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Brown algae invasions and bloom events need routine monitoring for effective adaptation

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Abstract

Brown algae blooms and invasions have affected 29% of the Earth's coast, yet there is sparse evidence of the impacts and adaptations of these events. Through a systematic review of empirical literature on these blooms and invasions, we explore the prevalence of conventional analyses of environmental, economic, and social impacts, as well as opportunities for adaptation and valorisation. The study reveals crucial inconsistencies in the current evidence base on algae impacts: fragmented metrics for quantifying blooms and their effects; inconsistent application and testing of prevention measures (e.g. forecasting, early warning systems); reliance on removal as a management approach with limited evidence of associated costs; and scant evidence of the effectiveness of impact mitigation or adaptation strategies. With a focus on economic and societal dimensions of algae events, we introduce emerging opportunities within the blue economy for bloom utilization. The findings highlight the crucial need for harmonized monitoring protocols, robust cost-benefit analysis of management and adaptation options, and evidence of pathways to valorisation of algae biomass.

Keywords: brown marine seaweed, algae events, sargassum, *Rugulopteryx, fluitans, natans, horneri, muticum*

Introduction

Since the start of the 2000s, blooms and invasions[1] of marine macroalgae ('algae events' hereafter) appear to be increasing globally, with those caused by brown seaweed affecting an increasing number of people across the planet[1-3]. These events appear driven by the intersection of natural/climatic[4,5] events and anthropogenic[6] factors. Although details are still lacking, climate change may impact the distribution or prevalence of seaweeds[7,8], as well as triggering other marine risks, such as the spread of aquatic pathogens[9], invasion of other non-native species[10], coastal erosion and flooding[11]. The severity of these emergent risks is difficult to predict, in part due to the complexity of the ecological processes and associated feedbacks between climate, natural and human systems[12]. The advances in science and technology are providing us with increasingly sophisticated tools to predict and simulate algae events, such as satellite remote sensing[13,14], machine learning algorithms[15,16], and oceanographic modelling[17,18]. This progress is improving our understanding of the complex factors that contribute to brown algae events. Yet there remain many gaps in our knowledge of the impacts of, and adaptations to, brown algae events, which need filling to enhance planning and management[19].

Algae events can create major problems for affected communities on land as well as for sectors dependent on access to the sea. Brown algae events threaten aquatic ecology[20] (e.g. biodiversity loss), affect societies (e.g. recreational beach access and respiratory health) and cause economic problems[21] (e.g. fishery and tourism sector losses) that affect people's lives[22,23]. Blooms formed by brown algae have not been as common historically as those formed by the green algae (phylum Chlorophyta), specifically genus *Ulva* (sea lettuce). *Ulva* bloom events accounted for 52% of all algae events between 1976 and 2018[21].

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[1] Here, 'blooms' refer to rapid increases in seaweed population density in a specific area, while 'invasion' is the uncontrolled spread of non-native seaweed species into new ecosystems.

Research on the impacts of algae events has not kept pace with their spread over the last two decades. Our understanding of how people interact with these events (both positively and negatively) remains relatively unknown. The empirical evidence (albeit limited) of the impacts of brown seaweeds of genus *Sargassum* (phylum Phaeophyta*)* points to reduced human access to coastal waters, and negatively affected fisheries, fishery-related and tourism sectors[24,25]. There is some evidence that people affected by these events can suffer food insecurity, economic losses, and experience health impacts, such as skin irritation and respiratory problems[26,27], especially those in poor coastal communities (largely in the global south) dependent directly or indirectly on healthy marine ecosystems[28]. On the positive side, there is evidence of exploitation of brown algae in aquaculture, and as a source of soil amelioration for agriculture[29-31]. Despite this, the impacts and benefits of algae events on people are not monitored consistently or reported systematically to allow for a global analysis and understanding of both positive and negative impacts.

Affected communities need guidance on the nature of these emerging risks, how to adapt to them and, where possible, how to extract benefits[32,33]. Brown algae play a positive role in building coastal resilience, as they have potential uses in agricultural products, coastal erosion stabilisers, and as a bioresource that can contribute to economic regeneration through the blue economy[34]. Valorisation of brown algae biomass may create new jobs and goods, opening new opportunities for enterprise and trade[35,36]. Bioenergy, water treatment, biomedicine or animal feed are some examples of brown seaweed uses that could increase capacity to achieve cost-effective and sustainable solutions to a growing human population[37-40]. A few innovative businesses have already implemented some local (and larger) scale valorisation strategies, serving as practical models for other regions dealing with algae events. Examples of products from brown algae that are commercially available include: plant tonic (e.g. Algas Organics in St Lucia), the creation of building blocks using 40% sargassum (e.g. Sargablocks in Mexico), and emulsifiers for cosmetics (e.g. Carbonwave in Puerto Rico)[37,39]

Brown algae events are now occurring in multiple coastal regions, including the Caribbean, West Africa, the Western Mediterranean and the Northwest Pacific. Each of these regions faces its own unique set of challenges, given the variability in the species of algae involved and the associated ecological, social, and economic impacts. Yet, to date, there is no comparative analysis of these events, their impacts, management strategies, adaptation options, and valorisation opportunities. To address these gaps we ask: (i) what is the evidence base of the algae events; (ii) what are the impacts and costs of the events on affected economies, societies and environments; (iii) what management and adaptation options are being used; and (iv) what are the positive benefits of these events and opportunities for valorisation?

To answer these, we analyse the impact of, adaptations to, and opportunities from four current, extensive and long-running brown algae events: (1) *Sargassum muticum* in Western America and Europe, 20th century-present; (2) *Sargassum horneri* in Asia, 2000s-present; (3) *Rugulopteryx okamurae* in the Mediterranean coasts, 2002-present; and (4) pelagic sargassum (*S. fluitans* and *natans*) in the tropical Atlantic, 2011-present. Each algae event has varying degrees of data available. The different time scales allow for the capture of events in different phases of their life cycle (e.g. new benthic invasion vs. well established invader). The four specific brown seaweeds were selected for analysis because they are: (i) the best documented examples of invasive and bloom-forming brown seaweeds; (ii) a mix of benthic and pelagic species (i.e. an ecologically diverse sample set that is more likely to capture the complex range of ecological and socio-economic effects of algae blooms and invasions); (iii) long-lasting and on-going events occurring in different parts of the world; and (iv) using different management approaches and offering different valorisation opportunities.

