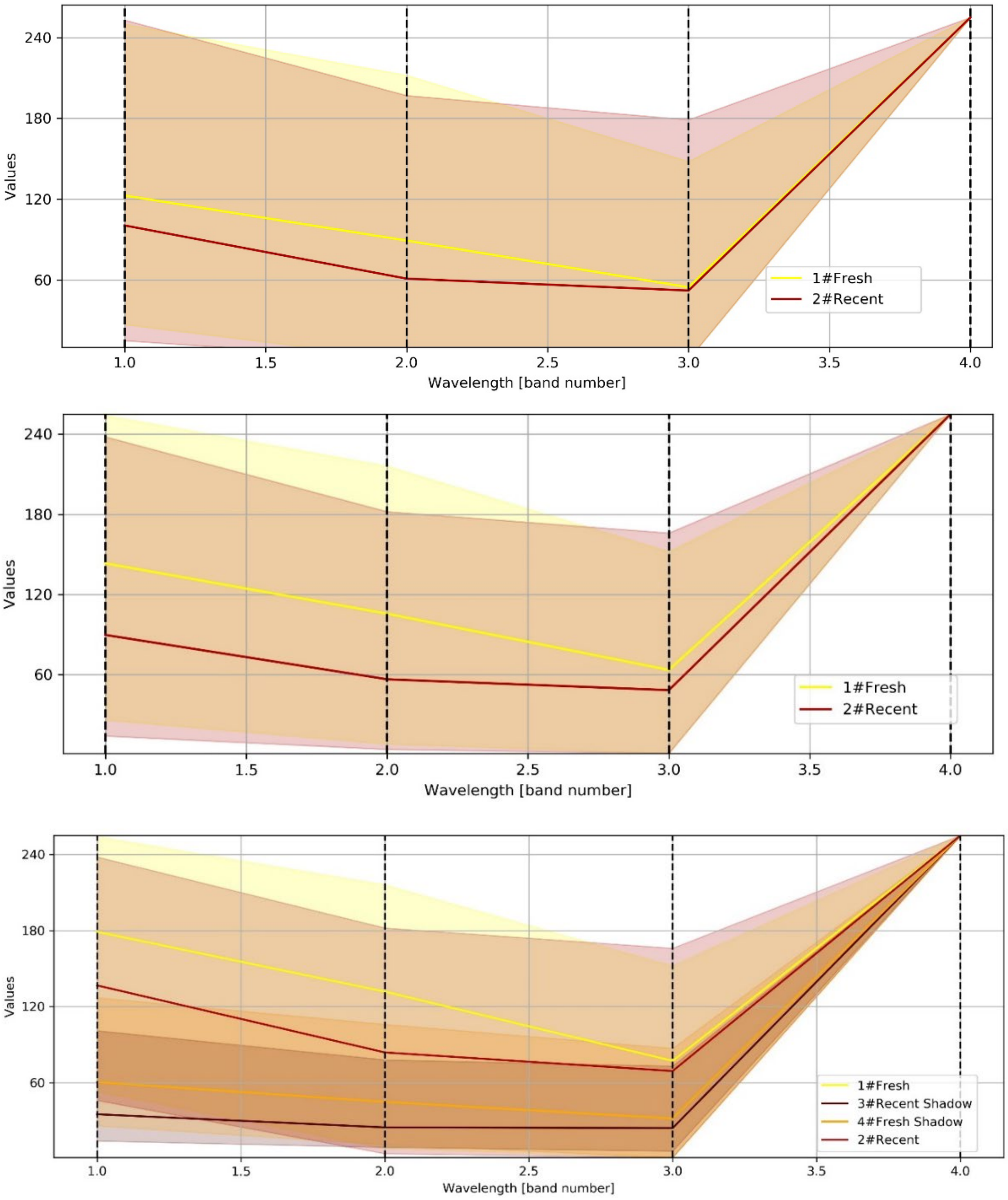

Figure 1 Classification spectra of drone imagery. Top: classification based on 40 cm ground sample areas; middle: top plus additional regions; bottom: middle but with shaded areas differentiated.

SM5.3 Error Matrices

Table 2 Error matrix for classification using ground sample points.

		Reference Data		
		Fresh	Recent	Total
Classified Data	Fresh	18450	19933	38383
	Recent	11260	29921	41181
	Total	29710	39854	79564

Overall accuracy = 62.0576%

Table 3 Error matrix for classification distinguishing shaded areas.

