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Environmental Research Communications

OPEN ACCESS

RECEIVED
9 January 2023

REVISED
12 April 2023

ACCEPTED FOR PUBLICATION
11 May 2023

PUBLISHED
20 June 2023

LETTER

Science and policy lessons learned from a decade of adaptation to the emergent risk of sargassum proliferation across the tropical Atlantic

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Keywords: pelagic sargassum, algal bloom, science-policy interface, coping, adaptation, environmental risk, climate change

Supplementary material for this article is available online

Abstract

Climatic and anthropogenic changes appear to be driving the emergence of new ecosystem and human health risks. As new risks emerge, and the severity or frequency of known risks change, we ask: what evidence is there of past adaptations to emergent risks? What scientific and policy processes lead to adaptive solutions that minimise the impacts of these events, and draw out opportunities? We identify science and policy lessons learned from coping with, and responding to, the sudden arrival of brown macroalgae (pelagic sargassum) that has proliferated across the tropical Atlantic since 2011. Drawing on an evidence base developed from a systematic search of literature relating to sargassum seaweed, and using event timelines and word clouds, we provide an analysis of lessons learned from a case study of adaptive responses across three continents to an emergent risk over the course of a decade. We reflect on successes and failures as well as opportunities taken in building adaptive capacity to address the risk in four key domains: policy, knowledge and evidence, monitoring and early warning, and technology and valorisation. Failures include: lack of environmental risk registries; missed opportunities to share monitoring data; and lack of a shared approach to manage the risk. Successes include: development of national management strategies; open-access knowledge hubs, networks and webinars sharing information and best practice; semi-operational early advisory systems using open access remote sensing data; numerous innovations customising clean-up and harvesting equipment, and research and development of new uses and value-added products.

Introduction

Climate change is directly influencing weather extremes and climatic means, and contributing, sometimes indirectly, to changes in ecosystem health, functions and services [1]. Human societies have historically adapted to past climatic and environmental conditions [2], but climate risks are increasing as climate change accelerates [3]. Despite this, there is evidence of a growing adaptation gap, whereby nations are failing to adapt at the speed needed to adjust to current climate variability and change [3]. This adaptation gap is further exacerbated by low investment in adaptation [4], and hindered by lack of research skills to monitor adaptation progress [5]. While some progress is being made on national engagement with adaptation policy and planning [6, 7], there remain significant gaps in adaptation policy instruments (e.g. in Europe [8]).

In the parallel area of disaster risk management, evidence suggests that significant work is needed to address the growing concern relating to large scale, transboundary systemic risks arising from our increasingly interconnected world [9]. Evidence shows that the increase in disasters affecting cites has not led to an increase in levels of adaptation [10]. Nor has there been an increase in ability to address socio-economic vulnerability and the root causes of disasters [9, 11] as pursued through the Sendai Framework [12]. As the risks from complex environmental and climatic change rise [9] and costs of government-led adaptations soar [3], there is a growing expectation that individuals must live with the changing risk [13].

Learning to live with climate-related risks is socially and politically challenging due to the need to accept potentially unwanted changes [14]. Where there are efforts to address the root causes of vulnerability, and a continuous process to engage with and manage the risk, evidence shows that living with risk can strengthen the adaptive capabilities of affected communities [15]. There is also evidence to the contrary that living with risk, where vulnerability is not addressed, can generate behaviours that have maladaptive outcomes [16], and where taking adaptive action does not guarantee a successful outcome [17, 18] as adaptation opens up new unexpected vulnerabilities. This literature highlights a variety of skills needed to avoid moving towards maladaptive responses, notably: understanding the nature of the changing risk; ability to recognise and respond to changes; societal ability to organize and act collectively; or the agency to determine whether to change or not. These skills align with the domains of adaptive capacity [19], and map onto four broad areas of research relating to emergent risks: monitoring the risk and early warnings; technology and opportunities to valorise the risk; utilising extant knowledge and evidence; and the policy context.

There are few well documented examples that offer guidance on effective processes to build adaptive capacity in a system or community exposed to a new or emergent climatic risk. The aim of this paper is to address this gap, by providing details of adaptation to the annual massive influxes of pelagic sargassum seaweed (henceforth referred to as 'sargassum'), a brown macroalgae dispersed across the tropical Atlantic, from its genesis in 2011, to the end of 2022. We analyse the process of adaptation over a decade, looking at adaptations, mistakes made, and late lessons learned, and create a framework for adapting to the influx of sargassum and other emerging risks.

Since 2011, thousands of tonnes of sargassum have repeatedly washed ashore in tropical Atlantic countries, affecting the biodiversity, economy and resources of coastal communities [20]. Sargassum affects multiple economic sectors spanning: fisheries, tourism, human health and subsistence livelihoods [21]. For tourism- or fisheries-dependent coastal countries, there is a concern that sargassum could pose a risk to long-term economic growth (See supplementary material, figure S1). Sargassum influxes now occur annually, and years with relatively high abundance, e.g. 2015, 2018, 2022, are occurring more frequently as indicated by the time-series of sargassum areal coverage in the Central Western Atlantic (CWA) (figure 1(A)).

