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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.

1. Introduction

Pelagic *Sargassum* seaweed was first reported in the Sargasso Sea in the 15th Century and has since been documented in this area (Fine 1970, Lapointe 1986, Wang *et al* 2019). 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 (Sissini *et al* 2017, Sanchez-Rubio *et al* 2018, Oviatt *et al* 2019, Wang *et al* 2019, Johns *et al* 2020). 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 Gower and King 2011, Wang and Hu 2016, Brooks *et al* 2018, Putman *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* 2020a). 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 (Milledge *et al* 2016, Chávez *et al* 2020b, Thompson *et al* 2020).

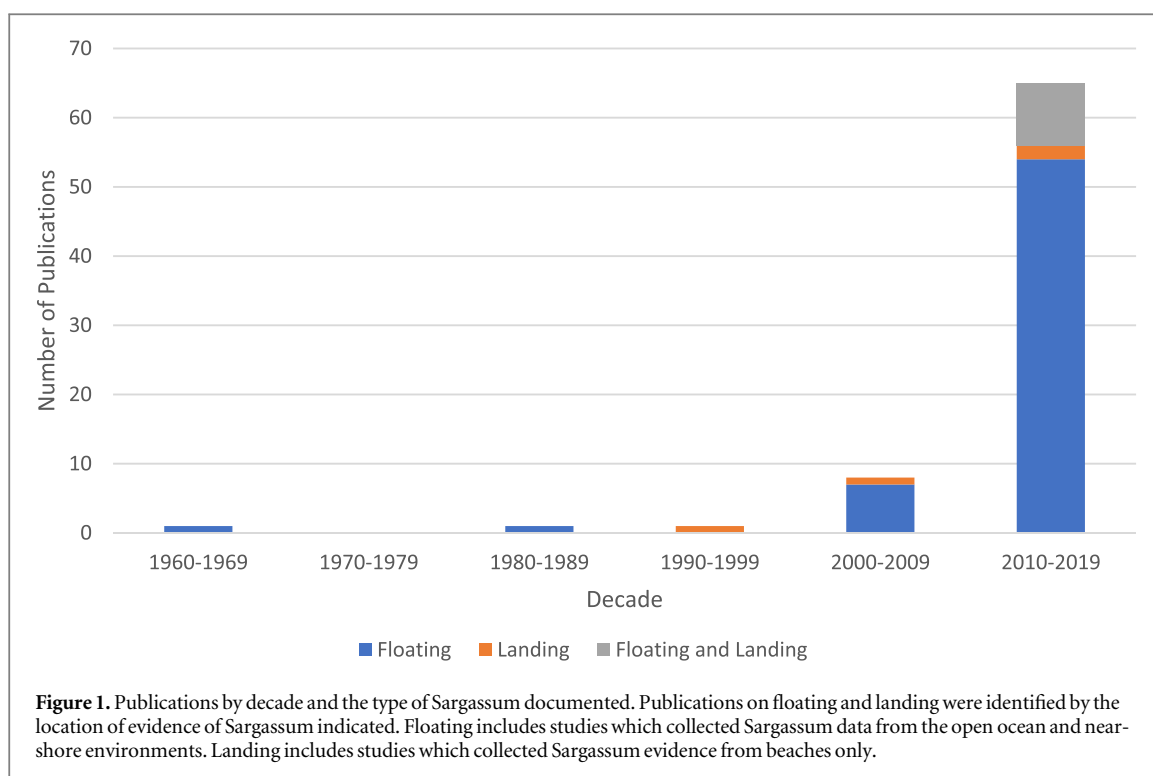
Large *Sargassum* influxes are generating high levels of concern among policy makers due to their impacts on economies, health, and society. Internationally, the United Nations Environmental Programme (UNEP) has created a Working Group on *Sargassum* within the Joint Group of Experts on the Scientific 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. Method

