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The human dimensions of harmful algal blooms: An evolving research agenda

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ABSTRACT

Harmful algal blooms (HABs) are a global phenomenon occurring in a range of aquatic environments, with the potential to have diverse environmental, social and economic impacts. There is growing interest in the human dimensions of HABs particularly as a result of the increased occurrence of HABs linked to anthropogenic activities. However, to date this has focused more on the economic and health implications of HABs events rather than broader human dimensions. This paper presents a series of research priorities that could strengthen social science research on HABs, highlighting topics related to public awareness and attitudes, community science, governance and co-development of solutions, links to the blue economy agenda, impacts on marine culture and heritage, and impacts on health and wellbeing. Finally, the paper presents a series of recommendations developing a transdisciplinary research agenda in order for the ongoing challenges of HABs to be addressed.

1. Introduction

Algal blooms represent a natural phenomenon caused by a mass proliferation of phytoplankton (cyanobacteria, diatoms, dinoflagellates) in waterbodies. Algal blooms are a natural aspect of many aquatic ecosystems and can sometimes support biodiversity, productivity, and resilience (Hallegraeff, 1993; Okaichi, 2004; Wang et al., 2021). For example, enhanced productivity of algae linked to higher trophic levels can be associated with greater resource exploitation opportunities in fisheries and ecotourism. However, algal bloom events can be harmful to the environment, human health and aquatic life due to the production of toxins and the consequences of accumulated biomass (Sanseverino et al., 2016). Harmful algal blooms (HABs) have been recognised as a significant challenge for marine, brackish, and freshwater systems worldwide – and while the majority of emphasis has been placed on HABs in freshwater systems (Griffith and Gobler, 2020; Schmale et al., 2019), there is increasing recognition of the extensive negative impacts on coastal ecosystems, fisheries, public health, and coastal economies (Hallegraeff, 1993; Anderson, 1997; Bauer, 2006; Liu et al., 2009; Anderson et al., 2015; Wurtsbaugh et al., 2019). Often linked to the eutrophication process, HABs can also be associated with other natural processes (e.g., shellfish filtering). Eutrophication is defined by increased algal growth in an aquatic system caused by nutrient enrichment, mainly nitrogen and phosphorus, which can lead to oxygen depletion in the water body due to intense microbial respiration (Nguyen et al., 2019). Eutrophication can occur naturally, for instance, through physical mechanisms such as monsoon winds or offshore jets and variations in the temperature of the sea surface. This can redistribute concentrations of chlorophyll-a and thus nutrients and zooplankton (Tang et al., 2006; Chen et al., 2014). Anthropogenic and human activities strongly affect these mechanisms and thus also have an impact on eutrophication, associated with increases in domestic waste and wastewater, use of fertilisers and detergents, and the waste products from animal feed in intensive livestock farming and aquaculture. Recent

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increases in HABs have occurred alongside the escalation of global warming, carbon dioxide increase, upwelling processes, and rising salinities (Anderson, 1997; Paerl, 2017; Wang et al., 2018). This paper will focus particularly on HAB events in coastal/marine systems which are caused by eutrophication, but, of course, it is recognised that other factors can trigger HABs.

While there has been some progress in understanding the causes, consequences and means to manage and control HABs (for recent reviews see Wells et al., 2015, 2020), most studies investigate the impacts of HABs resulting from anthropogenic origins and explore their ecological implications (Anderson et al., 2002; Heisler et al., 2008; Tang et al., 2006; Liu et al., 2009; Chen et al., 2014; Glibert, 2017; Nguyen et al., 2019). There is, however, a growing focus on the need to understand the social and economic effects of HABs in coastal areas, such as impacts on human health, disruption of access to coastal spaces, impacts on community wellbeing i.e. the human dimensions (see for example, West et al., 2021; Borbor-Cordova et al., 2018; Bauer, 2006; Bauer et al., 2009). To date, studies of this type have focused on effects linked to health with an emphasis on more readily identifiable costs of treatment and lost opportunity (Hoagland and Scatasta, 2006; Berdalet et al., 2016). Another common theme reflects output changes in sectors such as aquaculture, tourism, and recreation, caused either directly or indirectly by HABs (Anderson et al., 2000; Hoagland et al., 2002; Alonso-Rodrí; guez and Páez-Osuna, 2003). Some feedback effects are evident in these studies. Growth in demand for the outputs of these sectors may result in activities which either directly or indirectly influence the eutrophication processes causing HABs. For example, an evolving body of literature has explored the value of output lost through shellfish and fish deaths and disease, resulting employment and household income effects, and loss of brand reputation for seafood producers (Larkin and Adams, 2007; Holland and Leonard, 2020; Jardine et al., 2020). Some research has explored the HAB effects on tourism and domestic recreation (Brooks et al., 2016), highlighting the potential for HABs to cause both temporary and permanent displacement of tourism demands. Furthermore, costs to impacted sectors have been exacerbated by adverse media coverage of HAB events, focusing on issues of water quality, odour, colour and toxicity (see for example Hance, 2020). Finally, effects on local economies can be multiplied with falling tourism revenues, while also affecting local fisheries and other local businesses directly and indirectly linked to tourism. It is also worth noting that HABs may have disproportionate effects on coastal communities, particularly in lower income countries featuring less developed regulatory and monitoring infrastructure, with these pressures being likely to further increase in the future due to climate change (Holland and Leonard, 2020).