Initial sargassum blooms may have been triggered by a climate anomaly in winter 2009-2010, specifically an extreme negative phase of the North Atlantic Oscillation (figure 1(B)), which drove seed stocks southwards into the eastern tropics [22]. Since then, a variety of climate and related drivers of sargassum have been hypothesised. Blooms may have been exacerbated through nutrient enrichment [23, 24]. The Atlantic Meridional Mode (AMM, figure 1(C)) appears to play an important role in the variability of sargassum (both volumes and distributions). When the AMM is in a negative phase, i.e., when the sea surface cools and trade winds strengthen in the northern tropics, sargassum is more extensive. The main cause appears to be the southward displacement of the Intertropical Convergence Zone and strengthened upwelling of nutrient-rich waters [25]. The wider Atlantic, including the tropics, has also been anomalously warm over the period of sargassum proliferation, which may favour the growth of tropical variants. The majority of this warmth is attributed to a positive phase of the Atlantic Multidecadal Oscillation (AMO, figure 1(D)).

Variations in sargassum abundance have been further attributed to the intensity of Atlantic hurricane seasons (figure 1(E)), although the net effect is unclear, as hurricanes may both raise nutrient levels and increase fragmentation that boost growth rates, while increasing sinking and hence loss rates [26]. Changes in regional biogeochemistry, natural modes of climate variability and the intensity of Atlantic hurricane seasons may ultimately be related to anthropogenic climate change. Longer term, climate models predict substantial warming of the surface tropical Atlantic over 2005–50, in the range 1.0 °C–1.5 °C [27], in a region where sargassum is currently growing at close to optimum summer temperatures [28]. Associated ongoing changes in regional biogeochemistry, modes of variability and hurricane seasons are highly uncertain, with the effect of these on future sargassum abundance and distribution unclear.

To summarise, the recent proliferation of tropical Atlantic pelagic sargassum is likely attributable to multiple drivers, associated with a changing regional climate and associated changes in biogeochemical cycles, exacerbated by natural variability on a range of timescales; the ongoing and longer-term prospects for sargassum are largely unknown at the present time.

