Harmful Algal Blooms: Challenges and options for policy makers

NC34: Pelagic Monitoring Programme / Pelagic Natural Capital (PelCap) project

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Find out more at https://www.gov.uk/government/publications/natural-capital-and-ecosystem-assessment-programme.

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1. Executive summary

1.1 Summary of findings

A Harmful Algal Bloom (HAB) is defined as an algal bloom which can have a (potential) negative impact on human health, society, the aquatic ecosystem, or associated industries. A HAB is not a biological term as the grouping is based on a ‘negative impact’ and contains a variety of organisms, behaving and responding to pressures in a variety of different ways. This report focuses on HABs that impact the marine environment.

The most frequently reported impact from HABs in UK coastal and marine waters are closures of shellfish harvesting areas due to levels of algal toxins in shellfish flesh exceeding regulatory thresholds. HABs have also been identified as a significant cause of mortalities and welfare issues in farmed fish, particularly in Scotland. While industry has been supportive of early warning systems to provide an early indication of HAB events, there are limited options for mitigating actions once a HAB event has been predicted.

The relationship between HABs and eutrophication is complex with many cause and effect interactions. This complexity has made it difficult to identify and apply one universal indicator species that can be linked confidently to eutrophication in UK waters. Although HABs can be a direct or indirect manifestation of eutrophication, the interactions between the two are not linear, and whilst high nutrients have been responsible for HAB outbreaks, there are often many other factors that can drive or enhance HAB events.

Plankton have been estimated to contribute positively towards the provisioning, regulating and cultural services provided by UK seas, with an annual value of £3.24 billion and a Net Present Value (NPV) of £152 billion in 2019 prices. This number does not factor in the negative costs of plankton, including from HABs. In the UK, a study has estimated that human food poisoning from HABs can cost the NHS (at least) ~£300K per year. Economic studies into the costs of HABs are scarce so this number is likely to be an underestimate. Assessments of the financial costs of HABs must also consider the socio-economic impacts from mortalities of farmed fish, closures of shellfish harvesting areas and coastal beaches both in terms of absolute cost and on local employment.

UK statutory assessments do not include a dedicated HAB indicator. This is partially due to the diverse range of HAB species, ecologies and impacts in UK waters, and the complexity of associating a single pressure (e.g. such as nutrients) with HAB events. Some HABs have the potential to respond to preventative management actions and are thus suitable for inclusion in these assessments, however many HABs are natural phenomena and the presence of these HABs can still meet ‘good’ criteria despite causing severe negative impacts for industries and on the marine ecosystem. In this instance, management actions should be directed towards early warning systems or mitigation measures to reduce the impact from HAB events.

Identification of the impacts of climate change and ocean acidification on HABs in UK waters is complex. New technologies such as automated imaging techniques and molecular methods, along with remote sensing and advanced modelling techniques have the potential to improve early warning capacity for predicting and detecting HAB events, and help reduce negative impacts on industries.

1.2 Summary of recommendations

Monitoring and assessment

1. The current plankton life form approach used for the UK Marine Strategy and OSPAR Quality Status Assessment should be investigated to identify how best to include HABs into statutory status assessments. There is unlikely to be a single generic 'HAB' lifeform indicator. The presence of a HAB may still meet 'good' status despite the HAB having a negative impact.

2. Toxins produced by HABs that accumulate in shellfish flesh (shellfish toxins) are present within the marine food web and thus pose a threat to higher trophic levels (e.g. marine mammals, sea birds). Shellfish toxins should be included as a pressure for higher trophic levels in future environmental status assessments.

3. Benthic HABs are poorly studied in the UK. There is merit in identifying which benthic HAB species are currently present in UK waters to inform management plans should they begin to present problems.

4. The freshwater cyanobacterial blooms in Lough Neagh, Northern Ireland have resulted in cyanotoxins being detected at unsafe levels in both estuarine and coastal locations on the Atlantic coastline. A joined up management approach between land use, freshwater and marine agencies is required to deal with this issue especially in areas with significant agriculture, wastewater or industry.

5. Citizen science approaches to report the impacts from HABs should be explored and encouraged.

6. Increased collaboration and data sharing with the fish farming industry is required to better quantify the HAB events occurring at salmon aquaculture sites in Scottish waters and the resultant health and economic impacts and hence allow the development of improved mitigation approaches. There may be also opportunities here for the development and adoption of new technologies and the application of early warning systems.

Management and measures

7. Options to mitigate the impact from HABs are limited and confounded by climate change and ocean acidification. Accordingly, further investigation of mitigation measures is encouraged.

8. A socio-economic study on the impacts from the different HAB types experienced across the UK needs to be performed to identify the value of investment in improving management and adaptation measures to reduce HAB impacts.