However, despite there being a growing call for more research which investigates the complex socio-ecological system of HABs and their various impacts on society, there is a paucity of work pertaining to human dimensions of HABs, specifically in a coastal context, with economic studies dominating the field in the past. As stated by Berdalet et al. (2016), many of the social impacts linked to HABs remain conjectural and under-explored – this is of particular concern given the cross-cutting nature of HABs across areas of societal impact and well-being, including, for example, the UN Sustainable Development Goals (e.g. 6 – Clean Water and Sanitation, 3 – Good Health and Well-being, and 14 - Life Below Water). This paper seeks to further highlight these existing knowledge gaps, presenting a proposed social science research agenda for HAB research and further emphasising earlier calls from other scholars regarding the need for more research in this area (e.g. Bauer et al., 2009). The next section of the paper outlines the methodology adopted and then reviews selected literature that has examined the social, economic, and cultural effects of eutrophication and HABs. Drawing insights from existing literature, the paper goes on to highlight specific research themes that could move the HAB research agenda towards the relatively neglected area of social implications. The final section concludes and provides recommendations about how better understanding of socio-cultural effects can work to complement existing HAB research.

2. An integrated research agenda – identifying future research priorities

This research agenda was suggested by drawing on insights gathered by following specific steps, using standard approaches to identifying research priorities (Sutherland et al., 2013). First, an inductive review of the existing literature by the first and second author to support the development of the research agenda was conducted. In the literature review process, the following key words and terms were used to identify papers.

- 'Harmful algae blooms social effects',
- 'Eutrophication social effects',
- 'Harmful algae blooms economic impacts' and
- 'Eutrophication economic implications.

While this review process did not follow a specific literature review methodology, the use of the keywords identified a broad range of relevant literature which was used to identify initial research gaps. The findings of the inductive literature review procedure were presented in a hybrid project team workshop held in October 2021, involving economists, social scientists, geographers, as well as marine and coastal scientists from within the project team. Following the practice of other scholars (Cristancho-Lacroix et al., 2014; Tsang et al., 2020), the workshop had an informal setting with members of the project team, who represented a range of different disciplines and areas of expertise, including social sciences, economics, governance, ecological understanding of coastal systems and eutrophication and modelling. The discussions, presentations, recommendations and feedback in the workshop were collected by the moderator and incorporated into the development of a research agenda for HABs' human dimensions. In addition, the initial research gaps and possible research pathways were analysed and discussed in a process of sharing information and ideas, discussing different views and perspectives and generating knowledge and innovative arguments. Qualitative figures from the workshop, the notes of the moderator, and the literature review findings were used, seeking to suggest a research agenda on the human dimensions of HABs. Thus, following the participatory workshop process and this inductive literature review, the project team identified eight research priorities which form the basis of this agenda setting perspective piece and are now discussed. The research areas are grouped into three thematic categories: 1) Societal Understanding and Stewardship, 2) Understanding impacts of HABS and 3) Governance and Management.

2.1. Societal Understanding and Stewardship

2.1.1. Understanding societal attitudes and perceptions of HABs

In the context of eutrophication and incidents of algal blooms, there are gaps in our understanding of how these phenomena and subsequent risks are perceived by local populations and coastal communities (Borbor-Cordova et al., 2018). For example, how does the language used about algal blooms and eutrophication incidents influence society and individual perceptions and attitudes? This includes different terms, such as HAB and eutrophication, and the introduction of the concept of 'red tide' (Stumpf et al., 2010). How aware are various individuals that these events are part of a wider system issue rather than being isolated incidents (for example, potentially connected to poor wastewater management, water-based pollution, or agricultural run-off)? How can awareness of algal blooms and their causes increase, and how can this be used to improve remediation actions and behaviour at an individual, community, and commercial scale, thus addressing HABs more efficiently? With these questions in mind, there is a clear need to engage with the broader field of risk perception scholarship (see for example,

Bobor-Cordova et al., 2018; Cahyanto and Liu-Lastres, 2020) and to consider how this can be aligned with this growing area of work around HAB management.

Indeed, recent years have witnessed growing calls for improved understanding of public perceptions, attitudes and awareness of marine and coastal issues, including HABs (Borbor-Cordova et al., 2018; Bennett et al., 2021; Jefferson et al., 2021; McKinley et al., 2020). Public perceptions research, defined as an area of research grounded in social sciences and encompassing components such as knowledge, interest, social values, attitudes or behaviours (Jefferson et al., 2015), is increasing. However, there are limitations in our understanding of how society connects with certain aspects of marine and coastal systems (Jefferson et al., 2021). In the specific context of HABs, there is a lack of insight as to how well algal blooms and their associated drivers are understood by different audiences (Borbor-Cordova et al., 2018). The results of the project team workshop highlighted a need to understand how communities with a range of social, cultural, and economic contexts pertaining to different principal activities (e.g., fishermen, restaurant owners, tourist-related occupations, officials in health and environment management) perceive algal blooms (Borbor-Cordova et al., 2018). In this respect, questions remain around a common understanding of the main causes of algal blooms, how this understanding varies in different community contexts and what the perceived risks of HABs for communities might be. There is also a need for improved understanding of the impacts of both HABs and the management solutions implemented to address them and consequently, how to encourage necessary behaviour change relating to algal blooms to address issues pertaining to water quality, wastewater management, and more. Crucially, future research pertaining to HABs must recognise that society is comprises diverse audiences with different perceptions, values, and attitudes, and understanding such global variation will be integral to developing efficient management (Kirkpatrick et al., 2014; Jefferson et al., 2015, 2021). For instance, different groups focus on different aspects such as aesthetic quality of the coast versus health implications (Borbor-Cordova et al., 2018). Poor insight of these aspects can lead to ineffective management of the HAB problem.