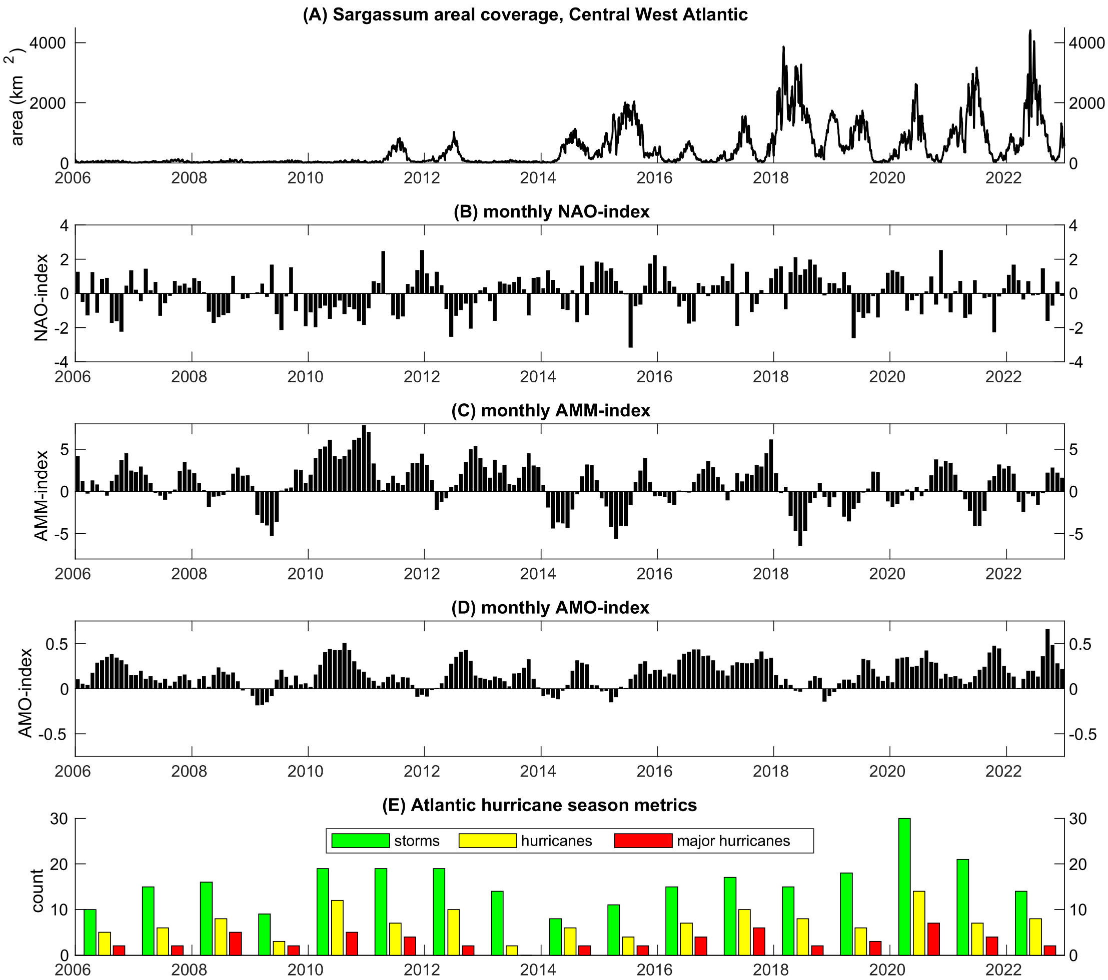

Figure 1. Changes in sargassum and associated climate metrics over 2006–22: (A) Cumulative area of sargassum in the Central West Atlantic (CWA) from 1 January 2006, updated to 20 July 2022 [based on Alternative Floating Algae Index data provided by the Optical Oceanography Laboratory at the University of South Florida, via their website, https://optics.marine.usf.edu]; (B) monthly North Atlantic Oscillation (NAO) index (from the US National Weather Service Climate Prediction Center, https://www.cpc.ncep.noaa.gov); (C) monthly Atlantic Meridional Mode (AMM) index (Trenberth and Shea, 2006; https://climatedataguide.ucar.edu/climate-data/atlantic-multi-decadal-oscillation-amo); (D) monthly Atlantic Multidecadal Oscillation (AMO) index (Chiang and Vimont, 2004; https://www.aos.wisc.edu/~dvimont/MModes/Data.html); (E) Atlantic hurricane counts (data collated from wiki pages for annual hurricane seasons).

Methods

Mapping the process of adaptation to an emergent risk since genesis of that risk brings significant challenges due to the lack of monitoring and evaluation data to track progress on adaptation from the onset of the hazard. This is the case with the sudden blooming and surprising arrival of brown macroalgae (pelagic sargassum) across the tropical Atlantic since 2011. To overcome the lack of real-time adaptation monitoring data, we adopt an *ex post facto* approach, and rely on secondary sources of data to identify adaptations and to reveal potential associations between science, policy, technology, and knowledge [19]. The data used in the analysis comprise: 36 international or bilateral policy documents related to management of sargassum in the tropical Atlantic extracted from Van der Plank *et al* 2022 [29]; the collection of literature in the CERMES Sargassum Reference Repository[8]; and 321 documents identified in a systematic review type search (Supp 1).

Analysis of the evolving responses to sargassum involved three key methods: quantitative assessment of the levels of evidence of reports in specific areas; an event timeline; and a qualitative assessment of the changing accumulations of research topics over time using word clouds. Word clouds have been shown to be an effective visualisation tool when assessing qualitative data [30]. Event histories (chronologies) and word clouds have been used where quantitative data are unavailable, for example, interdisciplinary assessment of the nature of energy use [31], associative research on sustainability reporting, and social and environmental management [32].

[8] Available online at: https://www.zotero.org/groups/2921152/sargassum_reference_repository/item-list.

Ex post facto research approaches, such as the qualitative analysis of the systematic review evidence base and the word clouds using abstracts and titles, rely on a retrospective review of events, and can only explore associations between events and outcomes, rather than determine causality. Nonetheless, we propose that the findings from this work offer insights into future monitoring adaptation programmes that could be established for the next climate-driven emergent risk.

Results

Components of adaptation

Scientific advancement and adaptation policy making during sudden onset, surprise events and stresses can be a process of learning from mistakes with little time for reflection, sometimes generating unexpected outcomes [33]. New adaptive approaches can be trialled, but decisions on adaptation effectiveness are challenging to make with little empirical evidence available to undertake rapid assessment [34]. Limited evidence exists on the nature of the effectiveness of adaptations, although key elements appear to be cooperation between organisations sharing best practice and evidence, collaborative decision making, and sharing science and physical resources e.g. technology and early warning systems [35]. Based on the scope of the literature available (found in the systematic review, the policy documents extracted from Van der Plank *et al* 2022 [29], and publications in the CERMES Sargassum Reference Repository) and the themes identified by Owen 2020 [35], we explore four domains of adaptation to the emergent risks from sargassum: policy, knowledge and evidence, monitoring and early warnings, and technology for valorisation opportunities [19].

Policy

When massive sargassum influxes started in the tropical Atlantic in 2011, there was no extant macroalgal bloom policy to guide adaptation, there was no guidance on who should respond and how, and there was no pre-allocated 'adaptation-to-unforeseen-risk' funding to pay for the clean-up costs required [36]. Early efforts to clean-up beached sargassum were ad hoc and involved multiple actors: government agencies, community volunteers, and private sector actors including hotel staff and fishers, often with little communication or coordination among them. A review of sargassum policies from 2011–2020 [29] across the Wider Caribbean Region (WCR) found varying degrees of effort by national and regional institutions, with no sustained increase in initiatives until 2017 when policy makers realised that sargassum influxes appeared to constitute a new normal [37]. Further, the first iteration of sargassum plans, policies and guidance documents took between four and ten years to be produced after the first impact in 2011 (figure 2).

Key sargassum policy documents (figure 2) did not emerge from any one country, but from larger regional organisations, such as the Caribbean Hotel and Tourism Association, the Gulf and Caribbean Fisheries Institute, and Regional Activity Centre for Specially Protected Area and Wildlife (SPAW-RAC). These documents were produced by existing institutions, notably SPAW-RAC adapted its mandate to address the new risks from sargassum. Yet despite the proven potential of regional solutions, governance mechanisms to coordinate and facilitate sargassum management efforts at a regional level are yet to be established 12 years after the first arrival of sargassum due to a combination of limited resources and institutionalised co-ordination mechanisms. Cross-regional initiatives between the WCR and West Africa face even more acute challenges to development and consequently have achieved only nascent progress [29].