9. The influence of offshore wind structures on HAB dynamics should be included in development plans.

2. Introduction

Unicellular photosynthetic microbes form the base of the marine food web. This group is comprised of phytoplankton and mixoplankton and is often collectively referred to as 'microalgae'. Historically, Harmful Algal Bloom (HAB) species were considered to belong to the phytoplankton functional group and included the prokaryotic cyanobacteria and various eukaryotic protist plankton. The majority of these microalgae were assumed to use photosynthesis as their main energy source with some 'outliers', (e.g., dinoflagellates), having the ability to consume prey. Recent work has revealed the true complexity of the nutritional strategies of these microbial organisms leading to a re-classification of the photosynthetic microalgae broadly into phytoplankton and mixoplankton (Mitra et al., 2023). Accordingly, HAB species are now categorised as either phytoplankton (e.g., cyanobacteria, diatoms) capable of obtaining nutrition via photosynthesis and through uptake of organic amino acid and proteins (osmotrophy) or, as mixoplankton which employs photosynthesis synergistically with predation.

When environmental conditions are optimal, these microbes can rapidly increase in abundance forming what has been termed an 'algal bloom'. Blooms of microalgae are naturally occurring and ecologically important phenomena in marine and freshwater ecosystems and often follow seasonal cycles in higher latitudes. For example, the spring diatom bloom where diatoms increase in abundance in temperate waters, provides food for filter feeding shellfish and copepods, and fuel the marine food web during the summer months (Sharples et al., 2006). Not all blooms provide benefits to the UK aquatic system. Blooms of certain species can have a negative impact on human health, society, marine ecosystems and associated industries. These are termed Harmful Algal Blooms or HABs (Davidson and Bresnan 2009, Berdalet et al., 2016).

The impacts from HABs are diverse. In the UK, some HAB species produce algal toxins which can accumulate in the flesh of filter feeding shellfish and pose a serious risk to human health if consumed (Gianella et al., 2021). When the presence of such toxins are detected above regulatory thresholds in shellfish harvesting areas it can result in their closure, sometimes for extended periods (Davidson and Bresnan 2008). HABs can also cause mortalities of marine organisms via production of toxins or deoxygenation driven by the decomposition of blooms (Davidson et al., 2009, Brown et al., 2020). Additionally, mortalities of farmed fish can result from irritation of gills, production of toxins and low dissolved oxygen concentrations (Morro et al., 2022, Treasurer et al., 2003, GlobalHAB 2023). Globally, water discolouration, scums and foams can have negative health impacts (e.g., asthma, dermatitis; Wiśniewska et al., 2020) as well as impact aesthetics affecting house prices, and the leisure industry (Berdalet et al., 2016).

In some instances, the frequency or duration of HABs can be seen as indicators of poor water quality resulting from anthropogenic nutrient input (Davidson et al., 2014). To date, the presence of HABs has not been considered as an indicator of failure to achieve 'Good Environmental Status (GES)' in the UK Marine Strategy due to the uncertainly between nutrient levels and the occurrence of HABs or HAB impacts. However, there have been recent discussions on the use of HAB indicators for national and European scale environmental status assessments (Saraminaga et al., 2023). Significant HAB events often have high visibility due to their impacts on livelihoods and/or society's connection to the marine environment (Willis et al., 2018). Ministers have been approached by the public to provide advice and management plans to reduce impacts on livelihoods, particularly during extreme events (BBC media, 2000). A recent example is the extensive *Microcystis* bloom in Lough Neagh, Northern Ireland. After considerable public outcry, ministers in the Northern Ireland Executive made it their highest priority on return to government and developed an action plan to address the issue (DAERA, 2024, Northern Ireland Executive, 2024).

This paper clarifies the categories of HABs in UK marine waters and potential management strategies that could be employed by government and policy makers to reduce impact on ecosystems, industry, and society. The different HAB genera and their impacts reported in UK waters are summarised in Table 1. Micrographs of the dominant UK HAB species are found in

Figure 1. Additional species with the potential to cause harm to farmed fish and included as target species for identification in a standardised phytoplankton monitoring protocol aimed at the fin-fish sector in Scotland are presented in Table 2.