To identify the entire population of literature that exists on the impacts of these events, management strategies, and adaptations, a systematic review approach was used (see Supplementary Material: Figure S1 and Supp. 1). Empirical evidence from 181 documents has been collated and analysed.

Results and Discussion

Approximately 29% of Earth's coast has been under stress from brown algae events for over a decade. Empirical research reports on the impacts of and adaptations to the four brown algae events in five continents (Africa, Asia, Europe, North America and South America; Table S1). Using simple digitisation of specific locations, and rough approximations of distribution of impacts[2], we estimate that collectively, the four algae are affecting approximately 180,000 km of the Earth's 620,000 km coast[3] (Figure 1). This approximation must be seen as an estimate only due to the vague description of areas affected by these four types of algae in literature, and figures are only intended to give an idea of the challenges faced by the world's coast.

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[2] Our results are a simple estimation based on the accuracy and representativeness of the data sources used, as well as the consistency of the manual delineation process (hand-drawn lines on maps of coastal areas identified as being affected by algae events in the literature). Figure 1 represents the data on a map projection using WGS 1984 Web Mercator (auxiliary sphere).

[3] Length of Earth's coast is inconsistently reported, we use NASA Science estimate of 620,000km at: https://science.nasa.gov/earth-science/oceanography/living-ocean

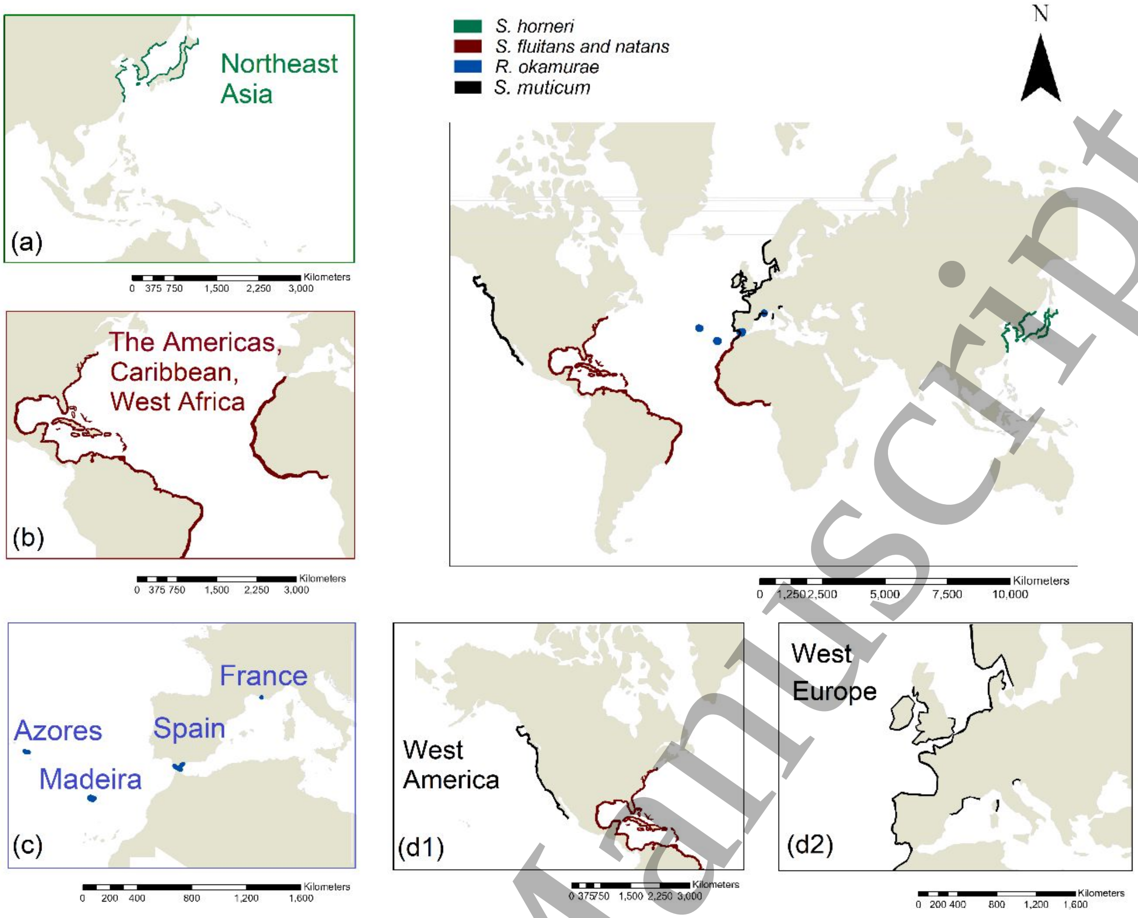

Figure 1 | Distribution map of estimated brown algae events along the coastlines. (a) *S. horneri* (green), (b) *S. fluitans and natans* (maroon), (c) *R. okamurae* (blue) and (d1-2) *S. muticum* (black). Note: figure do not show distribution of algal mats (floating or attached) in the open sea.

Sparse evidence exists of volumes of beaching brown algae events. There has been a growth in literature on floating algae (often using satellite imaging), yet actual empirical evidence of the volume of biomass in each event is spatially and temporally sparse (Table 1). For example, in 2018, pelagic sargassum across the entire Tropical Atlantic ocean was estimated at >20 million metric tons[3]. Yet, estimates of how much washed ashore (beached algae) are only available for Mexico in 2018 (estimates are 10,000-41,000 m^3 per kilometre of beach[41]). For some brown algae events, there is only evidence for one affected city or region e.g. for *R. okamurae* this is the event in 2015[42]. Temporally, for most locations (except for Barbados, Mexico and Dominican Republic), evidence of volume of biomass exists for, at most, only one year. Hence it is not possible to compile comparative evidence of quantity of beached algae experienced over time, across locations, or through events (the data in Table 1 do not show the same years). The considerable variation in reported volumes, both within and between different algae species, suggests that these numbers are subject to a range of uncertainties. These could include differences in the area covered by the reports, the methodologies used for estimation, and the time periods over which data were collected. Consequently, these estimates should be treated with caution and are unlikely to represent the true volume of algae events, especially beaching events.

Table 1 | Estimated volume per selected algae event type. Note: reported measures used by the authors; S1 extracted from Supplementary 1 List. Volume as tons* must be taken carefully due to unclear metrics reported by the resources.