		Fresh	Recent	Recent (shaded)	Fresh (shaded)	Total
Classified Data	Fresh	12681	2159	0	0	14840
	Recent	2387	12666	0	29	15082
	Recent (shaded)	127	642	12839	294	13902
	Fresh (shaded)	85	1042	869	5832	7828
	Total	15280	16509	13708	6155	51652

Overall accuracy = 83.5459%

Chapter 6 Synthesis and Conclusions

6.1 Introduction to synthesis and conclusions

This chapter synthesises the work presented in this thesis, it answers the research questions and discusses what has been done to achieve them and the significance of the findings. This section reflects on the aims, objectives, methods and results, and suggestions are made for future research, policy guidance is provided, and key messages are highlighted.

Please note, as each chapter has been published or is in review, each one has its own figure and table numbers, most of which are the same i.e. all published/submitted papers contain Figure 1, Table 1 etc… Therefore, in this chapter, to differentiate between figures and tables in the preceding analysis chapters I add a prefix to each figure/table according to the chapter where it is found. For example: chapter 3, figure 1 is referred to as 'chap3:fig1'; and chapter 4, table 1 is referred to as 'chap4:tab1'.

6.2 Key Findings

The goal of this thesis was to extend our knowledge of the spatial and temporal distribution of sargassum in the Eastern Tropical Atlantic (ETA) with a focus on analysis of the spatial and temporal distribution of pelagic sargassum across the Tropical Atlantic by answering the following questions:

i) How can we improve monitoring and detection of sargassum events at multiple scales?

ii) How can we better detect and track sargassum pathways across the Tropical Atlantic?

iii) What opportunities exist to improve beach detection and monitoring in cloud covered regions?

In this section (6.2) the answers to these questions are explored through assembling and analysing the contributions made from chapters 2-5 towards addressing the research gaps and furthering knowledge of the spatial and temporal distribution of sargassum.

6.2.1 How can we improve monitoring and detection of sargassum events at multiple scales?

This work presents three different monitoring methods across different spatial and temporal scales (as illustrated in chap1:fig1). Chapter 3 [O2 VARIABILITY, O3 DRIVERS] uses coarse spatial temporal resolution (50 km) and high temporal resolution (daily) satellite imagery to estimate sargassum biomass at monthly intervals and explore co-variance with potential drivers over the decade from 2011-2022. Chapter 4 [O4 TRANSPORT] uses satellite imagery at medium spatial (10 m and 110 m) and temporal (5-16 days) resolutions combined with high resolution in-situ position tracking data (with 5m location accuracy at hourly intervals). In chapter 5 [O5 BEACHING, O6 PROPERTIES] high spatial (1-2 cm), low temporal (single occasion at each location) resolution aerial imagery and beach surveys (40 cm diameter on a single occasion in each location) are used for monitoring beached sargassum. Together they demonstrate the benefits of monitoring sargassum events in both the open ocean and on shore across different spatial and temporal scales. There are, however, some microscales between the combinations explored in this thesis, and different combinations of cross-scale analysis which are not considered, such as high spatial resolution with high temporal resolution. **The different scales researched in this thesis have unique research outcomes providing information about the hazard, which is needed for developing effective early warning systems and risk management strategies. I demonstrate that cross-scale analysis is necessary to better monitor and detect sargassum, but also show the importance of integrating datasets that are often not considered together but which collectively generate new insights and plug data gaps.**

Existing research in the Tropical Atlantic focusing on floating sargassum has been undertaken at low and medium spatial resolution using satellite sensors, including MODIS, MERIS, OLCI, MSI, Landsat, and VIIRS (see summary table chap3:tab2). This has been supplemented with in-situ surveys by boat such as Ody et al. (2019), and aerial surveys such as Maréchal et al. (2017). The work in this thesis compliments existing research on floating sargassum blooms as it not only used datasets from sensors already used for monitoring and detecting sargassum (MODIS and OLCI in chapters 3 and 4), but also used novel datasets; in chapter 4 SAR (from senintel-1) and GPS trackers (deployed in-situ) were used, and in chapter 5 a field spectrometer and UASs were used to collect data for detection and monitoring. These new contributions offer an improvement on existing methods in three ways: (1) by addressing gaps in the spatial extent of detection and monitoring and applying existing methods to a new area, the Eastern Tropical Atlantic (Chapter 3); (2) exploring potential alternative monitoring and detection methods with the potential to overcome challenges of cloud cover that have been reported through using existing methods and datasets (Marsh et al., 2022 and Ody et al.,

2019) (chapters 4 and 5); and (3) introducing a novel method for tracking floating aggregations to monitor their transport pathways (chapter 4).