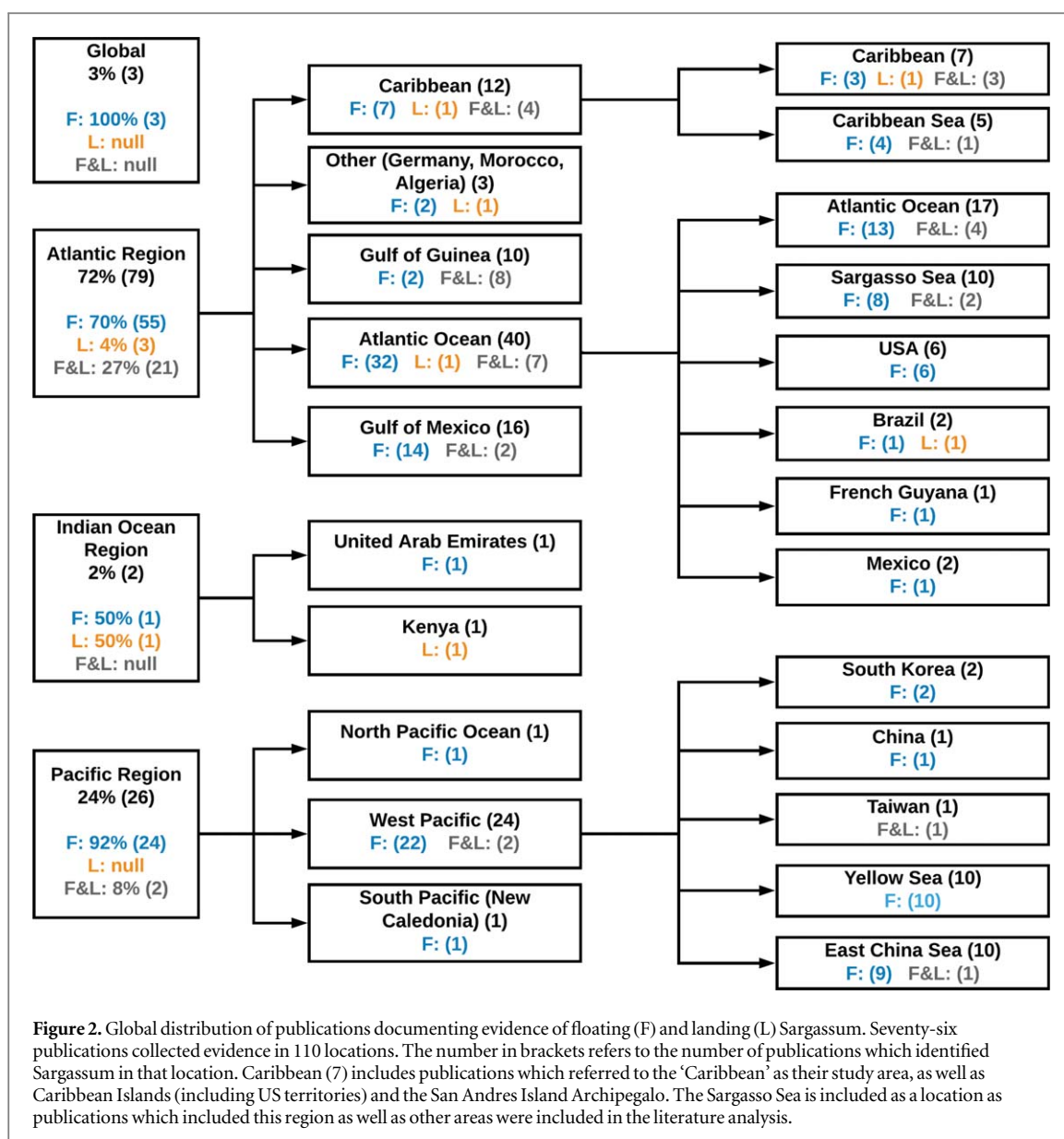
Systematic literature reviews are an important method for synthesising medical evidence (Bastian *et al* 2010) but are increasingly used in relation to analysis of environmental change (Berrang-Ford *et al* 2015). The systematic review method utilises search engines to identify all academic literature 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 (available online at stacks.iop.org/ERC/2/122001/mmedia)). 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 (i.e. empirical study, within our research focal area, pelagic sargassum, see supplementary material for details), 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-English language, not accessible, 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 subjectively rating each publication on a scale of 1–5 (1 = low; 5 = high) based on clarity of methods (justification and replicability), comprehensivity of presentation of results and relevance of themes to the research queries (based on criteria adapted from (Porter *et al* 2014)). The aim of 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, which were mostly judged to have a quality rating of 3 or 4; for ease of reading, the empirical publications are numbered in square brackets [1]–[76] and are provided in the annex.

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.