Where human dimensions of algal blooms need to be better understood there is a challenge to move away from traditional knowledge deficit models (i.e. delivery of knowledge or awareness raising materials or campaigns) or attempts to foster connection, stewardship and behaviour change. These are widely acknowledged as being ineffective in driving change (Kollmuss and Agyeman, 2002). Instead, by understanding existing community perceptions and attitudes towards algal blooms, the impacts on their everyday lives, as well as the barriers to changing associated behaviours, there is perhaps an opportunity to develop more effective management schemes and collective solutions to the HAB challenge, seeking more efficient governance on the strategies and actions to address eutrophication. From an ocean and coastal policy perspective, enhancing research efforts in this area would also contribute to other fields. This includes fostering better ocean and environmental literacy and citizenship (Buchan, 2021; McKinley and Burdon, 2020; Berdalet et al., 2016), as well as feeding into the goals set out by global policy levers (for example, UN Decade of Ocean Science for Sustainable Development, UN Decade for Ecosystem Restoration, the UN Sustainable Development Goals). Crucially, there is also a need to learn from Indigenous, traditional and local ecological knowledge holders and ensure that the valuable insights and ways of knowing and experiences of HABs and wider coastal systems held by these communities are effectively integrated into HABs management and solutions (Anderson et al., 2022; Kourantidou et al., 2022).

Related to this, there is also a need to consider the role of public awareness campaigns and how information about HABs is communicated to different audiences. There is a need to acknowledge the complex relationships in social-ecological systems within which the research and related policies will take place. Then a better understanding of people's perception and attitudes towards HABs could be crucial for the promotion, communication and regulation of actions to address eutrophication and public health strategies (O'Leary et al., 2024; Borbor--Cordova et al., 2018). Moreover, given the potential variation in public perceptions discussed above, awareness raising campaigns and communication pathways must be correspondingly diverse and draw insight from the information gathered through pertinent research. In terms of awareness raising and education initiations on HAB-related water quality issues and their management, questions remain as to how different audiences understand HABs and their drivers, how information relating to HABs is communicated by the various media. Recent documentaries reveal the value of more informal communication pathways to support environmental education (for example, in '*The Blue Planet*' documentary series; see also, Males and Van Aelst, 2021; Hynes et al., 2021). However, poor communication of issues, inconsistency of terms, inaccurate reporting and use of incorrect definitions, or terms can lead to public misunderstanding of the HAB issue, poor management and a lack of social acceptability of management strategies. For instance, *New York Times* have used different terminologies to describe the phenomenon (New York Times, 2023), with this possibly limiting the prospects for a better understanding of HABs. There is, therefore, a need to consider the impact and effectiveness of awareness raising as well as communication campaigns. This includes the role of formal institutions (including national and local governments, research institutions, and environment agencies) in delivering meaningful communication about HABs and their management.

2.1.2. *Fostering engagement through community science*

Building on foundations of citizen science, recent years have seen a growing body of work around the use of community science and its role in informing and improving environmental research, education and practice (McAteer et al., 2021; Smith et al., 2021). Community science is defined as "a participatory research approach through which members of the public produce scientific knowledge in contributory, collaborative, or co-production processes" (McAteer et al., 2021). The evolution of community science from the more commonly recognised citizen science stems from discussions regarding potential power dynamics and knowledge generation within traditional citizen science, and the opportunity of co-developed and collaborative research and engagement to improve community life (McAteer et al., 2021). Key questions here relate to how far fostering engagement through community science initiatives will.

- help address the social and human dimensions of algal bloom research and practice;
- improve scientific and social understanding of HABs' socio-economic implications;
- raise awareness and close some of the knowledge gaps highlighted in Section 2.1;
- improve governance and management interventions to address eutrophication.

For instance, the WaterKeeper Alliance, has been important in protecting and enhancing ecosystem and water quality in 15 countries (Conrad and Hilchey, 2011), with equivalent initiatives pertaining to HABs expected to have an important contribution in addressing the implications of eutrophication. Existing community/citizen science projects relating to harmful algal blooms are sparse. They also lack a coherent and comprehensive strategy, neglecting socio-economic aspects and adopting a natural science perspective overlooking multi-stakeholder engagement (Ansari and Schubert, 2018; Carvalho and Dobel, 2018).

Through an integrated community science programme, engagement with stakeholders directly pertaining to HABs, such as aquaculture farmers, tourism boat owners, and those stakeholders 'upstream' and across the whole catchment, will be valuable since these groups engage with water bodies frequently. Following the adaptation of community

science principles to water quality, HABs and marine science (Carvalho and Dobel, 2018; McAteer et al., 2021; Smith et al., 2021), periodic and targeted surveys with aquaculture farmers could help inform the health of the water body, the potential for harmful bloom events and prior mitigations, and the implications of such events for the farmers' practices, livelihoods, strategies and decisions.

Future HABs community science programmes should involve diverse groups as these could play an important role in: data collection on environmental and socio-economic implications; education and awareness raising activities; identification and development of location specific early-warning signs and site appropriate intervention strategies. Authorities in the target areas should organise periodic meetings and workshops for devising actions and monitoring progress, involving researchers, stakeholders and citizens, in a truly participatory process. The whole programme should meet periodically and inform on the progress of the task groups and future directions.

Developing open-access and widely available data repositories of local community science programmes and their activities would be helpful in the policy efforts to manage eutrophication, not just in localities, but at the national and international scale (Lippert et al., 2019). They could be used to inform decisions in the domain of environmental science and public policy relating to the prevention and mitigation of harmful algal bloom events as well as the improvement of strategies and solutions to the subsequent socio-economic implications. Following this process, future community science programmes ensure that there is potential for these initiatives not only to support ongoing monitoring and data collection, but also to provide insight into participants' motivations, experiences and changes in perceptions, attitudes, and stewardship as a result of their engagement in these programmes (Day et al., 2022; McAteer et al., 2021).