By making contributions to improve monitoring and detection of sargassum through cross-scale analysis, this thesis has supported constructing the spatial identity of this transboundary risk which will enable it to be better governed (Lidskog et al., 2011). To further improve monitoring of floating sargassum blooms at different spatial scales, accessible high spatial resolution satellite imagery in the open ocean is needed. At present, freely available higher resolution satellite data tends to be terrestrial and coastal orientated which creates challenges including accurately observing floating aggregations, their morphology and phenology. In chapter 3, sargassum wet biomass is detected and estimated from MODIS images with 1 km resolution and daily images are composited to monthly intervals to detect as much sargassum as possible. Whilst this method detects 95% of sargassum containing pixels, small aggregations cannot be detected. Open access higher spatial resolution space-born imagery with multiple spectral bands is needed.

6.2.2 How can we better detect and track sargassum pathways across the Tropical Atlantic?

Existing methods to detect, monitor and track pelagic sargassum are largely remote sensing based, this has been done at a variety of scales and using multiple different satellite sensors (see Marsh et al., 2023; and chap3:tab2). A particular challenge when using space-born imagery in the Tropical Atlantic is the presence of dense clouds. Clouds occur due to the Inter-tropical Convergence Zone, and the regular occurrence of tropical storms and hurricanes obscuring the view of the ocean surface and sargassum blooms (Wang and Hu, 2016; Maréchal et al., 2017; Ody et al., 2019; Marsh et al., 2022). Models (often in conjunction with remote sensing) have been used to estimate the pathways of pelagic sargassum to forecast beach landings; these often rely on ocean models and in-situ drifters to simulate currents. A challenge with modelled methods of estimation is the inclusion of parameters that are not well constrained, notably windage and variables which impact the growth of sargassum blooms such as temperature. There is a need to improve these sargassum models to reduce their uncertainty (Marsh et al., 2022; Van Sebille et al., 2021).

In chapter 4 of this thesis, a novel method to track individual mats by combining remote sensing with deployed in-situ GPS trackers is presented. This method contributes to improving detection

and tracking of sargassum in two main ways. First, by using in-situ GPS trackers, the challenges of using remote sensing and cloud cover are reduced as they provide regular position updates of individual mats, filling the temporal gaps between satellite imagery and enabling consistent tracking of an individual mat. Additionally, the use of synthetic aperture radar (SAR) to detect the mats means that the effect of cloud on detecting sargassum mats is reduced, allowing estimations of the area and type of sargassum to be made. Second, by combining tracker and satellite data, determining the extent to which a remotely-sensed mat is coincident with the tracker locations, and assessing the coincidence with surface currents and wind stress, the first steps are taken to improve forecasting pathways and better constrain the windage parameter in the forecast models.

Whilst chapter 4 presents an alternative method to overcome the challenges of cloud cover through GPS tracking and SAR data, identifying the floating mats, especially small mats (type 1, 2 and 3, as typified by Ody et al., 2019), and validating their location remains a challenge. By combining the information from chapter 3 with chapter 4, the drivers and variables which impact growth, mortality, aggregation, and fragmentation of pelagic sargassum can be better parameterised. This enables tracking and forecasting improvements as understanding interactions reduces uncertainty in models. For example, parameterising sea surface temperature's impact on sargassum growth and mortality enables forecast models to consider changes in the amount of sargassum which occurs along its transport pathway, this in turn enables the quantification of sargassum volume, which then facilitates appropriate management and response, despite the challenges of detecting smaller blooms using satellite imagery.