Knowledge and evidence

By 2010, there was a well-developed understanding of the ecology of sargassum, i.e. assemblages and structure of associated ecological communities. Knowledge about sargassum came from the widely researched Sargasso Sea, where sargassum is known as the 'golden rainforest of the sea' [38]. The word clouds in figure 3 provide a visual of the changing narrative around sargassum from 2000–2022 (Supp. 1). Figures 3(a) and (b) show the 2000s research keyword emphasis on the biodiversity benefits of sargassum in the Sargasso Sea: 'growth', 'distribution', 'turtles' and 'reef', and 'reef', 'biomass', 'fish' for the periods 2000–2005 and 2006–2010 respectively.

After the first tropical Atlantic influx in 2011, fear and misinformation about sargassum spread among coastal residents. Blame for the influx was initially incorrectly assigned to the offshore oil industry in the Caribbean (Authors, unpublished information), and the newly established oil and gas industry in West Africa [39]. Coincidentally, in 2010–2011, the Deepwater Horizon oil spill disaster in the Gulf of Mexico led to the smothering of newly arrived sargassum mats with oil. Responsive scientific research revealed that oil could become trapped in sargassum mats and adversely impact all lifeforms that encountered it [40]. During the period 2011–2015 the language of scientific research reoriented around the negative effects on the coastal ecosystems, and reflected research relating to the Deepwater Horizon oil spill. The main keywords for this period were: 'oil', 'reef', 'coral', 'habitat', 'effects', 'algal', 'uses/using' (figure 3(c)). Remote sensing methods for tracking sargassum

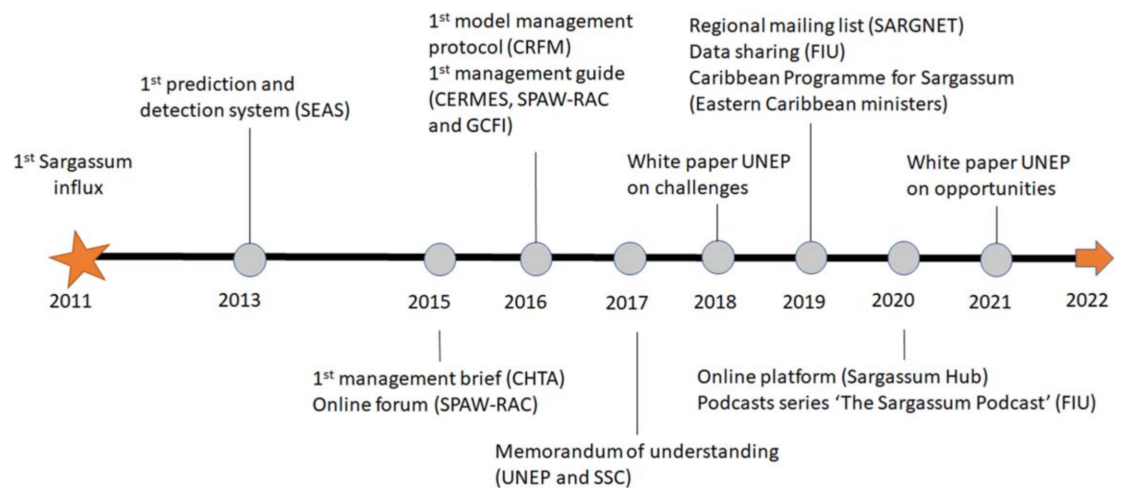

Figure 2. Timeline policy documents based on Van der Plank *et al* 2022 [29]. SEAS: Sargassum Early Advisory System; CHTA: Caribbean Hotel and Tourism Association; SPAW-RAC: Protocol concerning Specially Protected Areas and Wildlife in the Wider Caribbean Region; CRFM: Caribbean Regional Fisheries Mechanism; CERMES: Centre for Resource Management and Environmental Studies; GCFI: Gulf & Caribbean Fisheries Institute; UNEP: UN Environment Programme; SSC: South-South Cooperation; SARGNET: Sargassum Network; FIU: Florida International University.