S. horneri	***S. fluitans and natans***	***S. muticum***	***R. okamurae***
40,000 km^2 in 2020 (Yellow Sea) S1. 77	522,226 tons* in 2018 (Mexico) S1. 82	No data	5,000 tons* in 2015 (Ceuta, Spain) S1. 56
160,000 km^2 in 2017 (Zhejiang Province, China) S1. 175	1,400 – 1,843 tons* in 2015 (Atalaia beach, Brazil) S1. 155	No data	400 tons* in July 2020 (Tarifa, Spain) S1. 149
100,000 tons* in 2015-2018 (South Korea and Jeju Island) S1. 31	10,000 tons*/year (Barbados) S1. 162	No data	No data
No data	100 tons*/day (Punta Cana, Dominican Republic) S1. 82	No data	No data
No data	12,894 m^3 in 2019 (Puerto Morelos, Mexico) S1.80	No data	No data

Limited evidence and lack of consistent metrics used to report the magnitude of brown algae events and impacts. Research on brown algae events has increased significantly in the last five years, with 71% of the 181 reviewed documents published between 2018 and 2020 (Figure S1). Yet, there is still no standard metric for documenting or reporting volumes of seaweed either at sea or on land. Multiple measures are used in the academic literature e.g. km^2, metric tons[4], US tonnes (short tons)[5] and Imperial tonnes (long ton)[6], however most empirical research does not specify which measure of tons/tonnes are used[7]. In this analysis, simple calculations based on coastline lengths were used to estimate metric tons/km for the three events where data were found (Table 1): approximately 238 tons/km of *R. okamurae* arrive yearly to the coast of Ceuta (Spain); an estimated 103 tons/km a year of pelagic sargassum reach the coastline of Barbados; and 4 tons/km per year of *S. horneri* appear to arrive on the coasts of South Korea and Jeju Island. As the quantities of beaching across the world have not been monitored frequently or consistently, these numbers may not represent the reality of the events. Further there is no baseline of evidence of the scale of positive and negative impacts of brown algae events.

Brown algae events negatively affect nearshore environments and cause severe impacts on native macro fauna, although many aspects of environmental impact are poorly understood. Nearshore/onshore environmental effects of brown algae events are relatively well documented (compared to impacts on society and the economy) and reveal growing concerns about ecological responses of native species and ecosystem functions (Table S2; Figures 2, S2). All four brown algae biomass accumulations on beaches or at sea contain harmful elements, such as plastic, that seabirds can ingest[43], and all can create nesting difficulties for turtles[44]. The four seaweeds also cause hypoxia and deterioration of

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[4] 1 metric ton = 1000.0 kg

[5] 1 US tonne = 907.2 kg

[6] 1 imperial tonne = 1016.0 kg

[7] The challenge of measurement using comparative tonnes is also evident in relation to illegal wildlife trade and forest management, see for example Nijman, V., & Shepherd, C. R. (2021). Underestimating the illegal wildlife trade: A ton or a tonne of pangolins?. *Biological Conservation*, 253, 108887.

water quality in the tidal area (i.e. intertidal zone), affecting all levels of marine fauna and ecosystem functionality[45]. These problems appear particularly challenging for areas receiving pelagic sargassum and *R. okamurae* as these seaweeds can rapidly pile up on beaches in large volumes due to the movement of ocean currents and prevailing winds pushing the floating algae towards shorelines. Floating algae mats with an attachment form (such as *R. okamurae)* can rapidly smother the seabed, with 90% coverage to 20 m depth[42], and severely impact sessile native macrofauna[46]. In comparison to the other brown algae events, very little is known about the environmental impacts of *S. horneri*. Across all events further research is needed in relation to the impact of brown algae on nearshore nutrient availability, the transport of invasive animals and plant pathogens, and impacts on beach erosion rates. In the context of climate change mitigation, the potential for brown algae to absorb CO_2 for use as a greenhouse gas sink, needs investigation – along with better understanding of the lifecycles (growth and mortality) of the seaweeds.

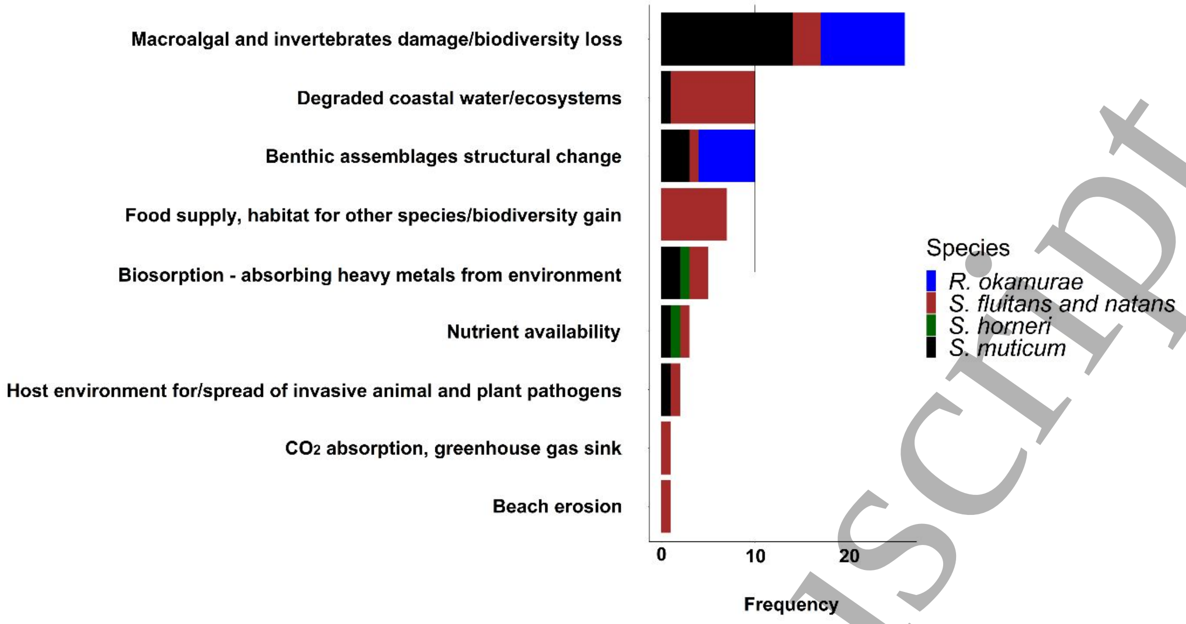


Figure 2 | Number of papers showing brown algae event impacts on the environment. Each bar shows the distribution of research by algae event.