6.2.3 What opportunities exist to improve beach detection and monitoring in cloud covered regions?

The systematic review (chapter 2) showed that very few studies have focussed on beach landings of pelagic sargassum (5% of studies). Most beached sargassum studies utilise in-situ surveys and collect sargassum samples for laboratory analysis to determine the chemical composition, and some have undertaken morphotype abundance analysis as well (see Garcia-Sanchez et al., 2020; Machado et al., 2022; Davis et al., 2021). However, a vast majority of these studies are undertaken in the Western Tropical Atlantic. Two studies have been undertaken in the ETA: Addico an deGraft-Johnson (2016), Oyesiku and Egunyomi (2014) both sampled beached sargassum along the coasts of Ghana and Nigeria respectively for chemical composition analysis. So far, remote sensing methods have not been commonly used in beach environments to monitor sargassum, Valentini and Baloiun (2020) used photographs to monitor and detect sargassum on the coast of Martinique. Only one study has targeted detection of decomposing sargassum on the shoreline, and is a case study for Puerto Rico (Leon-Perez et al., 2023). From this summary it is evident that there are opportunities to improve detection and monitoring of beached sargassum across the Tropical Atlantic region.

Detection and monitoring of beached sargassum, including morphotype analysis and decomposition are under-researched across the Tropical Atlantic region, particularly in the Eastern area. Chapter 5 aims to address the knowledge gaps surrounding beach detection and monitoring by investigating differences in morphotypes and the impact of decomposition on biochemical and phenotypic properties of beached sargassum. This is achieved through undertaking beach surveys using a field spectrometer and UASs in both the Caribbean (Barbados) and the ETA (Ghana). The chapter addresses three specific gaps: the lack of research in West Africa, beaching events, and analysis of decomposing sargassum. The spectral profiles of three morphotypes are identified, their biochemical composition is estimated, and classification of UAS imagery of beached sargassum is undertaken.

This work contributes to establishment of an operational framework to detect, monitor and valorise sargassum, specifically by establishing the spectral profiles of decomposition stages and morphotypes. The work demonstrates the capacity for using aerial imagery to detect biomass at different decomposition stages which can be used to make informed decisions for the appropriate response to inundations. Sargassum biomass has the potential to offer commercial opportunities in the blue economy, although, it is reliant on key chemical and physical characteristics of the sargassum for specific use. By estimating the chemical and phenotypic properties, sargassum biomass can be harvested for valorisation, which can alleviate some of the negative impacts of the influxes, especially the socio-economic impacts. A further benefit of using UASs to support data collection is that it overcomes challenges of cloud cover associated with space-born imagery across the region.

6.2.4 Key findings summary

This thesis has contributed to knowledge of the spatial and temporal distribution of pelagic sargassum (section 6.2), and also the creation of new empirical evidence, in the form of new datasets including GPS points of tracked sargassum mat transport pathways for five months in 2021; spectral profiles of sargassum morphotypes in Barbados and Ghana; and spectral profiles of sargassum decomposition stages from beach deposits that are freshly deposited (<1 day) and recently deposited (<3 days).

The following are a summary of the key findings of this thesis with the relevant objectives noted:

- The ETA is experiencing a statistically significant increase in sargassum blooms and biomass [O2 VARIABILITY].
- The increase in sargassum biomass in the ETA co-varies with increasing sea surface temperature, which indicates that it is a parameter potentially impacting the growth/mortality of sargassum biomass [O3 DRIVERS].
- GPS tracking and remote sensing can be used to better detect and track sargassum pathways and can be used together as a tool to fill spatial and temporal gaps of satellite data as GPS trackers provide continuous datasets despite cloud cover [O4 TRANSPORT].
- The average speed of travel of sargassum mats has been identified for the first time, this evidence reveals that surface currents are more influential than wind on mat transport [O4 TRANSPORT].
- Sargassum decomposition stages are spectrally distinct and can be detected using aerial imagery, with the potential for upscaling to satellite imagery [O5 BEACHING].
- The framework presented in chapter 5 for remote detection of beached pelagic sargassum has value for managing sargassum and improving valorisation potential [O5 BEACHING & O6 PROPERTIES].

6.3 Policy Recommendations

In this section the ways in which the knowledge and data generated in this thesis can be used to reduce the risks associated with sargassum are explored. The contributions to a risk management strategy are discussed.

The three analysis chapters focus on different elements of the cascading, interconnected, interacting and compound risks (as defined by Pescaroli and Alexander, 2018; and exemplified in IPCC, 2022), depicted in Chap6:figure1. Compound risks create a sargassum hazard pattern, where subsequent cascading risk loops contribute to the creation of social, economic, and environmental vulnerability in coastal communities.