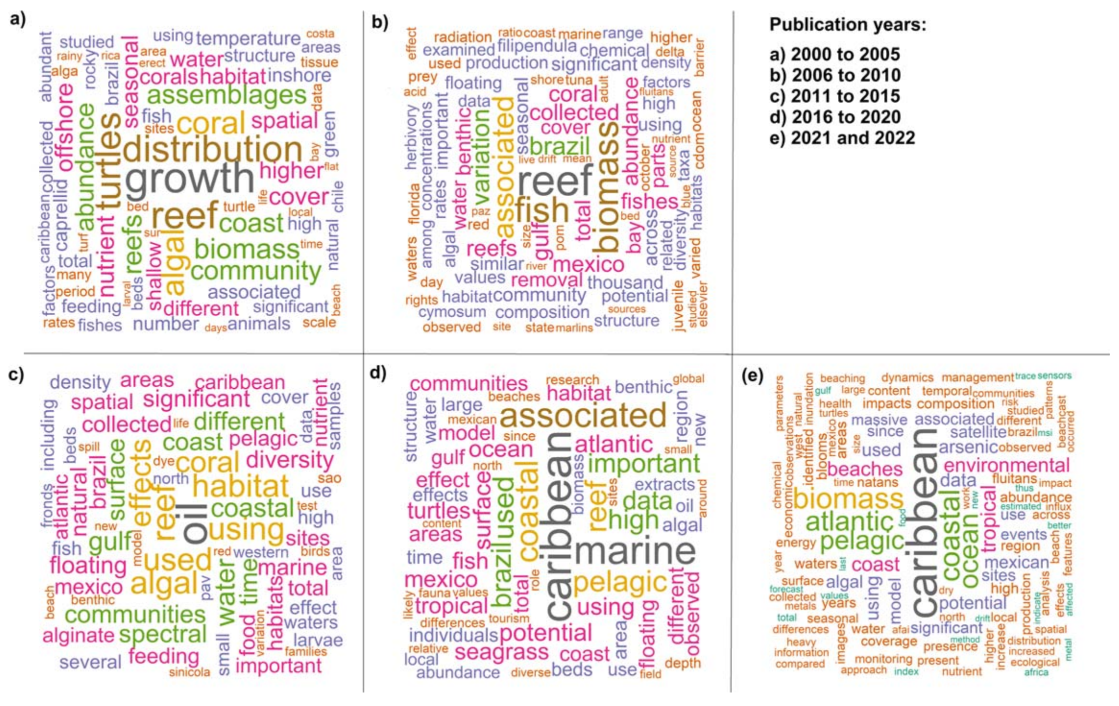

Figure 3. Word clouds on published literature on sargassum using abstracts and titles, generated with *tm* and *wordcloud* R packages, filtered by year of publication, and based on systematic search through Web of Science (Supp. 1). Word clouds exclude: conjunctions e.g. 'and', 'within', 'however'; research related verbs e.g. 'found', 'showed', 'revealed'; and related, but not directly linked words e.g. 'species', 'algae', or 'macroalgae'.

mats became increasingly present in this period, and new terms such as 'spectral' and 'spatial' can be seen more frequently in the word clouds.

From 2016–2020, scientific knowledge focussed on large scale monitoring of the WCR, documenting negative impacts on Caribbean coasts, tourism, beaches, and fisheries. Prevalent keywords in this period include: 'Caribbean', 'marine', 'pelagic', 'coastal', 'reef' (figure 3(d)). Research around potential uses and other affected areas (e.g. Brazil) became more evident. Recent literature (2021–2022) shows the widest diversity of terms, covering the larger scale ocean and climatic drivers of sargassum, ongoing investigation into the negative impacts on coasts and beaches, biochemical components of sargassum, sargassum species, and long term data collection.

'Africa' occurs in research keywords sufficiently often for the continent to appear in the cloud for the first time (figure 3(e)).

The word clouds reveal a shift in perspectives on sargassum over time: from an ecological asset (pre-2011), to a natural disaster (immediately after 2011), to a topic in need of deep scientific investigation, in areas including: dispersal, drivers, biochemistry, management, and business, notably how to exploit and create benefits from sargassum. It is worth acknowledging that it took 10 years to upscale research on the emergent risk of sargassum, from small, and localised studies on disaster impacts, to extensive basin-scale assessments of the causes, consequences, impacts and opportunities.

Monitoring and early warning

In the initial phase of the influx (2011–2014), regional scientists in the WCR without specialisations in macroalgal blooms had to quickly learn new science and apply new methods to meet local demand for knowledge on all aspects of sargassum (Oxenford, pers. comm). The lack of funding to support this reskilling combined with the lack of initial capacity meant that early data collected were very local, sector-specific, and sometimes proprietary, which limited public access to research data and transferability of knowledge to other locations (e.g. [41]). Between 2015 and 2018, the sargassum crisis was reported on by the international press (e.g. [42, 43]), and national research councils in the US, France, Netherlands, the United Nations FAO, and CARICOM started to fund research on sargassum. Soon after came the realisation that sargassum could be climate-driven [24], was likely to persist indefinitely [25], and required long-term adaptation [44]. The Caribbean-based research community was then joined by a better-funded international research community and started generating more widely accessible research outputs (figure 4(a)). A network of sargassum interested parties was established within a regional university (Centre for Resource Management and Environmental Studies (CERMES), University of the West Indies, Cave Hill, Barbados) to link scientists, sargassum managers and entrepreneurs looking for ideas on management approaches and for opportunities to use and valorise this biomass (figure 4(b)).