2.2. Understanding impacts of HABs

2.2.1. Understanding interactions between HABS and the blue economy

The blue economy is defined as 'the range of economic sectors and related policies that together determine whether the use of oceanic resources is sustainable' (World Bank and United Nations Department of Economic and Social Affairs, 2017: vi). A series of common themes are suggested that are either directly or indirectly perceived as socio-economic implications of HABs. These themes embrace output losses in fisheries, aquaculture, tourism, and recreation sectors (Anderson et al., 2000; Hoagland et al., 2002; Alonso-Rodrí; guez and Páez-Osuna, 2003; Dyson and Huppert, 2010; Gill et al., 2018; Moore et al., 2019; Bechard, 2020; Martino et al., 2020; Moore et al., 2020; Heil and Muni-Morgan, 2021; Alvarez et al., 2024). An interrelated contextual management issue for HABs and the blue economy is the comparative scale of output losses caused by HABs compared to those caused by other environmental disasters such as storms, and marine disasters such as oil and chemical spills. This issue of relative scale might mean that in terms of targeting of public resources, HABs may be lower on the list of public resource priorities. Consequently, the practical management of HABs will often need to fit within a wider set of management and monitoring structures to treat with severe environmental risks.

Understanding the scale of output losses has been an important theme in research. There has been a challenge in valuing the costs of damage associated with shellfish and fish deaths, their physiological change and disease, and then resulting employment contraction and loss of household income (Larkin and Adams, 2007; Alvarez et al., 2019; Moore et al., 2019; Bechard, 2020; Martino et al., 2020). There have also been difficulties valuing any loss of brand reputation for seafood producers resulting from HABs. Such issues have become more acute as aquaculture has turned into an increasingly viable option for sustainable food production and security, particularly in economies with limited land and corresponding large urban areas (Trottet et al., 2021). Indeed Hallegraeff (1993) argue that impressions of a global increase in HABs derives from our growing need to economically exploit marine resources.

There is a need in economic evaluation of HABs to consider how HABS may disproportionately impact individuals differently. For example, in terms of gender balance in the labour market and on the global level, women's participation in aquaculture is estimated at 70 percent of the total workforce when all production modes are included (Hishamunda et al., 2014). This may mean that female workers experience a higher degree of negative impact due to loss of work or earnings. Furthermore, on the distributional impacts of HABs, tourism sectors that might be affected by HABs typically in more developed economies feature relatively lower paid, casual and seasonal workers. More work is required to truly explore how these impacts will vary in different contexts.

In the tourism and recreation realm some studies have examined the potential for HABs to cause loss of tourism demand, and then with effects on the 'local' tourism-supply side. Here costs can be exacerbated by adverse media coverage of HAB events, particularly where effects are aired extensively on social media channels (Skripnikov et al., 2021). Local supply-side effects can be multiplied depending on how far local fisheries and the tourism sector are economically interconnected. Studies tend to focus on 'places' where the industrial structure is heavily weighted towards fisheries and the visitor economy (Hoagland et al., 2014; Alvarez et al., 2019, 2024; Bechard, 2020; Ferreira et al., 2023). The possible dynamic interconnection between fisheries and tourism sector outputs is a difficult management issue with an increase in demand for the outputs of aquaculture causing environmental problems that might reduce tourism consumption, and with the latter a key consumer of the outputs of the local fisheries sector.

Finally, interventions to monitor and mitigate the algal bloom problem have implications for the public purse, similar to the management of clean-up (Anderson et al., 2000; Hoagland et al., 2002). Set alongside this, studies have sought to explore the human health related effects of algal blooms (again often with consequences for the public purse), but with work focusing on the more identifiable costs of treatment, hospital visits and lost opportunity (Berdalet et al., 2016; Heil and Muni-Morgan, 2021; Hoagland and Scatasta, 2006). To shed more light on the interactions between HABs and the blue economy, there is a challenge to better understand and value the long-term economic effects associated with persistent HABs. For example, longer-term legacy impacts might be understood in terms of relative changes in property values in areas with more persistent HAB problems (L'Ecuyer-Sauvageau et al., 2019; Bechard, 2021).

Considering that the blue economy includes ocean-related industries such as tourism, fisheries and aquaculture (World Bank and United Nations Department of Economic and Social Affairs, 2017) and despite the extensive investigation of the economic consequences associated with blue economy and algal blooms, there are a series of areas where there has been a paucity of research. Existing research has tended to focus on the more direct economic consequences associated with losses in key tourism-facing and fisheries sectors (Anderson et al., 2000; Hoagland et al., 2002; Alonso-Rodrí; guez and Páez-Osuna, 2003). However, the indirect and induced effects on local economies have been partially overlooked. This includes how losses in tourism-facing sectors or aquaculture cause output losses in sectors that supply tourism or are supplied by aquaculture. Interestingly studies also tend to focus on damages to coastal economies caused by HABs but with a paucity of research that examines net economic system impacts and how those losses in some parts of the economy are made up in other parts as a result of tourism displacement from one location to another. Clearly intensified tourism consumption on 'unaffected' areas has its own environmental consequences. In addition, while work in the natural sciences examines HABs over extended periods, sometimes over decades, economic studies tend to focus on harms connected with discrete HAB events.

The following research questions that emerged in the project team workshop could provide a better understanding of the longer-term

cumulative economic effects associated with persistent HAB events through time and their intersections with the blue economy.

- How might loss of reputation change the nature and scale of the tourism and fisheries sector in the long term?
- How far do HAB events feed through to permanent displacement of tourism consumption (and here with implications for local communities)?
- How far does the persistence of HABs in one place alter the nature of tourism consumption in that place but then further afield through displacement effects?
- How far are longer-run economic effects associated with HABs and their management associated with new economic development opportunities and challenges for economies found to be more dependent on fisheries and tourism?

Critically here, much of the economic debate is linked to losses, but with different managerial and monitoring systems to treat HABs potentially having beneficial economic effects. This could include cases where algae are harvested and 're-used' in the context of strengthening the circular economy (see Meng et al., 2015; Corcoran and Hunt, 2021). Finally, there are important questions in respect of how persistent HABs 'work' alongside other risk factors (i.e. climate change, invasive marine species) to impact on the ecosystem services available from seas, estuaries, and then subsequently feed through to real economy effects (Groeneveld et al., 2018).