Table 1: Summary of HAB species and impacts in UK waters

HAB genus	High/Low biomass	Mechanism of 'harm'	Negative impact
Alexandrium spp.	Low biomass	Paralytic shellfish toxins (PSTs)	Closure of shellfish harvesting areas to protect human health Negative impacts on higher trophic levels
Dinophysis spp.	Low biomass	Diarrhetic shellfish toxins (DSTs)	Closure of shellfish harvesting areas to protect human health Negative impacts on higher trophic levels
Azadinium spp.	Low biomass	Azaspiracid shellfish toxin (AZAs)	Closure of shellfish harvesting areas to protect human health Negative impacts on higher trophic levels
Pseudo-nitzschia spp.	High biomass	Amnesic shellfish toxins (ASTs)	Closure of shellfish harvesting areas to protect human health Negative impacts on higher trophic levels
Karenia mikimotoi	High biomass	'Ichthyotoxins', Increased DO demand	Mortalities/welfare impacts on benthos and farmed fish and shellfish
Flagellate 'X', *Heterosigma akashiwo*	High biomass	Ichthyotoxins	Mortalities of farmed fish
Diatoms *Chaetoceros,* *Thalassiosira* spp. *Pseudo-nitzschia*	High biomass	Physical abrasion, DO demand	Irritation of gills of farmed fish with potential mortalities
Dinoflagellates (*Heterocapsa triquerta*)	High Biomass	DO demand	Farmed fish mortalities
Noctiluca scintillans	High biomass Water discolouration	Ammonia production	Negative impact on tourism, skin irritation on recreational swimmers/divers
Haptophytes (*Phaeocystis*)[1]	High Biomass	DO demand	Farmed fish mortalities, foam production, negative impact on tourism
Cyanobacteria *Microcystis*	High biomass	Water discolouration Microcystin toxin producer	Washed into coastal harbours from intensive blooms in freshwater systems e.g. Lough Neagh, risk of cyanotoxin exposure

[1] High biomass blooms of a variety of phytoplankton genera have caused mortalities of farmed fish in the UK. These are described in Bresnan et al., 2021 and Morro et al., 2022.

Figure 1: Micrographs of common HAB species from UK waters; (a) *Dinophysis acuta* (DST producer), (b) two cell chain of *Alexandrium* sp. (PST producer), (c) chains of *Pseudo-nitzschia* spp. cells (AST producer), (d) *Karenia mikimotoi* (fish and benthic mortalities) and (e) *Chaetoceros* sp. (physical abrasion of fish gills).