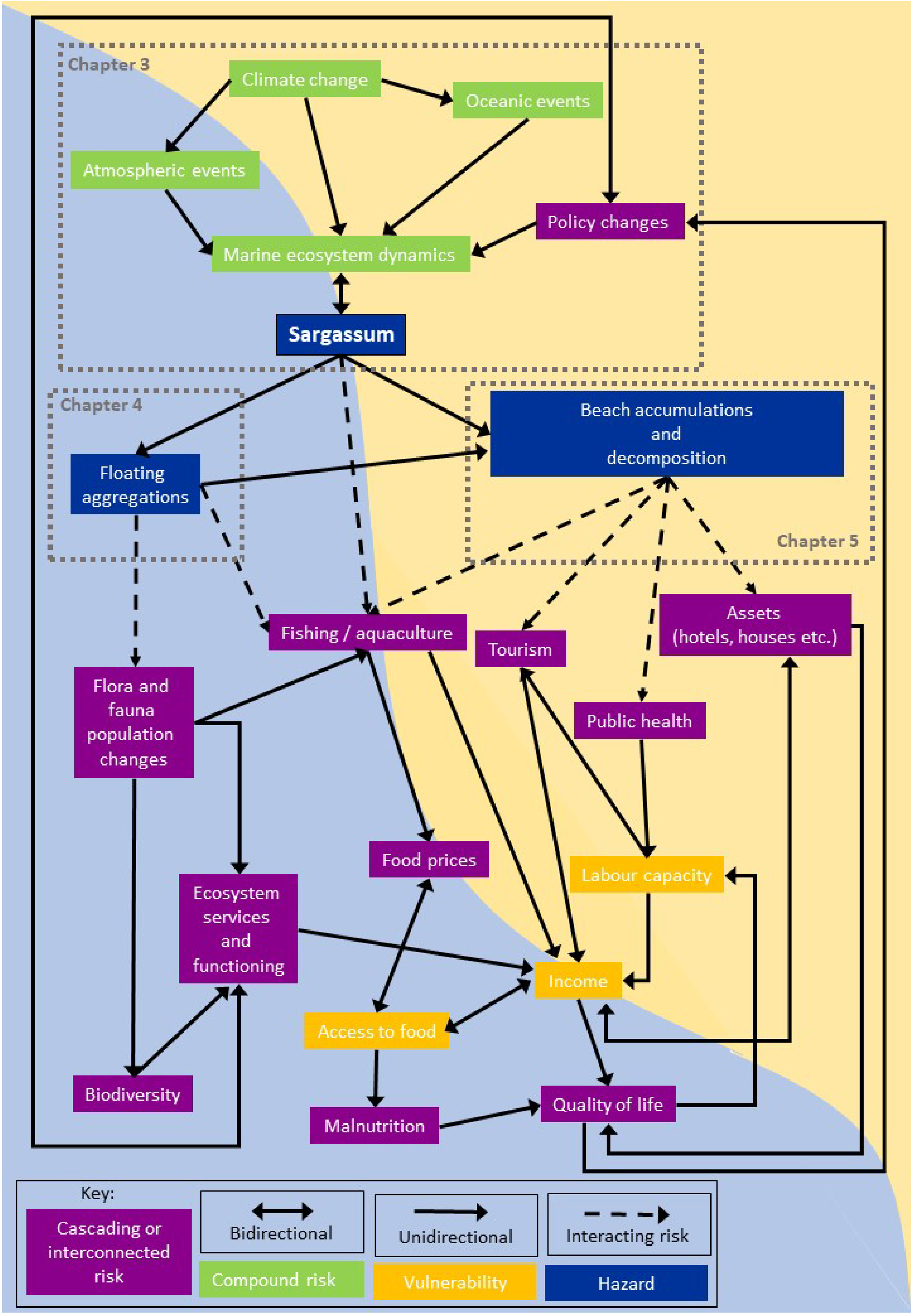

Figure 1 Illustration of the sargassum hazard risk connections and how interacting, compound, interconnected and cascading risk loops could create vulnerabilities.