2.2.2. Impact of HABs on marine culture and heritage

In understanding the social and economic consequences of HABs and linking these through to natural processes, some scholars have used the framework offered by cultural ecosystem services which typically "decrease along the eutrophication gradient as the landscape, the leisure activities, the territorial identity and the emblematic biodiversity are affected by green tides" (Kermagoret et al., 2019, p148). The depreciation of ecosystem services, as a result of an increasing HAB events, has been shown to lead to the supply of these services not meeting societal demands, adding pressure for the conservation of these cultural ecosystem services (Willis et al., 2018). Cultural ecosystem services (CES) are understood as a stream of benefits gained from personal interaction with natural spaces (Small et al., 2017; Alieva et al., 2022). Key benefits might embrace health and well-being (explored in more detail in Section 2.6), learning, network connections, aesthetics, identity, and cultural significance (see recently for example, Alieva et al., 2022; Burdon et al., 2022; Ponton-Cevallos et al., 2022). Personal interaction arguably embraces built heritage connected to natural heritage, and interactions with local economic activities that are dependent on coastal resources. For example, Cook et al. (2022) reveal how non-natural capital assets link with natural assets to supply ecosystem services, while Willis et al. (2018: 233) argue that CES are: "Important as they influence how people respond to the natural environment and they give indications of how they might behave in those environments and respond to changes in them."

In respect of HABs, investigations in the realms of CES and associated cultural heritage tend to focus on recreation and provisioning services (for example, in the latter case, ecosystem services in terms of provision of food and minerals). Rather less effort has been given to understanding how persistent HAB events might impact the processes through which residents and visitors gain welfare benefits from coastal heritage, or how this may in turn depreciate cultural identity, and aesthetic values. Willis et al. (2018) found that in the case of HABs in Cornwall, UK, an inability to interact with the sea and coastal environment can cause a depreciation of experiences that are important for welfare (i.e. relaxation, reduction in stress), and may induce emotional stress (e.g. through seeing dead fish). The aesthetic value placed on coastal heritage is inevitably impacted by elements including appearance, odour, colour, and perception of underlying environmental quality. Persistent HAB events clearly have a direct and indirect role here. They might change resident and visitor aesthetic responses to coastal heritage and potentially industries and activities linked to that same heritage, such as fisheries.

There are a series of related issues in the broader culture and heritage space. Through time, the process of eutrophication and resulting HABs might change what is passed on in terms of heritage, and what is learned about natural heritage by locals and visitors. In this respect, management and mitigation of HABs could change the nature and historical pattern of activity and the structure of cultural assets. Here then some activities might no longer be possible/viable, or learned about, or may have much reduced aesthetic values, such as age-old shellfish aquaculture/fisheries and associated built heritage. These problems could be particularly acute in coastal communities that represent some of the best examples of 'living heritage' having interwoven tangible and intangible features (Cook et al., 2022). Similarly, cumulative effects of concurrent HAB events may change cultural meaning of the sea to communities. Then, regular HABs might alter the ways in which seascapes influence everyday lives, regular practices and processes founded on natural heritage.

With this in mind, there is a need for improved understanding on how, and if, HAB incidents have an impact (direct or indirect) on societal experience and access to marine culture and heritage, and the associated ecosystem benefits which may be attributed to a particular coastal place. Further, there is a need for further research which considers how these events may impact the industries and, indeed, communities dependent on their coastal space as a marine heritage asset (also linked to Section 2.3).

2.2.3. Understanding the impact of HABs on societal health and wellbeing

Recent years have seen a growing consideration of the relationship between ocean and coastal environments and human health and well-being (White et al., 2013; Fleming et al., 2011; Borja et al., 2020; Chen and Yuan, 2020). The very nature of algal blooms, and related eutrophication events, means that this particular phenomenon has been recognised as a key issue by researchers exploring the relationships between oceans, human health and well-being (Borja et al., 2020). Exposure to algal blooms can occur in a range of different ways, including through recreational water activities or consumption of contaminated water or seafood (Hoagland et al., 2014). Correspondingly, the implications for humans are also varied, ranging from direct physical health impacts (for example, abdominal pains, fever, intestinal damage, illness due to inhaling brevetoxins from *Karenia brevis)* (Hoagland et al., 2009, 2014; Figgatt et al., 2016) to negative effects on well-being as a result of disrupted access to coastal spaces and associated loss of cultural activities or connection (Willis et al., 2018). However, while research into the human health implications of HABs has been carried out (Young et al., 2020; Karlson et al., 2021), the workshop indicated that research into the social dimensions of these issues was limited. This is evidenced by Kouakou and Poder (2019) which found only 16 studies that explored the health *costs* of harmful algal blooms. The focus is noted as being predominantly on the economic costs, with little consideration of the pertinent social or cultural effects (including, for example, deterioration in welfare due to disrupted access to cultural and recreational ecosystem services provided by water systems impacted by algal blooms). For example, Zhang and Sohngen (2018) reveal that a considerable proportion of the welfare gains for anglers from measures to control HABs relates to 'non-catch' elements of the fishing experience including improvements in the clarity of water.