Little is known about brown algae event impacts on societies; extant evidence suggests social impacts are largely negative. All affected continents (excluding Antarctica and Australia), report impacts of brown algae events on society (Table S2; Figure S2). We classify impacts on *society* as the impact on people (e.g. health, water/food access, employment). Negative impacts show evidence of damages. Positive impacts show actual or potential opportunities (e.g. food source, bioenergy) (Table S2).

Evidence of social impacts of brown algae events is particularly scarce (Figure 3), with only four papers that explore the social impacts of *S. horneri*[47-50], one paper that considers social impacts of *S. muticum*[51], and no literature that considers the social impacts of *R. okamurae*. Due to the limited evidence base for these three algae events, we only discuss the literature on the social impacts of *S fluitans* and *natans*. Negative societal impacts predominate in the pelagic sargassum literature. Human health impacts include nausea, skin and eye infections and respiratory issues[52-55]. The social impacts of reduced coastal access and water pollution are also prevalent: beached seaweed hinders access to clean water and sanitation (where freshwater resources are scarce e.g. low lying islands) as decaying seaweed can contaminate nearby aquifers[56]. On the positive side, beneficial impacts include: the potential for re-use of brown algae in locally or commercially produced items such as fish feed for aquaculture, biogas and as a plant fertiliser[37,57-59]. The overall lack of evidence of societal impacts for some of the brown algae events may be an artefact of the method used to search for papers, or it could reflect an absence of any evidence, pointing to the need for research on the social impacts of these events.

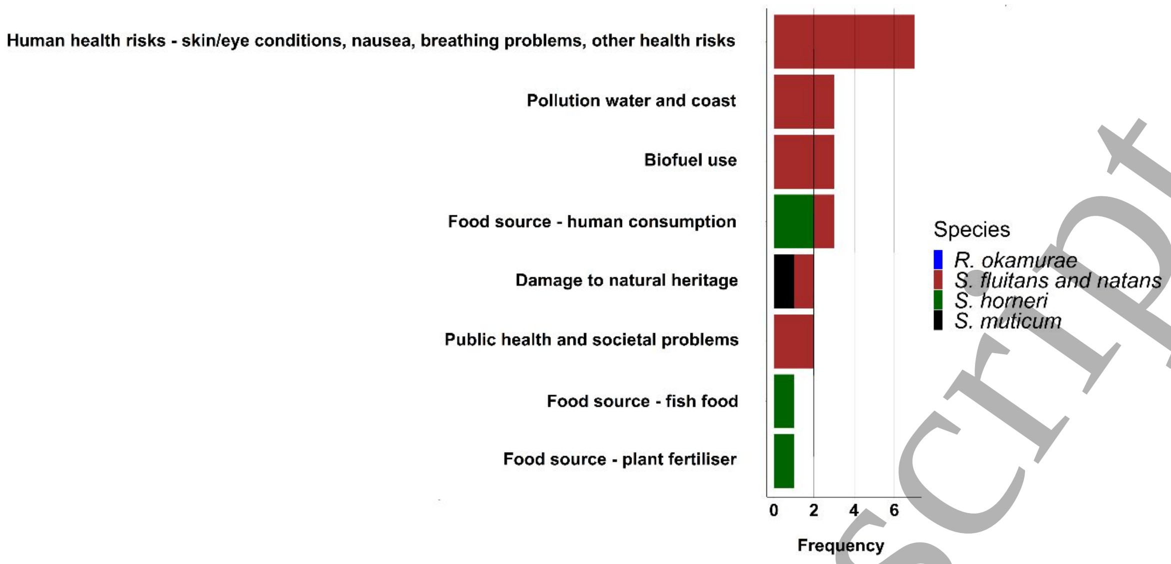


Figure 3 | Number of papers showing brown algae event impacts (positive and negative) on society. Each bar shows the distribution of research by algae event.

Economic impacts of brown algae events show a mixed picture, with negative impacts on coast-dependent sectors, but valorisation potential creating opportunities for agriculture. We classify impacts on the *economy* as costs, damages and benefits to economic sectors (e.g. tourism, fisheries or aquaculture)[60-62]. Damaging economic impacts are reported more extensively than positive benefits for all seaweeds (Table S2; Figures 4, S2). These positive benefits are mainly found as result of new emerging opportunities from brown algae uses[37,63-65]. Negative economic impacts occur mostly through two main routes: rising costs of coastal management (public and private), and damage to economically important coastal sectors, notably fisheries, tourism and aquaculture[66,67]. For example, significant quantities of *S. horneri* mats drifting from China (Zhejiang) are entangling in aquaculture facilities in Japan (Kitakyushu) which is increasing the costs of seaweed aquaculture[68]. Tourism sector impacts identified in the literature to date only reflect the additional costs of beach clean-up, or spending on preventative barriers or other measures[41]. There are no reports of impacts yet on lost tourist spending where tourists may choose to cancel or divert holidays away from locations affected by brown algae. Further there are no reports of positive tourism benefits e.g. attracting enviro-tourism[69]. Until the impacts on affected businesses are better reported, it will not be possible to make wider estimates of the impacts of the selected brown algae on employment or GDP.