By integrating the data on variability (chapter 3), sargassum transport pathways (chapter 4), drivers of growth and movement (chapters 3 and 4) and spectral properties for beach detection (chapter 5) into sargassum detection and forecast models, and implementing management policies, the cascade of risks can be interrupted by facilitating community preparedness. Chap6:fig1 illustrates the connections between floating and beached sargassum and the potential resultant social, economic, and environmental risks and vulnerabilities. To interrupt the cascading risk cycle, policy change could facilitate adaptations to the hazard which reduce the associated risks and vulnerabilities. The information in this thesis can contribute to a risk management strategy, and specifically can target community preparedness to avoid the risks and vulnerabilities in chap6:fig1.

Taking inspiration from the goals of the widely used invasive species management strategies from the UK and USA – Great Britain Invasive Non-native Species Strategy 2023-2030 (GBINSS) and the Aquatic Nuisance Species Task Force Strategic Plan for 2020 – 2025 (ANSTFSP) (chapter 1 section 1.1), the contributions of this thesis in the areas of 'surveillance, detection and monitoring' and 'research' goals for development of a risk management strategy are summarised in chap6:tab1.

Table 1 Summary of thesis contributions to elements ('surveillance, detection and monitoring', and 'research') of a risk management strategy for pelagic sargassum.

Surveillance, detection, and monitoring	**Research**
Tracking floating sargassum mats [O4 TRANSPORT]	Variability assessment (annual and seasonal) of sargassum biomass for the Eastern Tropical Atlantic [O2 VARIABILITY]
Detecting floating sargassum using space-borne imagery [O2 VARIABILITY]	Spectral characterisation of sargassum [O6 PROPERTIES]
Monitoring sargassum using UASs [O5 BEACHING]	Estimation of biochemical and phenotypic properties [O6 PROPERTIES]
Monitoring beaching events [O5 BEACHING]	Identifying knowledge gaps [O1 GAPS]
Variability assessment (annual and seasonal) of sargassum biomass for the Eastern Tropical Atlantic [O2 VARIABILITY]	Defining a sargassum event [O1 GAPS]
	Exploring co-variance of atmospheric and oceanic events with sargassum biomass [O3 DRIVERS]
	Determining mat morphology and phenology changes [O4 TRANSPORT]

The GBINSS and ANSTFSP both support acting quickly to address new risks, recognising that the sooner action is taken to address a threat, the greater the chance of success and the lower the cost. Again, the GBINSS and ANSTFSP highlight the importance of a strong research-led evidence base to inform risk assessments, detection, monitoring and public awareness activities. The work in this thesis provides underpinning research for a sargassum risk management strategy through delivery of objectives [O1 GAPS, O2 VARIABILITY, O3 DRIVERS, O4 TRANSPORT, O5 BEACHING, O6 PROPERTIES].

For invasive species, as population size and distribution increase, evidence indicates that management effort needs to increase (ANSTFSP). Whilst pelagic sargassum is not invasive in the Atlantic, it has become more prolific in the last decade. An array of risk management approaches has been introduced for some countries within the Caribbean (van der Plank et al., 2022), yet there is no sargassum management guidance for the ETA. This thesis contributes items to the development of a risk management strategy for countries bordering the ETA by providing two main elements.

The first contribution is an assessment of the annual and seasonal variability of sargassum in the ETA (for both the north and south of this region – chap3:fig2). For the northern ETA (around the Gulf of Guinea area), there is one peak sargassum period in September and another between March and May (usually a smaller peak). In the more southerly ETA (around the River Congo), there are also two annual sargassum peaks (January-April, and July/August), although there is not one peak that is consistently larger than the other. Additionally, this thesis shows co-variance of sea surface temperature and sargassum biomass; when the monthly sea surface temperature is lowest, there is a sargassum biomass peak immediately afterwards, demonstrating a link between sargassum growth and sea surface temperature (chap3, section3.3).

The second main contribution of this thesis for policy makers in the ETA is in relation to the speed and pathway of sargassum mats. Now for the first time the speed of mats in the Tropical Atlantic has been identified (chapter 4 section 4.3.2). Based on the speed of travel of six GPS trackers in the Caribbean Sea, I can estimate, for the first time, that sargassum mats travel at an average speed of 32.8 cm/s. With this basic understanding of speed of movement, sargassum managers in the ETA can now estimate the time of arrival of oceanic mats of sargassum into coastal ETA. For the main currents in the ETA, oceanic movements are relatively well established. In broad terms, the large oceanic currents approach the ETA from the West (the source waters for the Guinea Current are from the Canary Current or North Equatorial counter current depending on the season), then travel east along the coast of West Africa and then south to the mouth of the River Congo before turning to the West. However, less is known about smaller local currents, eddies, monthly variation, and changes due to compound risks, that could have a significant impact on the final location of sargassum beachings.