Berdalet et al. (2016) present a clear framework revealing the multiscale and diverse connections between algal blooms and human health and well-being (see Fig. 1). However, despite recognition of this knowledge gap, recent years have not witnessed a corresponding increase in attention from the research community. The arrows at the top of Fig. 1 need to be treated with caution, as the anthropogenic forcings of HABs are context-dependent, uncertain, and not necessarily the same

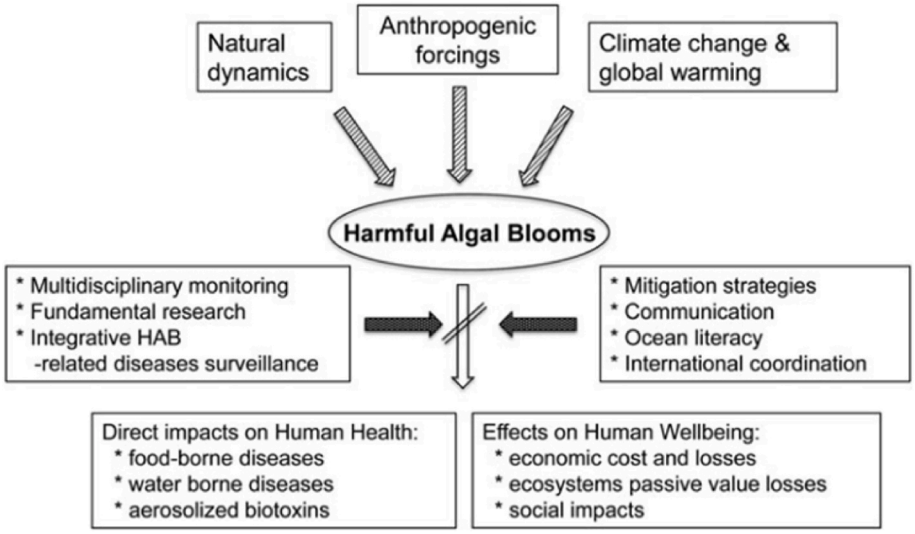

Fig. 1. Conceptual links of the drivers of Harmful algal blooms, the primary impacts on human health and wellbeing and potential solutions (Berdalet et al., 2016).

size as the other arrows. This is because the contribution of humans as a cause of HABs and their effects is not uniformly distributed spatially, temporally, or across communities. Further monitoring of the impacts of HAB events on health and welfare is essential (Fleming et al., 2011). However, fully understanding the economic, social, and cultural scale and scope of impacts on human health and wellbeing requires insight and expertise from across the social sciences. This could include, for example, the impact of a HAB related illness of a community's use of a coastal space or resource and the potential implications of this on local businesses; the potential disruption of an individual or community sense of place or identity as a result of not being able to access a particular coastal areas due to persistent and recurrent HAB events; or, indeed, instances of there being no change in behaviour or activities in response to HAB events, resulting in illness within communities and what the drivers of these decisions might be.

2.3. Governance and Management

2.3.1. Co-developed long-term solutions to HABs

Development of effective management and governance strategies, which provide long-term solutions to address HAB events, must engage communities and stakeholders. While the most effective solutions to HABs are contested, it has been noted that proposed solutions can often focus on mitigation of HAB effects rather than addressing underlying issues which may be causing HAB events (Anderson, 1997, 2009). This includes, for example, mitigation mechanisms such as aquaculture site management to reduce potential deterioration of water quality; shellfish-monitoring for identification of harmful algal species; toxin analysis and temporal reconstruction of HABs' occurrences to identify what may have initiated an event; land use and water quality management; broader coastal clean-up activities; and coastal habitat restoration, for example using seagrass that protect algicidal bacteria (Smits and van Beek, 2013; Cuellar-Martinez et al., 2018; Wang et al., 2018). Although each of these can be viewed as an appropriate response to HABs, they do not fully account for the complexity of the whole socio-ecological systems inherent to HABs and how this should be accounted for when identifying and implementing solutions. There is, therefore, a need for more comprehensive strategies focusing on prevention rather than managing HABs during an event. This could include designing and implementing long term context specific solutions, which can be applied across the whole environmental system, including addressing drivers of HABs which may occur upstream. This is opposed to the implementation of small scale and short term/temporary fixes. To achieve this, it is essential to better understand the direct and indirect causes of HABs, both from physical and socio-economic aspects, engaging communities and industry stakeholders as crucial actors in the co-development (i.e. the process of working collaboratively with a wide range of actors and stakeholders to design projects, tools and activities) of solutions to increase the likelihood of successful implementation of management strategies (linking to Section 2.1 on understanding perceptions and attitudes of HABs among communities). Achieving this requires a rethink of how HABs are considered from a management perspective. Here then it is not the just the HAB event which needs to be managed, but activities which predate it. In addition to developing an in-depth understanding of the socio-economic context of areas affected by HABs which could help to identify potential triggers or drivers, a wider vision needs to be developed. This could seek long-term, comprehensive, resilient and proactive solutions, which should be spatially and contextually tailored, since 'one size fits all' solutions are not expected to work (Anderson et al., 2019). There is then a need for socio-spatial contextualisation of policies to ensure they do not exacerbate social inequalities (explored in more detail in Sections 2.7 and 2.8). Finally, there is a need for policy makers to consider the risk of spillover effects. That is, intervention management of HABs in one area could lead to increased risk for HAB intensification in another region or other significant consequences. Therefore, a system approach for management and governance of HABs across the whole catchment system (see more in Section 2.7) supported by meaningful community engagement, which fosters co-development of solutions, is crucial to account for economic, social, ecological and cultural dimensions, and ensure that solutions to one problem can exacerbate the risk for another one (West et al., 2021).