3.1. Floating and landing publications

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

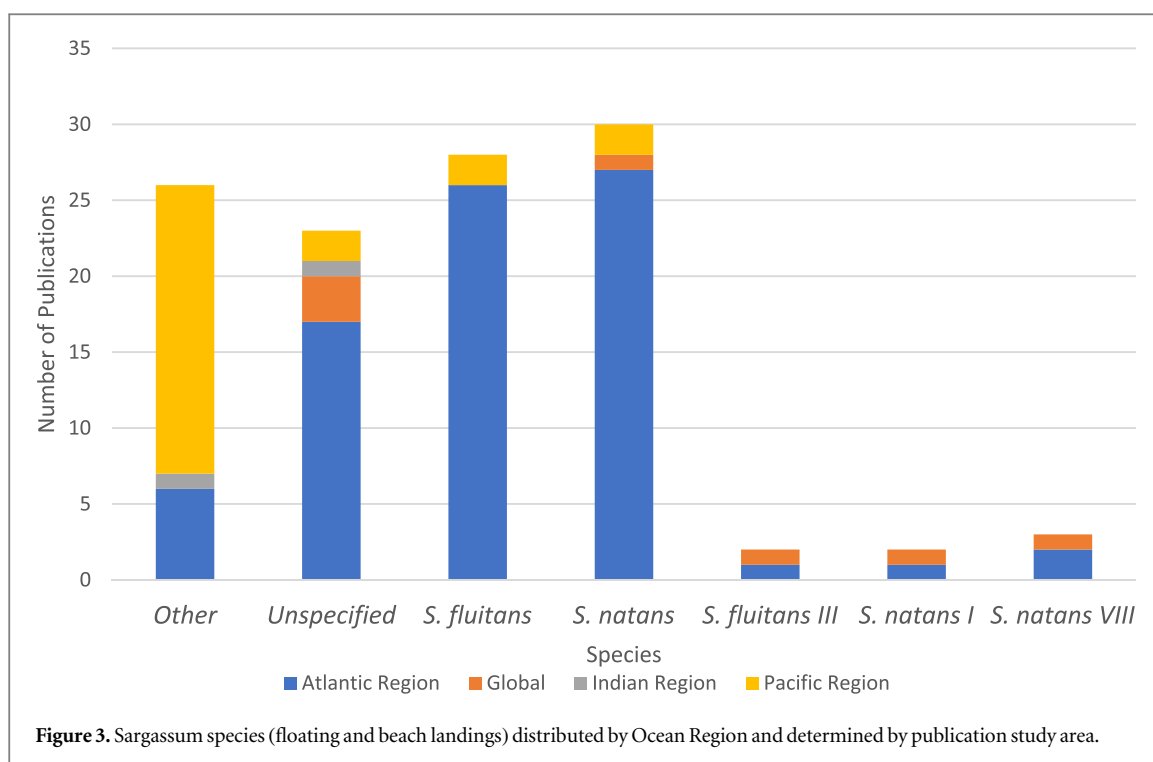


Figure 3. Sargassum species (floating and beach landings) distributed by Ocean Region and determined by publication study area.

(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).

3.2. Spatial extent of floating and landing *Sargassum* research

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].

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.

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

Table 1. Theorised sources for areas affected by *Sargassum*.

<i>Sargassum</i> 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

Agreement occurs when >60% of publications suggest the same source. No agreement is given when there are less than two publications for the location.

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.

3.5. Prevalence of *Sargassum* species in research outputs

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.

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%	[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]
	<i>In-situ</i> 25%	
	<i>In-situ</i> and remote sensing 28%	
Pacific Ocean Region (24% n = 18)	Remote sensing 33%	[9, 31, 35, 37, 42, 43, 62, 36, 4, 41, 74, 75, 6, 34, 52, 53, 73, 76]
	<i>In-situ</i> 39%	
	<i>In-situ</i> and remote sensing 28%	
Indian Ocean Region (3% n = 2)	Remote sensing 50%	[44, 49]
	<i>In-situ</i> 50%	
	<i>In-situ</i> and remote sensing 0%	
Global (4%, n = 3)	Remote sensing 100%	[18, 22, 59]
	<i>In-situ</i> 0%	
	<i>In-situ</i> and remote sensing 0%	

3.6. Types of methods and data used to document the occurrence of *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 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].

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.

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 (Davis et al 2020, Milledge et al 2020). 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.

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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