Together, these major contributions provide six areas for policy development:

1. *Ocean Monitoring in the ETA*: Instead of expensive year-round monitoring in the ETA, targeted high resolution monitoring of floating sargassum should begin at the very start of the months with lower sea surface temperatures. For the whole of the ETA this implies that monitoring parameters for growth of sargassum and detection of sargassum mats/pathways should be undertaken January to April and July to September to better link months with lower sea surface temperature to sargassum growth, and to generate early indications of beaching events.
2. *Beach Monitoring in the ETA*: In terms of improving beach monitoring, countries in the ETA could use UASs with at least RGB cameras (ideally with near infrared bands as well) to detect the decomposition levels and potentially estimate the aerial coverage of the sargassum as it is deposited. The state of decomposition is important for managers to identify the amounts of fresh and old sargassum. Fresh sargassum appears to have larger quantities of important and reusable biochemical compounds which have the most benefits for entrepreneurs for re-use and valorisation. In contrast, decomposing and decaying (old) sargassum appear to have the most negative impacts (health issues, smell, environmental impacts and nuisance), as well as having fewer important and reusable biochemical properties. By estimating the amount of the different states of decomposition of beached sargassum, managers can ensure that maximum benefits are extracted while leaving the lowest level of impacts on the affected communities.
3. *Beach Clearance/Removal in the ETA*: Recognising the seasonality of sargassum in the ETA, sargassum managers need to have communities on stand-by and resources available and ready to clear the sargassum from beaches just before peak sargassum months (i.e. Jan-April and July-Sept). By having teams ready to clear deposited sargassum, this will minimise the negative impacts of the sargassum on the affected communities. In addition, to extract maximum benefit from the larger quantities of biochemical compounds in the fresh sargassum, beach removal needs to occur regularly after the high tide that brings the sargassum in.

4. *Guidance For Marine Fishers and Ocean Users*: As sargassum peak season approaches, clear communications can be provided to marine users to alert them to the risk of high abundance of sargassum within the next few weeks, and the likely transport pathway (based on major currents). Communications could include information on how to avoid specific and regularly affected areas (if regular detections with satellite or drone or another type of aerial monitoring are being undertaken). This could be linked to the fishing guidance currently provided to fishers related to the health of fish stock. With more regular detection, more specific area guidance could be provided to fishers.
5. *Guidance for Tourist Hotels in the ETA*: As with fishers, the seasonality of sargassum, especially peak seasons, can be communicated to the tourism sector operators and workers. Guidance could be produced for the hotel and tourist sector across ETA countries on the timing of the sargassum season, updated estimates of how much sargassum could arrive, guidance on importance of early removal and regular clean up, and when peaks are likely to occur.
6. *Early Warning Communications and Guidance on Preparedness in the ETA:* Government agencies tasked with sargassum management in the ETA can draw on the findings of this thesis to support the development of early warning systems on the timing and quantity of sargassum arrivals. Information from improved monitoring in the low sea surface temperature months, could support individual countries to better prepare in specific months for community clean up and sargassum removal. Guidance to affected communities should include when to prepare and what actions to prepare based on the quantity expected.

6.4 Avenues for future work

Further work to continue to improve monitoring and detecting pelagic sargassum are needed to support more informed management of sargassum across the Tropical Atlantic. Additionally, further contributions to ‘surveillance, detection and monitoring’, and ‘research’ elements for development of a pelagic sargassum risk management strategy for the ETA region are needed. In this section, suggestions to progress work to this end are made.