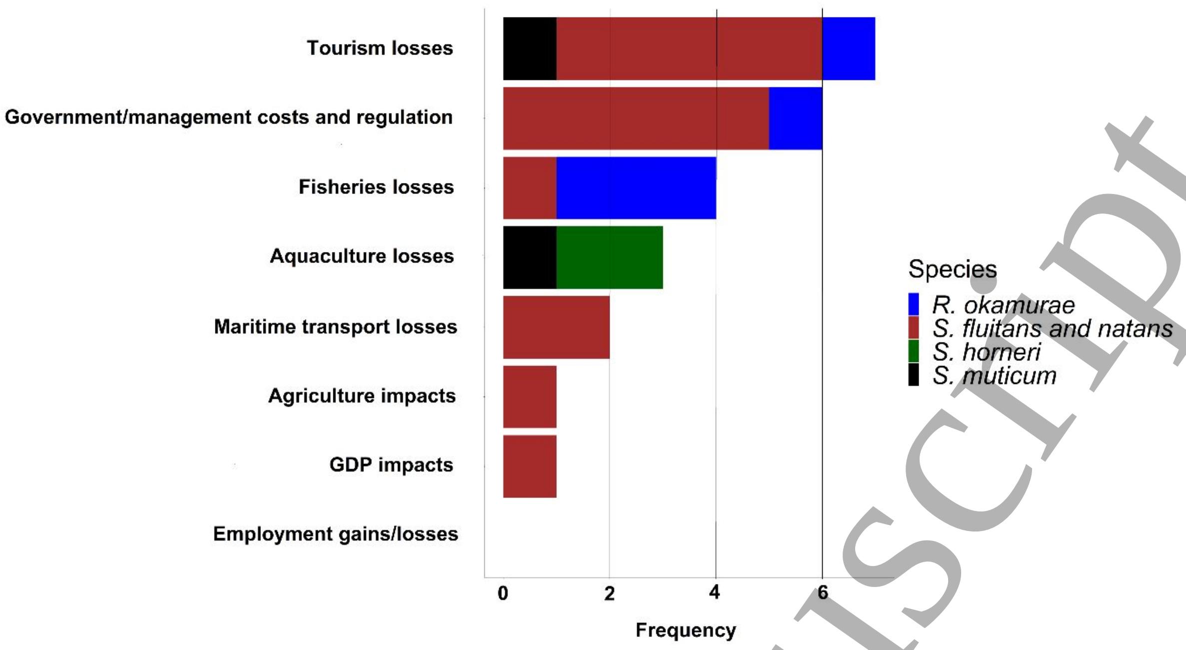
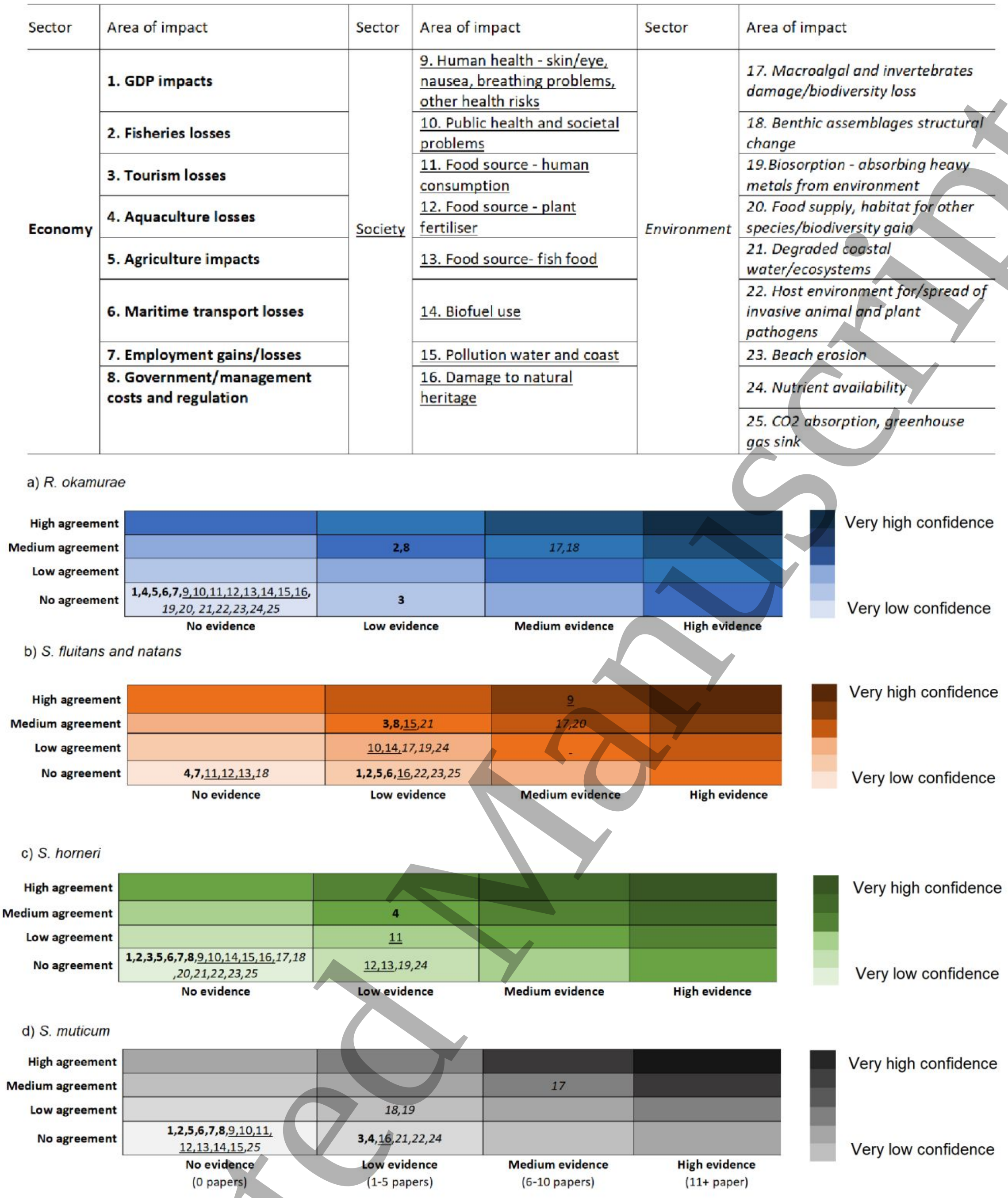


Figure 4 | Number of papers showing brown algae event impacts (positive and negative) on the economy. Each bar shows the distribution of research by algae event.

Very low levels of confidence in our knowledge about the impacts of brown algae events. By identifying how much evidence exists on selected brown algae impacts on the economy, society and the environment, and assessing the extent to which the literatures agree with each other (following IPCC guidelines on communicating uncertainty[70]), we conclude that, as of now, there is not enough consistent evidence or agreement among published studies to make definitive conclusions about the impacts of brown algae events, with the exception of biodiversity loss. There is a growing body of consistent evidence showing that in areas affected, pelagic sargassum, *S. muticum* and *R. okamurae* (but not *S. horneri*) adversely impact local algae and invertebrates, contributing to increased biodiversity loss (Figure 5). More empirical evidence and modelling work is needed on the events themselves, the impacts experienced, the costs and damages, and the management and adaptation options. Building on the need for further empirical evidence and modelling, recent literature has made significant advances in this area. Advanced statistical models, remote sensing and machine learning algorithms have been introduced to simulate algae events, taking into account a variety of environmental and anthropogenic factors[13,15,17,18]. Despite these advances, gaps in our knowledge still exist. Hence, there is a pressing need for interdisciplinary research that combines ecological, economic, and social perspectives to create a more comprehensive understanding of algae events and their multifaceted impacts.