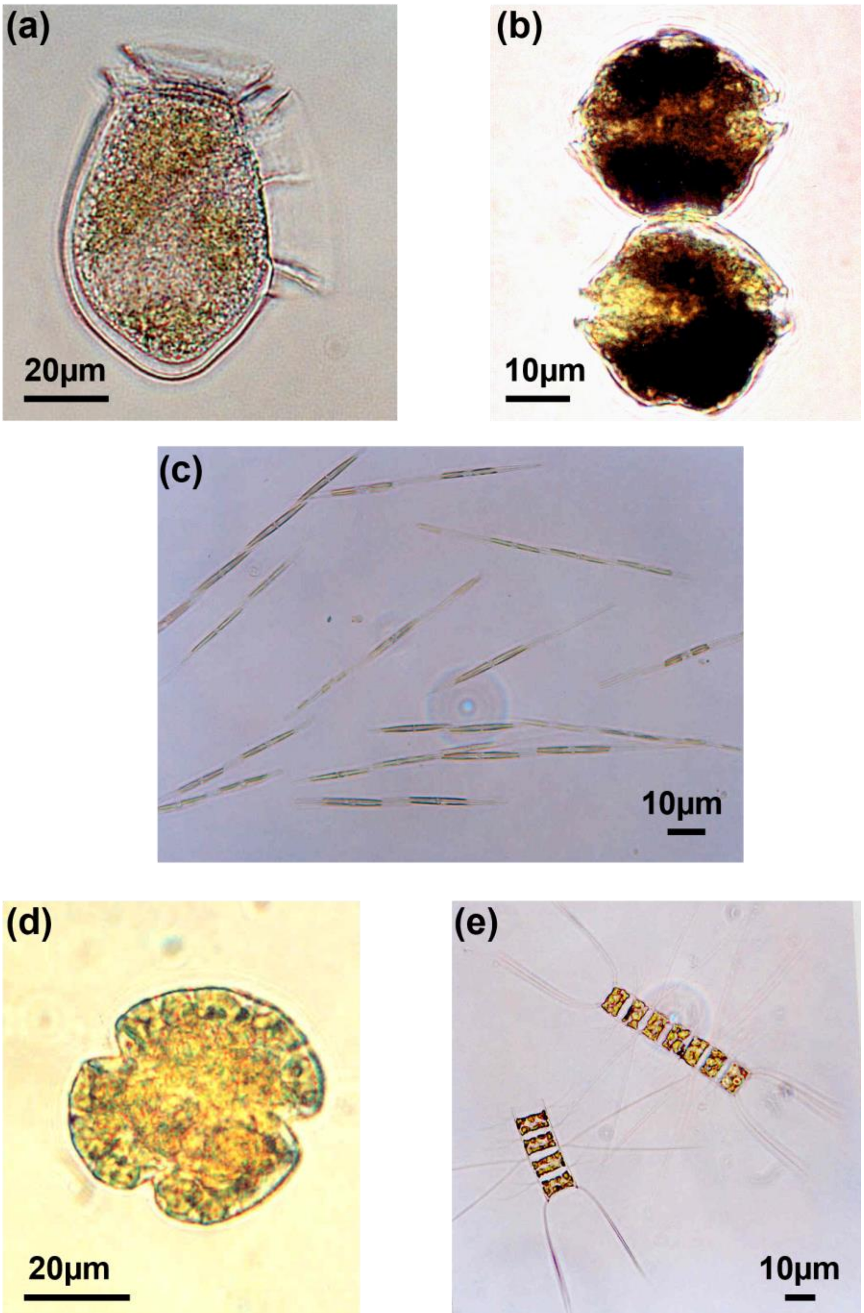

Table 2: Target species list for identification by fin-fish farmers. Taken from 'Towards a standardised phytoplankton monitoring operating procedure for the finfish sector' (Weeks et al., 2022).

HAB genus/species	Impact
High importance	
Alexandrium spp.	Production of ROS* and/or PUFA**, potentially toxic
Asterionella japonica	Physical
Ceratium/Tripos spp.	Physical, hypoxia
Chaetoceros convolutus	Physical
Chaetoceros concavicorne	Physical
Chattonella spp.	Toxic
Chrysochromulina	Toxic
Cochlodinium spp.	Toxic, hypoxia
Dictyocha/Vicicitus spp.	Physical, toxic
Heterosigma akashiwo	Production of ROS*
Karenia mikimotoi	Hypoxia at high density, toxicity from PUFAs
Pseudochattonella spp.	Physical, toxic
Pseudo-nitzschia spp.	Potentially toxic and physical
Pseudopedinella spp.	Potentially toxic and physical
Rhizosolenia spp.	Physical
Centric, pennate or chain-forming diatoms	Physical in high numbers
Medium Importance	
Chaetoceros socialis	Physical
Phaeocystis spp.	Potential hypoxia
Low Importance	
Amphidinium carterae	Potentially toxic
Chaetoceros spp. (any other species)	Physical
Fibrocapsa japonica	Toxic
Karlodinium spp.	Potentially toxic
Prymnesium spp.	Toxins that impact gills
Skeletonema spp.	Physical
Thalassiosira spp.	Physical

* ROS: Reactive Oxygen Species such as hydroxyl radical (OH), hydrogen peroxide (H_2O_2) and superoxide (O_2) – thought to contribute to fish gill injury.

**PUFA: polyunsaturated fatty acids such as DHA associated with lytic activity and finfish mortality.

2.1 What is a HAB?

The term HAB refers to a 'bloom' of photosynthetic microalgae including phytoplankton (e.g., cyanobacteria, diatoms) and mixoplankton (dinoflagellates) which results in a negative impact on human health, society, the marine ecosystem or associated industries (Shumway, 1990, Hallegraeff, 1993, Mitra and Flynn, 2006, Hallegraeff et al., 2024). HAB species occur across different domains and diverse taxonomic groups (Adl et al., 2005, Mitra et al., 2023, Lundholm et al., 2024). Currently there are ~ 200 toxin producing HAB taxa in marine systems worldwide, the majority (>50%) of which are dinoflagellates (Hallegraeff et al., 2021). The impacts from HABs, as well as their ecology, life strategy, and relationship with natural and anthropogenic pressures, vary widely and can also be regionally specific (Gowan et al., 2012). The main commonality of the HAB grouping is a 'negative impact' either on human health, society, the marine ecosystem or associated industry and it can be a societal rather than biological term. In some instances, the term 'bloom' is a misnomer as a number of HAB species can have deleterious impact on the environment when present at low cell abundances. For example, very low cell densities (< 1,000 cells L^{-1}) of *Alexandrium catenella* can lead to closure of shellfish harvesting areas due to the presence of Paralytic Shellfish Toxins (PSTs) in shellfish flesh at levels above regulatory thresholds (Bresnan et al., 2008).

There are multiple terms used to refer to HABs. Some blooms of HAB species with a distinct pigment composition can result in a red discolouration of the water; these are sometimes referred to as 'red tides' (e.g., *Noctiluca scintillans*). This term is used more routinely in the USA and Asia as well as in older publications from the UK from circa 1960s/70s to refer to shellfish toxin producing HAB species (Adams et al., 1968). An ICES workshop in 1984 used the term 'Exceptional Marine Blooms' when referring to "a range of phenomena involving deleterious effects of plankton growth or metabolism" (Parker & Tett, 1987). 'Nuisance algal bloom' is the name given to algal blooms that discolour water, cause odours and is applied particularly to cyanobacterial blooms (also referred to as Blue/Green algal blooms due to their pigment composition) which occur in freshwater systems (Watson et al., 2016).