2.3.2. Design and implementation of multi-scale, whole system governance

Linked to Section 2.6, the next research priority identified focused on the need for the identification and development of a whole system governance approach to address the challenges of HABs. This would take into account the fact that the drivers of HAB events might be geographically distant from where the impacts are most felt. Exploring, for example, how governance and management might cross both policy (e.g. agriculture, coastal management, or catchment management) or even geographical boundaries (e.g. such as seen in the River Wye, UK where agricultural land use in England is impacting water quality downstream in Wales). As explored throughout the paper, HABs often have complex causes which therefore require an equally complex and multiscale approach to governance and management. While the visible impacts of HABs might be localised, the causal footprint of an algal bloom might be complex, with a different geographical and social scale and context. For example, algal blooms in coastal areas can have a causal

footprint that is geographically distant, often well inland, of the problem. Consequently, an industry activity might be economically valued in one place, and even be seen to support a sustainable stream of ecosystem services. However, it might be viewed as causing severe environmental externalities in an adjacent area. In the case of the management of HABs, there is a need for systems that will embrace diverse public sector, community, and private sector actors. Critical here is a management approach and system that connects industries and affected communities with those organisations in charge of monitoring and regulating coastal activity, together with those planning and regulatory authorities that work with inland farming and industrial 'eutrophication' point sources. To date, there has been limited attention given to the efficacy of different governance/management systems in addressing HABs in coastal systems (see, West et al., 2021; Berardo et al. (2019); Creed and Friedman (2020) for examples from freshwater systems). Moreover, there is a need to develop a typology of different governance and management systems in varied geographical contexts, and differences in effectiveness over time and, crucially, how these could be effectively applied to governance in areas impacted by HAB events. Key here is better understanding how different sets of actors from planning authorities, regulatory authorities, industry, and the community in a defined HAB footprint area are best combined to manage the problem, and then how far approaches in one area might be transferable to other contexts or are more unique and geographically constrained. More research is therefore required in areas impacted by HABs to better understand the effectiveness of existing governance instruments. This is both in terms of managing the drivers of HABs, as well as implementing the solutions, and, where these have not been effective, to propose, test and implement innovative approaches to governance which take account of the whole system. To deliver this, there are several governance concepts which may be of interest. For example, catchment to coast initiatives, the role of upstream management, potential links to marine spatial planning and the engagement of local communities with co-development of effective governance structures (Jardine et al., 2020; Corcoran and Hunt, 2021).

A challenge for multi-scale governance is expected to be that resources are limited and with competing needs for these resources, as highlighted in the project team workshop. There are also questions on how far scientific and industry evidence of HAB effects is internalised effectively into decision-making. Making multi-scale governance effective depends on the development of transparent and trusting relationships. These ensure inclusion and consideration of all viewpoints, and that the best available science, are reconciled to develop buy-in to effective management options to address HABs. In developing this area of research, we expect there to be real value in comparative case study analysis in different places and to explore how and if governance and management in one place are affected by approaches elsewhere. In order to deliver truly co-developed solutions to addressing HAB events, it is recommended that more research should be done to develop a comprehensive picture of who is impacted by HABs, what activities might trigger HAB events, and who could potentially be engaged in delivering and implementing solutions. Further, related to Section 2.1., it is also recommended that societal understanding of impacts and solutions be assessed to limit the risk of unintended consequences (see Section 2.8).

2.3.3. Ensuring socially just, inclusive and equitable recognition of challenges and solutions relating to HABs

Literature on HABs and their impacts to date has afforded limited focus on elements of social justice, inclusivity, and equity (Anderson et al., 2000; Hoagland et al., 2002; Alonso-Rodrí; guez and Páez-Osuna, 2003; Nguyen et al., 2012; Trainer and Yoshida, 2014). Similar to other socio-ecological issues, such as fossil fuels, CO_2 emissions, and more widely climate change, HABs and their impacts can reinforce existing social and economic inequalities (Bretschger and Valente, 2011; Huan, 2018). That is, areas that significantly contribute to environmental damage eventually experience relatively insignificant socio-economic and ecological impacts compared to territories which make a much smaller contribution to environmental problems but experience disproportionately negative impacts (Roberts and Parks, 2007; Constant and Davin, 2019). In respect of HABs, studies have indicated that their impacts are not equal across space and society. For example, while fishers and other resource users with a direct link with the coast do not make the greatest contribution to HABs' production, they are frequently among those most affected (Anderson et al., 2000; Alonso-Rodrí). This inequity is emphasised by studies that present satellite images showing different concentrations of HABs across space in a specific area (Tang et al., 2004; Ware and Thomson, 2011; Smits and van Beek, 2013; Paerl, 2017; Zhao et al., 2018), with this being linked to a geographically uneven distribution of HAB risk.

In addition to meaningfully integrating diverse knowledges and perceptions into our understanding of HABs, including that from Indigenous and traditional knowledge holders, given the increasing focus on social justice in other marine and coastal socio-ecological issues (see for example, Bennett et al., 2021), and taking account of evidence from existing HAB studies, there is a clear need to understand the nature of socio-geographical, and socio-political, inequalities which may occur in the case of HAB events and for these to be considered when developing management and governance strategies. That is, studies on HABs would provide valuable insights from examining which social groups and areas have greater contributions to HABs' production and how the implications of HABs are distributed across space and society, feeding this into the whole system approach to governance explored in Sections 2.6 and 2.7. Here, we therefore suggest, that where recurrent HAB events take place, stakeholder mapping and in-depth assessment of the impacts of HAB events, and also their management or solutions, on communities across the entirety of the affected area should be conducted. Engaging in this sort of social research would contribute to a better understanding of the human dimensions of each HAB event, and ensure any unintended consequences as a result of management interventions are identified (e.g. increased costs for an industry which may not have contributed to the HAB).

3. Conclusions and recommendations for the future

This paper further emphasises the research gaps within the existing HABs research landscape. The academic debate is extremely imbalanced, with literature dominated by natural sciences and very limited focus on social, economic and cultural drivers and impacts of HABs. This mirrors a trend seen in other areas of marine and coastal resource management. While the research topics presented here and summarised in Table 1 are not meant to be exhaustive, the paper provides a foundation for future thinking around the development of an interdisciplinary research agenda for addressing the social, economic and cultural challenges and impacts of HABs in a range of geographical contexts.