Sector	Area of impact	Sector	Area of impact	Sector	Area of impact
Economy	**1. GDP impacts**	Society	9. Human health - skin/eye, nausea, breathing problems, other health risks	*Environment*	*17. Macroalgal and invertebrates damage/biodiversity loss*
	2. Fisheries losses		10. Public health and societal problems		*18. Benthic assemblages structural change*
	3. Tourism losses		11. Food source - human consumption		*19.Biosorption - absorbing heavy metals from environment*
	4. Aquaculture losses		12. Food source - plant fertiliser		*20. Food supply, habitat for other species/biodiversity gain*
	5. Agriculture impacts		13. Food source- fish food		*21. Degraded coastal water/ecosystems*
	6. Maritime transport losses		14. Biofuel use		*22. Host environment for/spread of invasive animal and plant pathogens*
	7. Employment gains/losses		15. Pollution water and coast		*23. Beach erosion*
	8. Government/management costs and regulation		16. Damage to natural heritage		*24. Nutrient availability*
					25. CO2 absorption, greenhouse gas sink

a) *R. okamurae*

	No evidence	Low evidence	Medium evidence	High evidence
High agreement				
Medium agreement		**2,8**	*17,18*	
Low agreement				
No agreement	**1,4,5,6,7,**9,10,11,12,13,14,15,16, *19,20, 21,22,23,24,25*	**3**		

b) *S. fluitans and natans*

	No evidence	Low evidence	Medium evidence	High evidence
High agreement			9	
Medium agreement		**3,8,**15,*21*	*17,20*	
Low agreement		10,14,*17,19,24*	-	
No agreement	**4,7,**11,12,13,*18*	**1,2,5,6,**16,*22,23,25*		

c) *S. horneri*

	No evidence	Low evidence	Medium evidence	High evidence
High agreement				
Medium agreement		**4**		
Low agreement		11		
No agreement	**1,2,3,5,6,7,8,**9,10,14,15,16,*17,18* *,20,21,22,23,25*	12,13,*19,24*		

d) *S. muticum*

	No evidence (0 papers)	Low evidence (1-5 papers)	Medium evidence (6-10 papers)	High evidence (11+ paper)
High agreement				
Medium agreement			*17*	
Low agreement		*18,19*		
No agreement	**1,2,5,6,7,8,**9,10,11, 12,13,14,15,*25*	**3,4,**16,*21,22,24*		

Figure 5 | Quantity of evidence and levels of confidence in knowledge about impacts of (a) *R. okamurae*, (b) *S. fluitans and natans*, (c) *S. horneri* and (d) *S. muticum* on **economy** – bold, society – underline, and *environment* – italics. Table shows areas of impacts by sector, panel shows the distribution of evidence of impacts and scale key to the levels of confidence in knowledge about impacts on economy, society, and environment (following IPCC guidelines on communicating uncertainty[70]).

Large gaps in knowledge about effectiveness of and costs of alternative management strategies. Management strategies for each selected brown algae are country-specific. In Spain, biodiversity law recommends that invasive seaweeds such as *R. okamurae* are ignored[71]. The majority of the evidence of management approaches relates to pelagic sargassum.

Prevention of impacts – depending on national legislation and capacity – is the most common strategy. Forecasting (e.g. early-warning systems) to aid prevention has increased in areas affected by *S. muticum,* and pelagic sagarssum[72,73]. However, for pelagic sargassum, current forecast systems do not cover the entire Tropical Atlantic, they focus solely on North America and the Eastern Caribbean[17,74]. In Asiatic countries, molecular-based detection approaches are being investigated to differentiate between floating and benthic *S. horneri* to improve preparedness, removal, and management[75].

Nearshore and offshore prevention methods have been trialled for pelagic sargassum including: floating inflated interception barriers to stop seaweed arriving inshore, and 'in ocean' mechanised collection via small vessels - both with varied success[37,76]. There is almost no documentation of the costs of prevention across all four selected brown seaweeds (Table 2), and no clear approach to evaluation of the effectiveness of alternative strategies. Furthermore, the use of varying units (e.g. \$/ton, \$/metre, \$/year) for representing the cost of preventative management in algae events creates a substantial hurdle for comparative analysis.

Table 2 | List of estimated mean costs[1] of preventative management for each selected algae event type. Note: S1 extracted from Supplementary 1 List. Volume as ton* must be taken carefully due to unclear metrics reported by the resources.

Management type	***S. horneri***	***S. fluitans and natans***	***S. muticum***	***R. okamurae***
Early-warning systems[a]	No data	$2,000/month [S1. 82]	$2,895/site[72]	No data
Beach, port and/or aquaculture removal[b]	$85/ton* [S1. 31]	$32/ton* [S1. 27]	No data	$80/ton* [S1. 53]
Private resorts cleaning[c]	No data	$206,800/year [S1.27]	No data	No data
Barriers[d]	No data	$995/metre [S1. 27]	No data	No data
Boats/trawling[e]	No data	$600,000/year [S1. 27]	$23.7/ton* [S1. 37]	No data
Cutting[f]	No data	No data	$28.5/ton* [S1. 37]	No data

Suction[g]	No data	No data	$26.8/ton*[S1. 37]	No data
Transport[h]	No data	$1,300.00/ton* [S1. 42]	No data	No data
Disposal[i]	No data	$80/ton*[77]	No data	No data

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[a]Forecasting approach for the arrival of brown algae events; [b]Collection labour, withdrawal (freight) and tractor labour; [c]Physical arrival of algae events to land and human sea structures; [d]Physical structures to confine pelagic brown seaweed; [e]Collection using nets and transport of brown seaweed in open waters; [f]Blade cutter to remove brown seaweed attached to substrata; [g]Air-driven cutter to remove brown seaweed attached to substrata; [h]Transport of brown seaweed to the processing facilities; [i]Conversion of brown seaweed biomass into waste.