There have been attempts to refine the definition of marine HABs to distinguish between different ecological impacts such as Ecosystem Disruptive Algal Blooms (EDABs) which refers to blooms that can disrupt or degrade ecosystem structure and function (Sunda et al., 2006) and Toxin Producing Algae (TPA) which identify the taxa that produce toxins (Gowen et al., 2008). However, these terms are not commonly used and the term 'HABs' is still applied to a broad variety of scenarios by scientists, managers, and policy makers with little distinction between the type of HAB or type of impact. This poses problems with expectations to develop a generic 'HAB indicator' to evaluate environmental status under the UK Marine Strategy as there is no generic HAB. A more refined consideration of the type of HAB, impact, and potential drivers is needed.

A distinction also needs to be made between the presence of a HAB species and a harmful algal event (HAE) where there is a distinct negative impact arising from the presence of the HAB. The Intergovernmental Oceanographic Commission of UNESCO (IOC) defines a HAE (IOC 2021) as one or more of the following occurrences:

> (a) water discoloration, scum or foam causing a socio-economic impact due to the presence of toxin producing or harmful microalgae;
> (b) precautionary closures of shellfish harvesting areas due to the presence of algal toxins and/or presence of potentially harmful microalgae;
> (c) biotoxin accumulation in seafood above levels considered safe for human consumption;
> (d) any event where humans, animals or other organisms are negatively affected by microalgae.

Increasing anthropogenic use of the environment can introduce a bias into our understanding of the status of HABs. This is particularly relevant in places where the aquaculture industry is active as the level of monitoring and recording of HAB species and events can be driven by the intensity of shellfish or fish farming effort (Hallegraeff et al., 2021). For example, the introduction of shellfish harvesting activity into a new area, can result in increased reporting of harvesting closures due to toxin levels in shellfish above regulatory levels. This increased reporting can be due to an increase in monitoring effort associated with an expansion of shellfish harvesting into a new area as opposed to an expansion/increase in the toxin producing species.

Some algal blooms may only be considered HABs due to the presence of a particular industry. For example, a bloom of the diatom genus *Chaetoceros,* may occur without any negative impact in an area with no fish farm activity however, if there is a fish farm present, the spikey setae of the *Chaetoceros* cells may cause gill irritation in farmed fish with knock on impacts on fish welfare or mortalities. In this instance, the algal bloom is considered a HAB. Thus, for some species, blooms can only be considered HABs in the context of the presence of industries they impact. This means that developing generic management or 'HAB' assessment measures can pose a problem for policy makers whose role is to manage sustainable use of UK seas.

2.2 Statutory requirements and initiatives involving HABs

Current statutory regulations which require the monitoring of HABs or plankton in the UK are summarised in Table 3. These regulations fall under two categories (i) protection of human health and (ii) environmental/ecological quality/status assessment. In addition there are multiple national and international initiatives e.g. via the Marine Climate Change Impacts Partnership (MCCIP) (Bresnan et al., 2020), the International Council for the Exploration of the Sea (ICES, 2021) and the International Oceanographic Commission of UNESCO (IOC) -Food and Agriculture Organisation (FAO) of the United Nations, Intergovernmental Panel for HABs (Hess and Enevoldsen 2023) which focus on HABs and their impacts, and place the UK situation in a broader European and global context.

Currently, the UK Pelagic Habitat Expert Group (PHEG), which was formed in response to the Pelagic Habitat assessments required under the EU Marine Strategy Framework Directive (MSFD) (208/56/EC) in 2008 and subsequent UK Marine Strategy (UKMS) since 2016, is looking at the potential to use data collected under the EU Shellfish Hygiene Directive (2019/627) in statutory status assessment of the pelagic habitat. This dynamic group brings together members from all institutes in the UK who are working on plankton ecology who hold long term time series of plankton data. The PHEG has been fundamental in driving the development of indicators, databases and assessment methods for the statutory assessment of the plankton community in UK waters (McQuatters-Gollop et al., 2019, Ostle et al., 2021). This has considerably improved our understanding of how the plankton community in UK waters is changing (Bedford et al., 2020a, Holland et al., 2023, McQuatters-Gollop et al., 2024) as well as how assessment scale impacts results (Bedford et al., 2020b, Graves et al., 2023).