Reflecting on the topics identified and discussed in the paper, a series of recommendations are presented with a view to supporting the future development of this research landscape.

While research effort has focused on the ecological dimensions of HABs, there are evidence gaps in terms of human dimensions. Our paper sets out a series of research themes requiring exploration. For these to be adequately examined, the research community must embrace inter-, and indeed, trans-disciplinary approaches. A future research agenda around HABs must therefore recognise the rich diversity of relevant disciplines, and draw on the wide range of qualitative and quantitative skills, experiences, and knowledge types that should be included to ensure meaningful and effective governance and management. For this to be achieved, there is first a need to ensure the availability of integrated funding mechanisms which allow for interdisciplinary research and its application within identifying solutions and developing whole system governance strategies to address the challenges that HABs present. In addition, as with other areas of marine social sciences (Jefferson et al.,

Table 1
Summary of research themes and suggested research needs and research questions.

Major thematic categories	Research Theme	Research requirements and potential research questions
Societal Understanding and Stewardship	Understanding societal attitudes and perceptions of HABs	•What are societal perceptions and understanding of HABs and their drivers? And how do these vary with differing social, economic, geographic and cultural contexts? • How can an improved understanding of societal perceptions be used to develop more effective governance and decision-making?
	Fostering engagement through community science	• How can community science initiatives engage communities in monitoring drivers of HABs? • What would motivate individuals to get involved in HABs related community science initiatives? • How could capacity for engagement with HABs and their management be enhanced through community science initiatives and projects?
Understanding Impacts of HAB	Understanding interactions between HABS and the blue economy	• What are the implications of HABs events on coastal community economies? • How resilient are coastal communities to the 'shock' of a HAB event that might impact their industry/economy? • What are the indirect impacts of HABs events on a sustainable blue economy?
	Impact of HABs on marine culture and heritage	• How might regular or persistent HAB events impact the ways in which seascapes influence everyday lives, regular practices and processes founded on natural heritage? • How do HABs impact how communities access and experience places which marine heritage and culture resources and benefits?
	Understanding the impact of HABs on societal health and wellbeing	• How do HAB events impact community connection to their coastal environment? • How do HABs disrupt/challenge individual or community sense of coastal identity? • How do HAB events influence individual and community well-being?
Governance and Management	Co-developed long-term solutions to HABs	• What examples of co-developed solutions could be applied to management of HAB events? Are there other areas of environmental management which could be drawn upon? • What methods of co-development would be most effective in addressing issues relating to HABs? • What stakeholders and actors should be involved in co-development of solutions and related governance?
	Design and implementation of multi-scale, whole system governance.	• What does the governance landscape of HAB management look like? Who are the actors, what are the policies and how do these vary across policy and geographical contexts? • What are the potential overlapping points between related areas of governance (e.g. coastal management, water quality, catchment-based management)?
	Ensuring socially just, inclusive and equitable recognition of challenges and solutions relating to HABs	• Who is not represented in existing social research on HAB events? • What are the potential unintended consequences of HAB management/solutions and how do these impact different communities?

2021), there is a need to consider how to most effectively understand, measure and evaluate the various human dimensions explored in this paper. Our paper sets out a series of research themes requiring exploration. For these to be adequately examined, the research community must embrace inter-, and indeed, trans-disciplinary approaches. Future studies will also need to consider different geographies with varying socio-economic contexts. Research into the socio-economic effects of HABs may historically have focused more in areas where the problem has had effects on more vocal stakeholder groups (e.g. tourism-facing sectors and aquaculture), and in more economically developed parts of the globe where there are scientific resources readily on hand to examine the phenomenon. Similarly future work in terms of human dimensions of HABs will need to address differences in effects on human dimensions in terms different HABs organisms. There is also a need for those who fund research into the human and societal effects of HABs to be careful in how they design their requests for research such that there is scope in proposals to use actors from different disciplinary areas. Depending on the research questions, methodological approaches and data collection techniques will vary and must be designed to ensure they are appropriate for the social, cultural, economic and geographic context at hand. For example, tools such as questionnaires, often used in ocean perceptions research (see Jefferson et al., 2021; McKinley et al., 2020; Potts et al., 2016) could be a valuable method of collecting insights from large populations, while qualitative methods provide opportunities to gather more in-depth information on a case-by-case basis. Furthermore, given the complexity of the drivers and impacts of HABs, there is a need to ensure that this interdisciplinarity encompasses the whole system and the wider science-policy-practice interface on a range of topics related to HABs. These include upstream land use, catchment to coast based governance and management initiatives, monitoring and

management of water quality and individual and/or collective behaviour change. Linked to interdisciplinarity, there is an opportunity, and indeed a need, to diversify the suite of qualitative methods being used to explore the human dimensions relating to HABs (Jefferson et al., 2021). Increasingly, there is a role for adopting creative and arts-based approaches to exploring the perceptions and attitudes towards HABs and how HABs impact different communities. Finally, there is perhaps a need to do an evaluation of existing skills and knowledge relating to HABs research. This will identify existing evidence gaps, pinpoint development of research priorities for different regions and communities and support the identification of where additional skills and training are required to build capacity around HABs research.

CRediT authorship contribution statement

Emma McKinley: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Nikos Kapitsinis:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Max Munday:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Muaaz Wright-Syed:** Writing – review & editing, Writing – original draft. **Yen Thi-Thai Doan:** Writing – review & editing, Writing – original draft. **Thu-Huong ThiHoang:** Writing – review & editing, Writing – original draft. **Khac-Uan Do:** Writing – review & editing, Writing – original draft. **Tung Thanh Le:** Writing – original draft. **Rupert Perkins:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Reza Ahmadian:** Writing – review & editing, Writing – original draft, Funding acquisition, Conceptualization.

Declaration of competing interest

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