[1] Mean costs: costs of management were not reported consistently across the papers. Where one value was provided in the cited paper, this was used verbatim in the table. Where a range of values was presented in the cited paper, the mean value within the range was estimated and included in the table.

Removal costs estimated at US$27-85 per metric ton. Once the event-causing brown algae are in the nearshore or have made land, the most common management approach is *in situ* removal (in ocean or beaches)[68,75,78-81]. Mechanical removal has been used, although it is increasingly criticised as this can damage coastal habitats leading to erosion, dune destruction or loss of critical nutrients[82,83]. Methods for removing attached forms of seaweed, notably *S. muticum,* are: biocontrol, by hand, trawling, cutting and suctioning directly from the substrata[84]. Unregulated harvesting using these approaches may also damage coastal habitats[85].

As is the case with estimates of impacts, costs of removal are generally not expressed in comparable units (Tables 2, 3). Costs of algae removal vary across geographical locations and species types – from $27 to $85 per ton. Several factors contribute to this variability, including differences in local labour and equipment costs, variations in the density and accessibility of algae, and the specific methodologies employed for removal[41,86]. Furthermore, environmental regulations governing removal can also differ from one jurisdiction to another, affecting the overall costs[87]. Costs can also be influenced by the urgency of removal; an immediate need for clearing algae due to tourism concerns or health hazards could escalate costs[41]. The lack of standardization in both measuring and reporting these costs make it difficult to perform a straightforward comparative analysis.

Table 3 | Estimated costs of removal for each selected algae event type per ton*, location where data was extracted from, and year of publishing. Note: S1 extracted from Supplementary 1 List. Volume listed as metric ton*, however the type of ton used in the literatures are often not specified.

Species	Cost ($ per ton*)	Study location	Year
S. horneri	85	Korea [S1. 31]	2020
S. fluitans and natans	32	Mexico [S1. 27]	2020
S. muticum	27	Isle of Wight and Portsmouth [S1. 37]	2009[1]
R. okamurae	80	South Spain [S1. 7, 49]	2021

[1] The data contained in the 2009 report reflects evidence collected in 1986, hence this cost per ton is likely to be significantly under-estimated.

Blue economy opportunities from brown algae events are emerging. Nearly half of the literature identified in the systematic search (47%) explored the potential for developing blue economy opportunities through re-use of seaweed biomass. Over half of this literature (51%) explores pelagic sargassum, valorisation options including: animal feed, biochemicals, bioenergy, biomedicine, biosorption, fertiliser, functional cosmeceuticals, food and 'other' (e.g. textile, cellulose, construction, bioplastic, antifouling, lubricants). One third (31%) of the literature on valorisation was for *S. horneri*, with almost all the same research areas as pelagic sargassum. For *S. horneri*, valorisation through cosmeceuticals and food have been investigated most frequently. The least amount of literature on valorisation was found for *S. muticum* (12%) and *R. okamurae* (6%), for which the focus was on biochemicals, bioenergy, biosorption, fertiliser and 'other' (Table S4, Figure S3).

A wide range of valorisation options have been investigated, especially for pelagic sargassum, several of which appear to offer potential for realisable economic benefits[37]. Current research suggests that most brown algae may contain beneficial components to produce medicine, pharmaceutical products and cosmetics[36]. Further research is needed to better understand the components of this biomass and inform valorisation. Direct ingestion offers less potential, Davis et al. 2021[88] discourage the direct use of pelagic sargassum as food or feed due to high levels of arsenic. In contrast, *S. horneri* has been successfully used as a dietary ingredient for aquaculture fish[49], which contributes directly to the improvement of the food industry for human consumption. The potential of these emerging re-use options could transform the way communities look at algae events, improve their management and generate new policy approaches, with important implications for business opportunities.

Discussion and future outlook. Literature on brown seaweeds (notably *S. horneri*, pelagic sargassum, *S. muticum* and *R. okamurae*), has grown considerably over the last ten years, yet there is still a paucity of comparable knowledge about volumes of beached or floating biomass per event, and an absence of evidence about the costs or effectiveness of management options. The quantity of evidence on the economic and social impacts of each macroalgae is low, with no more than 18 papers exploring economy and 23 society (out of 181) in total (mostly corresponding to pelagic sargassum). Yet there is increasingly cohesive evidence alerting us to negative impacts on native macrofauna and local biodiversity (64 papers in total). Improved reporting of the nature of the algae events and their management costs, especially removal, transport and disposal, numbers of people affected, and total economic losses might direct greater political and social attention to preparing for and managing the events.

The transferability of knowledge about size and frequency of brown algae events across and within regions is, in part, hampered by the lack of reporting standards, namely how to measure impacts and volumes arriving in events (e.g. km of coast, km^2, m^2, m^3 or tons), and the measurement unit (e.g. Imperial, US or metric tons). A common reporting standard for volumes of brown algae could significantly improve future comparative work to allow sharing of knowledge across regions, although the regional politics of measurement units may hinder this. In the absence of any other standard, we propose that the minimal standard/requirement for both, floating and beached brown algae, is area-coverage reporting (ideally in km^2). Estimates of weight should specify the type of tonnage: metric, Imperial or US to allow comparability. At the very least in all reporting of brown algae, there should be a clear description of the nature of the measure and metric used.

Comparable impact reporting for brown algae events is also needed. With the recent development of the Invacost[8] method, estimates of economic costs of some invasive species are being compiled, although this is dependent on the production of peer-reviewed articles and of grey literature assessing costs. No similar reporting method (or associated metrics) exists for societal impacts, such as numbers of people affected, or effectiveness of

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[8] Invacost provides a global estimate of the economic cost of biological invasions https://invacost.fr/en/accueil/89 Diagne, C. *et al.* InvaCost, a public database of the economic costs of biological invasions worldwide. *Scientific Data* **7**, 277, doi:10.1038/s41597-020-00586-z (2020).

management strategies adopted. Standard impact categories for other biological hazards (e.g. bacterial disease, grasshoppers) exist and could be drawn on to document the social impacts of brown algae events and invasions. Two publicly accessible disaster loss databases exist that could host the evidence base or guide the creation of impact categories e.g. DesInventar (United Nations DesInventar Open Source Initiative - Official Website) or the International Disasters Database Em-DAT[9] (EM-DAT - The international disaster database (emdat.be)) [90].