Table 3: Statutory policy drivers relevant to HABs applicable in the UK

Regulation	Purpose	Activity	UK Statutory Body
EU Shellfish Hygiene Directive and recommendations (2019/627)	Protection of human health	Monitoring shellfish growing areas for toxins in shellfish flesh and causative organisms	Food Standards Agency Food Standards Scotland Food Standards NI
EU Water Framework Directive (2000/60) now **The Water Environment (Water Framework Directive) (England and Wales) Regulations 2017 (England, Wales, NI)** Controlled Activity Regulations and River Basin Management Plans **(Scotland)**	Statutory Environmental Assessment	Monitoring coastal and transitional waters for nutrients, chlorophyll and phytoplankton community	Defra (England/Wales) Environment Agency SEPA DAERA National Rivers Wales The Scottish Government (Scotland)
Marine Scotland Act (2010) **EU Marine Strategy Framework Directive (208/56/EC)** now **UK Marine Strategy,** **OSLO/PARIS Commission (OSPAR) North East Atlantic Environment Strategy**	Statutory Environmental Assessment Statutory Environmental Assessment	Monitoring offshore waters for nutrients, chlorophyll and phytoplankton community Monitoring offshore waters for nutrients, chlorophyll and phytoplankton community	The Scottish Government (Scotland) Undertaken by the UK Marine Monitoring and Assessment Strategy (UKMMAS) Evidence Groups which are coordinated and guided by the UK Monitoring and Assessment Reporting Group (MARG), reporting to Defra

3. HABs and aquaculture

3.1 Shellfish

The most frequently reported impact from HABs in the UK is the closure of shellfish harvesting areas due to algal toxins in the flesh of filter feeding shellfish above regulatory levels which pose a risk to human health if consumed. The earliest report comes from nearly 200 years ago when a human fatality associated with paralytic shellfish toxins (PSTs), produced by the dinoflagellate *Alexandrium* was recorded in Leith, Edinburgh in 1827 (Ayres 1975). Subsequent reports were sporadic until 1968 when more than 70 people were affected by PSTs after consuming wild-caught shellfish from the north-east of England (Ayres and Cullum 1978). Routine monitoring of shellfish for PSTs began in that region in response to this event. Monitoring expanded in 1990 to cover more of the coastline in Scotland, England, Wales and Northern Ireland, again in response to high concentrations of PSTs. The implementation of the EU Shellfish Hygiene Directive (91/492/EEC now 2019/627) in the UK in the 1990s led to the start of statutory monitoring for diarrhetic shellfish toxins (DSTs) produced by the dinoflagellate genus *Dinophysis* in 1992 and amnesic shellfish toxins (ASTs) produced by the species within the diatom genus *Pseudo-nitzschia* in 1998. The presence of Azaspiracids (AZAs) produced by the dinoflagellate genus *Azadinium* has been monitored since 1998 (Dhanji-Rapkova et al., 2019). Since 1990, shellfish toxins have become an annual concern for the UK aquaculture industry (Davidson and Bresnan 2009, Bresnan et al., 2020, Gianella et al., 2021, Whyte et al., 2023). A list of shellfish toxin producing species recorded in the UK is presented in Appendix 1 (from Bresnan et al., 2021).

Figure 2 uses the IOC Harmful Algal Information System (HAIS) to plot the incidence of Harmful Algal Events and toxin producing phytoplankton species in UK waters. HAIS is comprised of the IOC-ICES-PICES Harmful Algal Event Database (HAEDAT) which holds data about the occurrence of harmful algal events from across the globe and UNESCO's Ocean Biodiversity Information System (OBIS)/HABMAP. HAEDAT data since 2010 have been plotted to better reflect the current monitoring effort. OBIS/HABMAP is used to plot the distribution of causative HAB species as well as data from Food Standards Agency, Food Standards Agency NI, Food Standards Scotland, Scottish Coastal Observatory and Environment Agency England/Wales Water Framework Directive phytoplankton monitoring programmes. The distribution of monitoring effort for the presence of shellfish toxins has been redrawn from Bresnan et al. (2021). More information about HAIS can be found in Zingone et al. (2022).

Figure 2(a), 2(c), 2(e) and 2(g) shows a strong regional distribution of HAB events associated with shellfish toxins with the majority of closures of DSTs, PSTs and ASTs recorded on the west coast of Scotland, Shetland Isles and the Southwest of England. This reflects the distribution the shellfish farming/harvesting industry and associated monitoring effort (Figure 2(h)). Despite the high incidence of closures of shellfish harvesting areas due to levels of toxins above regulatory thresholds, there have been only two incidents of human illness associated with HABs (both DSTs) in the last 15 years. In 2013, diners at a chain of restaurants in London became ill with DSTs after consuming mussels (*Mytilus edulis*) harvested from Shetland. This event was associated with a sudden wind driven advection of *Dinophysis* from offshore into a shellfish harvesting area (Whyte et al., 2014). This event led to the development of the alert system (www.HABreports.org) to provide some level of prediction in occurrence of HAB events and facilitate better management of harvesting (Davidson et al., 2021). In 2019, a batch of mussels, *Mytilus edulis,* was served to diners in Cornwall before a recall notice had been observed, resulting in six diners becoming ill with symptoms associated with DSTs (Young et al., 2019). This event highlighted the lack of awareness of shellfish toxins amongst clinicians and public officials.