To make improvements in detecting and forecasting sargassum more work is needed:

- To provide freely available high-resolution imagery to monitor smaller blooms in open-ocean areas across the entire Tropical Atlantic.
- To evaluate the role of parameters shaping sargassum events, including sargassum growth and mortality, movement, and proliferation, that are hypothesised by both the scientific community as well as local communities need exploration. This is both to verify important drivers and to discount others. For example, more work is needed to assess:
    - potential links between oil spills and sargassum;
    - the connectivity between oceanic and atmospheric events and rainfall with sargassum biomass;
    - water pollution monitoring with biochemical analysis to determine sargassum uptake of nutrients and pollutant metals.
- To improve understanding of sargassum transport pathways. GPS trackers could be released on sargassum mats across different months of the year and from multiple starting points, including the ETA, South Caribbean, Gulf of Mexico and Central America. This would create a basin-wide transport database and reduce uncertainty in tracking, growth and forecast models.
- To increase future capacity for monitoring and valorisation of sargassum biomass, seasonal and sub-regional variation of sargassum biomass biochemical and phenotypic properties should be explored.
- Outside of this thesis, but important for those affected by sargassum, better understanding of sargassum compound risks, and the interactions of people, land management, livelihoods, and businesses with sargassum will enable more accurate long-term forecasting of sargassum impacts.

Methods to address gaps in datasets due to cloud and lack of freely available high temporal and spatial resolution data are needed. The GBINSS note that citizen science initiatives such as 'Plant Alert' can help improve monitoring through contributing to information flow. In the case of sargassum, citizen science projects can be useful to fill data gaps in satellite imagery, as the entire Tropical Atlantic is affected by cloud either year round (in the ETA) or seasonally (in the Western Tropical Atlantic), as well as providing data coverage of temporal gaps in satellite data collection.

Citizen science projects can also be key to addressing spatial extent data gaps in under-researched areas. Some citizen science beach monitoring projects have been launched in specific countries but to improve monitoring efforts and support addressing gaps in datasets, citizen science could be expanded across the Tropical Atlantic region. Beach monitoring data collected from citizen science projects could be invaluable for providing datasets that can be used to monitor sargassum beaching events and provide information on arrival times and quantities arriving to establish local variability.

Further laboratory studies could be performed including undertaking wave tank tests on sargassum movement with GPS housing to measure its performance in different wave environments, additionally to improve estimates of windage and surface current impacts on sargassum movements. Further methods for data collection include exploration of using synthetic aperture radar (SAR) imagery from fixed instruments at the coast or on ships, or from UASs to improve aerial monitoring of sargassum, especially where visibility is challenging due to weather conditions. Additionally, newer satellites should be considered for data collection, such as the PlanetScope Dove Satellite, which provides 3.7 m resolution data. Sargassum monitoring at higher spatial resolution would enable smaller mats to be detected, and the morphology of mats to be better identified remotely. Also, NASA's PACE (Plankton, Aerosol, Cloud, ocean Ecosystem) satellite collects ocean-focussed hyperspectral imagery which should enable sargassum to be better distinguished from other floating vegetation, and could also be used to explore identification of chemical compounds and pigments of floating sargassum remotely. Other applications for methods developed in this thesis should also be considered including using ocean surface GPS trackers for tracking other floating marine objects such as debris, and other species of macroalgae.

6.5 Conclusions

Sargassum blooms and beach landings are impacting communities and shorelines across the Tropical Atlantic region. This thesis has assessed the spatial and temporal distribution of pelagic sargassum through application of a cross-scale analysis, using an interdisciplinary approach and mixed methods. The goal of this work was to extend our knowledge of the spatial and temporal distribution of sargassum in the Eastern Tropical Atlantic with a focus on analysis of the spatial and temporal distribution of pelagic sargassum across the Tropical Atlantic. This has been achieved though: (1)

undertaking a cross-scale analysis of pelagic sargassum in the Tropical Atlantic; (2) characterising the seasonal and annual trends of sargassum influxes in the Eastern Tropical Atlantic; (3) exploring the hypothetical drivers of movement and proliferation of floating blooms; (4) detecting, monitoring and tracking individual floating mats of sargassum in the Western Tropical Atlantic through using a combination of in-situ GPS trackers and satellite imagery data; (5) undertaking fieldwork campaigns of beached sargassum on shorelines in Barbados and Ghana; (6) identifying the biochemical and phenotypic properties of beached sargassum.

This thesis has provided new insights about sargassum influx monitoring, it has created new datasets showing transport pathways and speed of movement, and developed methods to support sargassum monitoring to enable re-use opportunities. Sargassum is likely to continue to be a problematic hazard for communities across the Tropical Atlantic, but this research, and work that builds on its findings should help those affected by sargassum be better prepared for events, and hopefully find ways to re-use sargassum to the advantage of those most affected.

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