The paucity of management strategies for brown algae events is not due to an absence of possible frameworks. Management frameworks exist for biological invasions (e.g. Blackburn et al., 2011[91]), encouraging management through application of: management, prevention, eradication, containment and mitigation, with the various components relevant at different stages of the invasion (e.g. transport, introduction, establishment or spread). Disaster governance also exists for natural hazard management (e.g. Disaster Risk Reduction cycle comprising: mitigation, preparedness, response and recovery stages[92]). Yet despite these possible management framings, to date, management of all the brown algae events analysed in this paper has been ad hoc and national scale, either ignoring the event, or attempting prevention[93]. In contrast to other disasters, there is zero literature on long term risk mitigation measures for brown algae events, little on realistic approaches for developing early warning systems, or for guidance of post-event recovery of social and economic systems[94]. This absence of management guidance highlights the importance of one clear and urgent area for new research – how to apply extant frameworks (both management of biological invasions and disaster risk management) to mitigate the long-term risk of algae events, specifically to reduce the negative economic and social impacts? This needs to be supported by research into post invasion/bloom event ‘recovery’. What strategies work best for rapid clean-up of areas experiencing negative social and economic impacts? How can economic value quickly

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[9] Rosvold, E.L., Buhaug, H. (2021) GDIS, a global dataset of geocoded disaster locations. Sci Data 8, 61. https://doi.org/10.1038/s41597-021-00846-6

be found in the bloom forming/invading species to ensure that economic benefits flow to offset negative impacts?

In the short term, insurance may play a role in supporting the people and environments affected. Pay-outs from the insurance sector may support the larger formal tourism and fishery firms cope with immediate impacts, and provide an initial indicator of experienced losses (through Em-DAT reporting). Insurance is not a safety net in the informal sector and regions with lower insurance penetration will not be supported financially (or reported as experiencing impacts in the global datasets). There is scope for research into the potential of creating innovative insurance products to cover the negative environmental impacts of brown algae impacts, as research on other hazards indicates that insurance can incentivise risk mitigation and encourage rapid recovery[95].

Without clear understanding, and predictability, of the quantity and periodicity of the brown algae events, proactive management interventions seeking economic opportunities from them may be limited. Generating comparable data on the nature of events and the associated impacts would create a baseline of evidence from which management strategies can be developed. Other innovations such as sharing of local approaches to management through regional, or international networks is another important element in turning a problem into an area for opportunities that can contribute positively to economic and social development.

Methods

Research approach. A mixed methods analysis combining World Bank coastal shapefile data, analysis of geospatial data, and reanalysis of literature collated via systematic review was considered.

Systematic review question framing. A narrative systematic literature review approach[96] was adopted to investigate how brown algae events affect human development.

Systematic review search and screening protocol. By introducing keywords (Figure S4), the initial analysis was limited to finding titles, keywords and abstracts recorded in public and referenced databases using Web of Science and Scopus. Google Scholar was used to aid finding reports from the grey literature. The search was derived from four categories of keywords that were applied in combined search sets: (1) Species, (2) Location, (3) Impacted areas and (4) Positive and negative descriptors (Figure S4). Within each set, Boolean 'OR' operators were applied between keywords, and combined set search was achieved with Boolean 'AND' operators. Categories 1 and 2 were species-specific, therefore only certain combinations of keywords were allowed:

- *S. horneri* 'AND' (Yellow Sea 'OR' China 'OR' Korea 'OR' Jeju Island 'OR' Asia)
- *S. fluitans and natans* 'AND' (Tropical Atlantic 'OR' Caribbean 'OR' Africa 'OR' Ghana 'OR' Nigeria 'OR' Sierra Leone 'OR' Florida 'OR' Mexico 'OR' Belize 'OR' Brazil 'OR' America)
- *S. muticum* 'AND' (British Columbia 'OR' Pacific coast 'OR' North America 'OR' Alaska 'OR' UK 'OR' Europe 'OR' Mexico 'OR' Mediterranean 'OR' England 'OR' Ireland 'OR' Scotland)
- *R. okamurae* 'AND' (Mediterranean 'OR' Spain 'OR' Morocco 'OR' France 'OR' Azores)

A total of 863 documents was extracted from the searching process, where 186 resulted in replicates that were removed before screening. Methods for the screening protocol followed six descriptors for exclusion that applied to all four algae events and one descriptor specifically for *S. fluitans and natans*. Furthermore, two descriptors for inclusion were considered, which applied to all four algae events (Table S5). Documents' screening was performed into three main steps: (i) title screening (excluded n = 349), (ii) abstract screening (excluded n = 166) and (iii) full text screening (excluded n = 79). After exclusions, 181 documents ranging from 1997 to 2023 were selected for analysis (see Supplementary information for the full list of documents for review) where the interaction between people and *S. horneri* (n = 26), *S. fluitans* *and natans* (n = 63), *S. muticum* (n = 29) and *R. okamurae* (n = 21) were reviewed (Figure S5; Supp. 1).

Analysis of systematic review and geospatial data. Literature information (i.e. authors, title, year and journal of publication), algae species of interest and country where the study was performed were recorded for each reviewed document. The documents reviewed were classified by thematic groups (economy, society, environment, opportunity and politics) for the subsequent category analysis (Table S3), and the geographic distribution was performed by continent. Information was classified related to the impact of algae species as if the impact was positive (e.g. providing a new natural resource to convert into bioenergy) or negative (e.g. causing hypoxia in the tidal area and death of benthic species). Numerical data on economic expenses and volumes were also extracted, where the mean value was estimated using the range of values cited in the literature. Predicted arrival per km was obtained using the total coastline lengths of location where data was extracted as per ton (or tonne) per year. The calculated geometry of the total coastal length (geodesic) of the World Bank-approved coastlines shapefile was performed in ArcGIS Pro 3.0.0. All data analyses were completed in R version 4.1.2[97].

Limitations. Despite the fact that this study shows important results, there was very little literature on some of the themes, for example the effect on social or economic inequalities, or on the politics of bloom management. For some species, this may be linked to the language in which the research has been developed. Language was acknowledged as a barrier to access research articles, so there are chances of having existing literature on benefits and impacts that are not included in this study. In many occasions, literature on *sargassum* did not show any sign of identification at the species level and, therefore, added additional challenges on whether they should be included into the list of review documents (Table S5).

Data availability

The datasets generated during and/or analysed during the current study are available through University of Southampton repository upon acceptance.

Competing interests

The authors declare no competing interests.

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