The aim of the EU Shellfish Hygiene Directive is to protect human health and thus monitoring effort is directed to areas of shellfish harvesting activity, while areas with no shellfish industry (e.g. along the east coast of England, Scotland) have little sustained monitoring for either shellfish toxins or coastal phytoplankton and information about the status of shellfish toxins in this region is scarce.

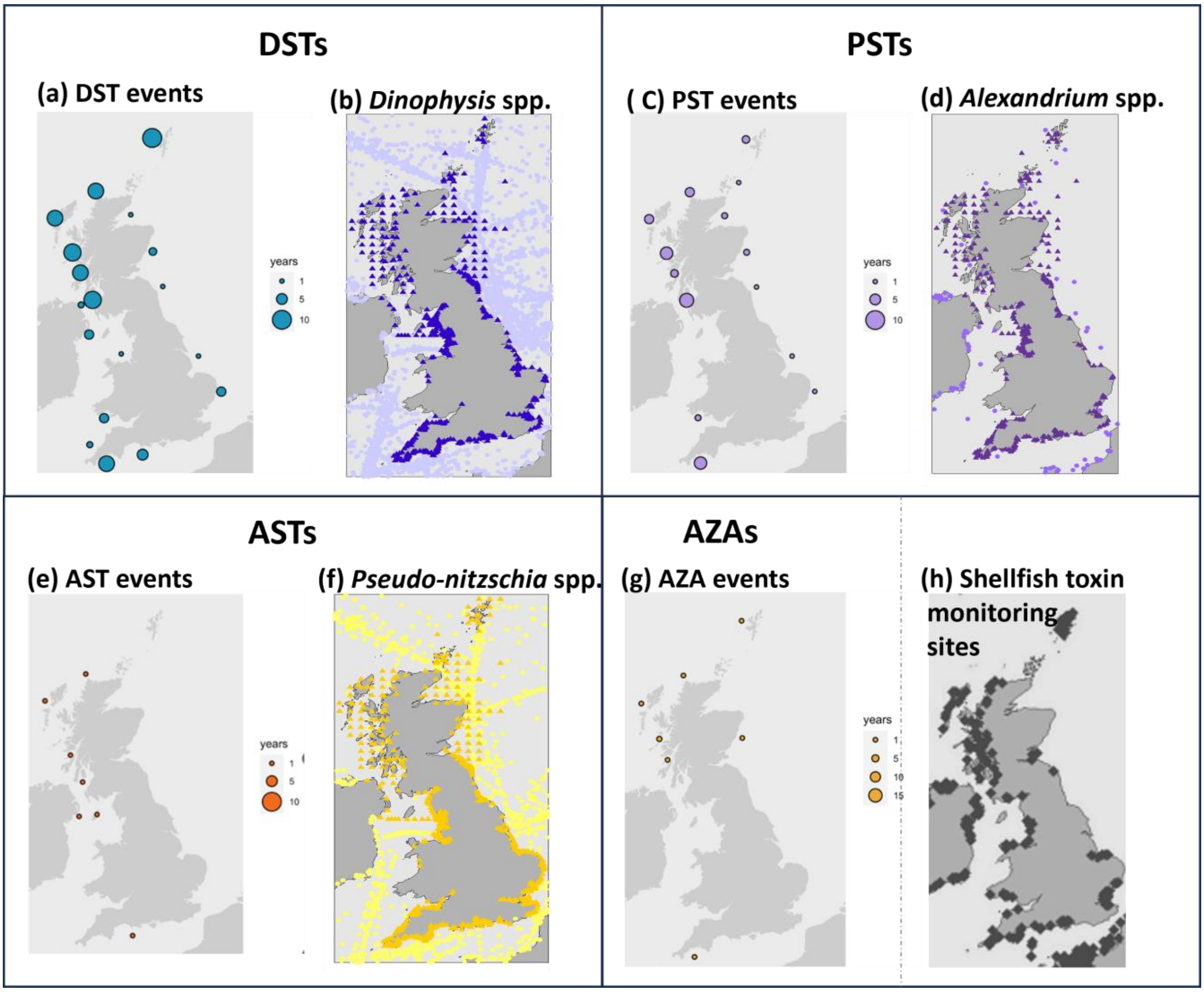

Figure 2: Number of years with toxin events in the UK over the last 10 years and distribution of causative organisms; (a) DSTs and (b) *Dinophysis* spp., (c) PSTs and (d) *Alexandrium* spp., (e) ASTs and (f) *Pseudo-nitzschia* spp., (g) AZAs and (h) location of shellfish toxin monitoring effort. Distribution of toxin producing species comes from data from OBIS/HABMAP, Food Standards Agency, Food Standards Scotland, Food Standards Agency NI, Scottish Coastal Observatory and Environment Agency England/Wales Water Environment Regulations data. Toxin event data comes from the IOC-ICES-PICES HAEDAT database. Shellfish toxins monitoring sites are shown in (h) (redrawn from Bresnan et al., 2021).

3.2 DSTs and *Dinophysis*

The HAB species which cause the most closures of shellfish harvesting areas in the UK belong to the dinoflagellate genus *Dinophysis.* The two main species responsible in UK waters are *D. acuminata* and *D. acuta,* with closures enforced every year in Scotland and frequently in the southwest of England (Swan et al., 2018, Bresnan et al., 2021, Brown et al., 2022, Whyte et al., 2023). In Northern Ireland, closures of shellfish harvesting areas due to levels of toxins above regulatory limits are infrequent. Hydrographic and oceanographic conditions play a role in the abundance of *Dinophysis* cells in UK waters. *Dinophysis* cells are transported in the European current along the southwest coast of the UK, west coast of Scotland, Orkney and Shetland and advected onshore (Whyte et al., 2014, Bresnan et al., 2021, Dees et al., 2023). Water movements along the English Channel influence the distribution of *Dinophysis* in that region (Brown et al., 2020, 2022), with weather, particularly wind direction also being important in determining whether a bloom develops at shellfish sites in this area. Using data from 2014 – 2017, low air temperatures in June were associated with low toxicity in shellfish flesh in that region (Panton and Purdie, 2022).