It was quickly apparent that management, use and impact assessment required data about the recent past and future spatial and temporal distributions of sargassum [45]. A key challenge for regional scientists was to provide reliable distribution data for both floating and beaching sargassum. The college of Marine Science at the University of South Florida drove the methodological assessment of distribution using satellite remotely sensed data. The resulting monitoring system, the 'Sargassum Watch System' (SaWS) is freely shared online. This work underpinned a monthly sargassum forecast for the whole Caribbean started in January 2018 (Sargassum Outlook Bulletin), and a bi-monthly sub-regional bulletin for the Eastern Caribbean (Sub-regional Sargassum Outlook Bulletin) started in October 2019. Other early warning systems provided different perspectives, such as the Texas A&M University's 'Sargassum Early Advisory System (SEAS)' that automatically detects sargassum at sea, and, since 2018, the European Space Agency/CLS 'SAMtool' which identifies the presence of sargassum using dataset from Sentinel satellites and models its drift.

Research on sargassum distribution focused initially on freely available data at large spatial scale, notably images from satellite sensors with coarse spatial resolution. In creating near real time sargassum forecasts, problems with lack of high spatial resolution free satellite images and obscured images due to cloud cover have led to recognition of the importance of different sources of remote sensing data, such as from uncrewed aerial systems (UAS), and directly observed field data [20]. Despite their importance, use of UAS and field data collection is lagging behind in affected countries due to lack of capacity and accessibility to these new technologies [46]. This is further delaying development of operational monitoring frameworks. In a recent review of current seasonal forecasts of sargassum, the considerable scope for improvement in large scale monitoring and forecasting, using data from multiple sources at multiple scales, was highlighted [47].

Technology and valorisation

Early research on pelagic sargassum in the tropical Atlantic focussed on impact and event monitoring, while valorisation research only took off later (figure 3(c)). While many species of brown algae have been investigated for their composition and valorisation, most of what we know about these aspects of bloom forming pelagic sargassum, e.g. species, morphological types (morphotypes) and biomass composition, was published five to ten years after the initial arrival (in the tropical Atlantic) of pelagic sargassum [48–54]. Valorisation has been a relatively new dimension of sargassum science and policy. Financial and human resources and high specification technology are needed to undertake detailed chemical analyses of newly proliferating species and morphotypes, and are not typically available outside of universities, or corporate laboratories. In 2011, little was known about the biochemical composition of the *Sargassum fluitans* and *S. natans*, and how it could be used. In 2023, it is only now evident that the most dominant sargassum morphotype in peak Caribbean sargassum seasons has been *S. fluitans* III [48, 55, 56]. Nevertheless, morphotype composition of sargassum rafts is highly variable across space

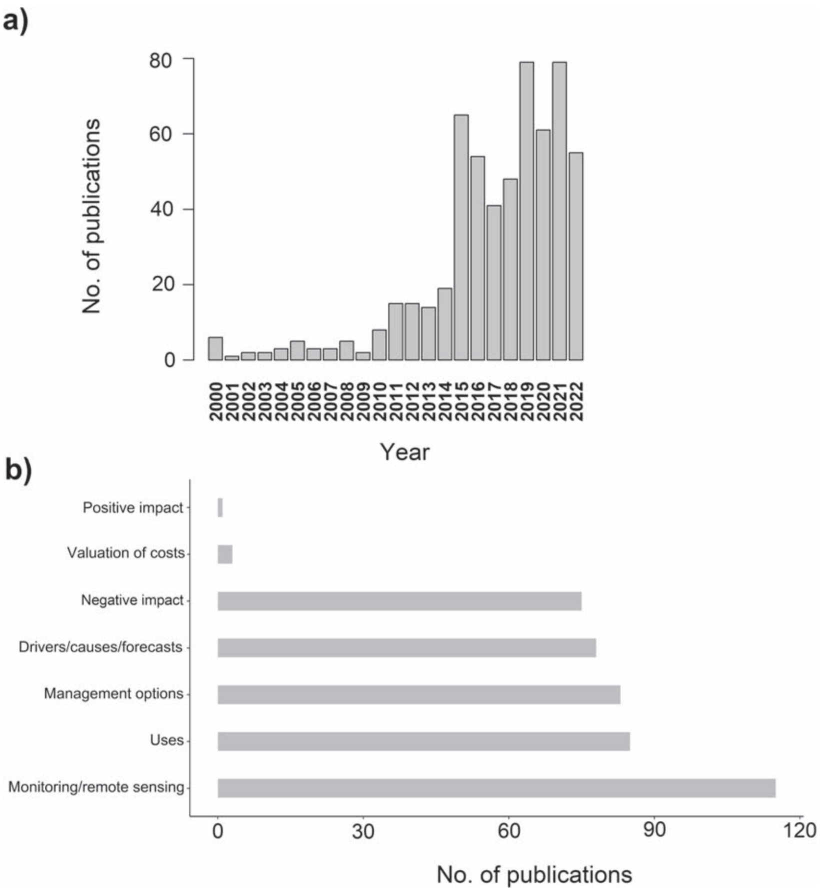

Figure 4. (a) Number of reports (scientific publications, regional and national briefings, and media reports) relating to sargassum produced from 2000–2022, sourced from the CERMES Sargassum Reference Repository, available online at: https://www.zotero.org/groups/2921152/sargassum_reference_repository/item-list. (b) Number of reports addressing impacts, management, uses, drivers, monitoring, valuation and positive impacts (using CERMES Reference Repository tags allocated to papers within the database).

and time [48, 57], and the quality and quantity of commercially important compounds such as mannitol, alginates, fucoidans and fucoxanthin vary among morphotypes [51, 56].

Initially, the application of technology both created problems and unlocked solutions to sargassum influxes. The early rapid adoption of technology to manage the influx of sargassum, before the problem was well understood, led to mistakes being repeated across regions. One example is the use of heavy equipment on beaches to clear the large volumes of sargassum (e.g. bulldozers and other tracked vehicles), as there may have been nothing else available and/or this was considered an appropriate approach to sargassum removal around 2011 [58]. Further research has shown that tracked vehicles and other heavy equipment can cause beach damage through loss of sand, destruction of turtle nesting sites, and erosion [59]. On the positive side, low-cost technology has proven effective in processing and storing sargassum biomass e.g. burlap bags, or Sun drying, both of which we know can change its biochemical composition [56]. However, these are not viable alternatives for mass inundations with tonnes of sargassum to shift and store.

Technology has been central to the process of exploring opportunities to use sargassum through valorisation, e.g. as potential renewable source for blue economy ventures [60]. Laboratory based chemical analysis is critical to sargassum use, for example revealing that sargassum contains variable levels of arsenic, often above accepted limits for applications involving food, animal feed, and agricultural soil [51, 53, 61]. There may be technological solutions to resolving high arsenic levels, but as yet, no such solutions have been published despite the critical need for a solution which would safeguard the environment and safe consumptive uses of the algae [62].

Almost all use opportunities from sargassum require some engagement with the use of technology. Some technologies are small-scale and can be rolled out cheaply to create benefits for affected communities or entrepreneurs, e.g. small biogas digesters for biomethane production, or sargassum storage for compost production (ideally mixed with other plant material or biological wastes) [54, 63–68]. Other use options require investment in sargassum specific technology, e.g. a sargassum brick press for the production of adobe bricks, as is currently being used in Mexico [69]. Early investigations suggest that sustainable products could be manufactured from fresh sargassum biomass through a biorefinery approach [70, 71]. The supply chain for such

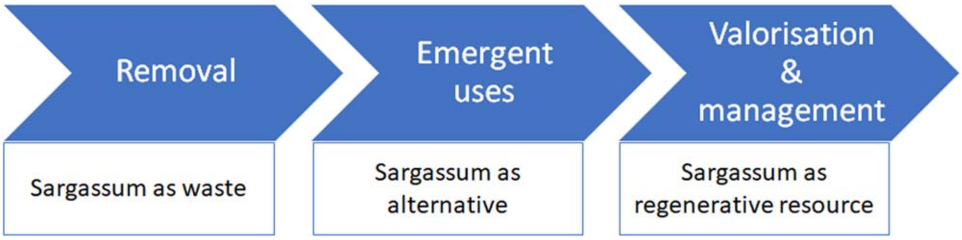

Figure 5. Transition from perception of biomass as hazard or waste, to perception of the biomass as an opportunity.

products could involve coastal communities and fishers harvesting the biomass at sea [72]. However, it will likely require technologies to allow production at scales that are beyond the reach and affordability of the smaller communities [69, 73].

Adapting to the emergent risk of sargassum influxes

The surprise nature of the sargassum influx, its extensive spread across the tropical Atlantic, the historical governance capacity constraints in affected small islands and developing countries, and the lack of an emergent risk adaptation plan ultimately hindered progress in adapting to sargassum in the early years.

In terms of leadership, our findings show that unless the new management approach for emergent risks explicitly intersects with large, established, well-supported and related institutions and processes, the burden of coordination for management of new or emergent risks can fall on those with the least resources to undertake that task. The importance of engaging active and related (directly or indirectly) regional organisations in scientific research and policy development in relation to future emergent risks cannot be overstated.

At the science-policy interface, with hindsight, action to better organise and mobilize knowledge and to prescribe a research agenda that met the needs of the affected people should have begun in earnest at the onset of the sargassum influxes in 2011. Researchers within the region focussed on research and innovation in areas of existing expertise, instead of working collaboratively to develop strategic research plans to highlight all of the research gaps that became immediately apparent. Without the underpinning science input, early management efforts were best guess attempts to steer a course without clarity over direction or desired impact.

Technologies have been extensively used in adaptation, for example in relation to personal protective equipment to reduce the spread of infectious diseases, flood safeguards or remote sensors to detect physical changes to land or seascapes. In most cases, technology is introduced or adapted as a reactive solution to an existing or recurrent problem, requiring modification during implementation. Again, with hindsight, when dealing with sargassum—a biological risk—a key adaptation milestone has been research on: biomass composition, taxonomy (species and morphotypes), biochemicals and elements. Such a freely available evidence base may support greater entrepreneurial engagement in solving the problem.

Whilst there are multiple possible applications for sargassum [69], successful valorisation of these depend on: investment inputs; market demand for novel products; and research to inform and refine applications. For any bio-technological solution to emergent risks, an enabling research environment relating to investment and innovation is central. Policies and guidelines on safe use of the biomass and environmental protection are critical to effectively and quickly exploit opportunities from emergent risks. In the case of sargassum, Caribbean islands that are poised to transition to 'large ocean economies' through exploitation of emerging blue economy opportunities like sargassum are well placed to develop such an enabling environment [21] (figure 5).

Discussion

There is no formal guidance on how to adapt to emergent risks, nor plans or strategies on how to generate opportunities from risks and hazards. We ask: are there generic adaptation steps that could be taken by policy-makers faced with new climate-related emergent risks? Can adaptations not only mitigate the risk, but also create opportunities for growth and development? While individual case studies generally shine a spotlight on a specific context, our in-depth analysis of adaptation to the unfolding pelagic sargassum phenomenon provides insight into the reality of delivering multiple dimensions of adaptive capacity across three continents over the course of a decade. Our analyses reveal the successes and failures of adaptive actions in terms of policy development, knowledge management, scientific advances and technological use.

First, our analysis shows that extant national policy weaknesses, and institutional capacity constraints, became rapidly apparent in the context of sargassum. Historical governance capacity constraints in affected areas have slowed policy progress in adapting to sargassum. From this, we highlight the importance of understanding national weaknesses in disaster risk management policy capacity. Calls for flexibility in policy processes and governance institutions to cope with new emergencies [74] are well intended, but the reality of maintaining superplus capacity in low income developing countries or small states government bodies remains problematic [75]. Recognising the existence of national institutional capacity deficits (in some regions), and learning from the case of sargassum, distributed regional bodies (environmental, economic, social, or other) may need to drive adaptive actions in the face of new transboundary risks. For this to occur, regional organisations would need to shift from pursuing technical co-operation on economic issues to political organisations capable of reallocating internal resources quickly, developing proactive relationships with affected country governments, engaging rapidly in scientific research, and mobilising information to inform policy development. Early, pre-emptive discussions among regional body member states to identify appropriate regional leaders to the next emergent risk by theme (e.g. health, marine, land, disease, biodiversity) could reduce the time needed to set up initial post-disaster governance capacity. The problem is that greater integration of this type comes at the expense of national sovereignty.

Second, in the case of sargassum, knowledge development, sharing and communication was slow to occur and hindered effective collaborative early adaptation. Lack of willingness to share data across agencies and countries, and silos in governance architectures are common features of small and low-income states and hinder many aspects of environmental and climate governance [76]. Yet, both Caribbean islands and African countries already have experience of pooling resources to insure against disaster risk (short-term humanitarian response), e.g. through the Caribbean Catastrophe Risk Insurance Facility (CCRIF) - the first multi-country risk pool in the world [77] - and the African Risk Capacity [78]. Lessons can be learned from this proactive approach to risk creating a long-term development response for adaptation to emergent risks that are here to stay, such as sargassum. Additional thought could be given to supplementary regional pooled insurance schemes for emergent risks. As with disaster risk facilities, these funds could be triggered at the first arrival of a new hazard, and used to deliver rapid and targeted research to ensure that knowledge on monitoring and forecasting, biochemistry, impacts and use is shared across the affected area, to governments, researchers and entrepreneurs. This may ultimately lead to a new hybrid form of governance for the new risk, e.g. co-management, public-private partnerships or social-private partnerships [79].

Third, our research shows that lack of understanding of the risks and opportunities, and lack of access to appropriate technology slowed entrepreneurial action on sargassum. Again, lack of access to technology is a known impediment to green entrepreneurship, especially among micro-enterprises [80]. Enabling research and development environments, with support for the research sector and extant programmes for skills development and training can create the space for grassroots environmental innovators [81]. With national policies in place to support innovation (such as reporting on new risks and opportunities), new technologies to address emergent risks can be rolled out more quickly.

Creating new policies from scratch are not necessarily needed, as global environmental risk and opportunity standards already exist (e.g. ISO 14001 [82]) that recommends regular assessment of current and emergent environmental risks and opportunities. Similarly, the global initiative 'Taskforce on Climate-related Financial Disclosures' provides broad guidelines for reporting climate-based risks and pursuing concurrent opportunities, although initial indications are that it is not yet delivering the desired depth and quality of reporting [83]. Applying these standards within government institutions, and regularly revisiting state-level climate-related and nature-related risk and opportunity registers would be an important start. These registers could potentially reorient small scale entrepreneurs and larger commercial businesses towards areas of risk and opportunity to make them more ready to respond to changing risks.

Conclusion

Our research highlights that early action to anticipate risks can reduce the longer-term damages from emergent risks. Most critical, prior to impact, is the development of a supportive institutional environment for research and development relating to biological/ecological risks in all jurisdictions, including the agreement in principle to rapidly create a shared research fund to investigate new risks. These suggestions are not new, and the suggested actions to address them are not without precedent. Yet, without informed knowledge about the nature of the risk, distribution of impacts and possible adaptations, the damages from emergent risks are likely to be higher than need be.

Acknowledgments

The authors have declared that no competing interests exist. They wish to thank the three reviewers who offered detailed comments, these have significantly strengthened this paper. Thanks to Frank Muller-Karger at USF for comments on a final draft.

This publication is supported by the United Kingdom Economic and Social Research Council through the Global Challenges Research Fund (GCRF) project, *Teleconnected SARgassum risks across the Atlantic: building capacity for TRansformational Adaptation in the Caribbean and West Africa (SARTRAC)*, grant number ES/T002964/1. The authors are grateful for the collaboration of the entire SARTRAC team which has informed this work.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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