A socio-economic survey calculated that an increase in closures of shellfish harvesting areas in Scotland due to high levels of DSTs by 1% can result in financial losses of £1.37 million in an industry with a turnover of £10.1 million (2015 value of £) (Martino et al., 2020). A prolonged bloom of *Dinophysis* in the southwest of England in 2018 led to a harvesting ban for 18 weeks with an associated loss of sales revenue estimated to be £1 million (Brown et al., 2022).

3.3 PSTs and *Alexandrium*

Evidence from the historic literature recorded the first fatality in Scottish waters due to the consumption of shellfish contaminated with PSTs over 200 years ago (Ayres 1975). Since then, blooms *of Gonyaulax excavata* (now *Alexandrium catenella*) in the 1960s in the North-East of England caused human illness with an exceptional bloom in the 1990s resulting in widespread closures of shellfish harvesting areas (Ayres 1975, Joint et al., 1997, Brown et al., 2001). When routine monitoring started in the 1990s, high levels of PSTs were recorded along the east coast of Scotland and Orkney (Bresnan et al., 2008). More recently, monitoring along the east coast of Scotland and Orkney has reduced due to the lack of active shellfish harvesting sites. PSTs are recorded above regulatory limits in selected sea lochs in the west coast, the Shetland Islands and the south-west coast of England. In Scotland, the main causative organism is what is now called *Alexandrium catenella* with *A. ostenfeldii* also a confirmed PST producer (Collins et al., 2009, Brown et al., 2010). In the south-west coast of England, shellfish harvesting closures are associated with *A. minutum* (Lewis et al., 2018). Closures in Northern Ireland due to PSTs are scarce with one recorded in 1996 however cysts belonging to *A. catenella* have been found sediments in Belfast Lough (Perez Blanco and Lewis 2014).

In 2017, a number of dogs were fatally intoxicated with PSTs after eating star fish that had washed onshore after a severe storm. This event was unusual as it occurred in an area with little *Alexandrium* detected (Turner et al., 2018). This issue is discussed in more detail in section 9.0.

3.4 ASTs and *Pseudo-nitzschia*

The main impacts caused by Amnesic Shellfish Toxins (ASTs), produced by the diatom genus *Pseudo-nitzschia* in the UK, have been experienced by the King Scallop (*Pecten maximus)* fishing industry. This is due to the lengthy retention time of the AST toxin, Domoic Acid (DA), in *P. maximus* gonad tissue above regulatory levels (Bresnan et al., 2017b). The introduction of amendments to the EU Shellfish Hygiene Directive (854/2004) permitted a move to shucking, end product testing and sale of the excised adductor muscle of *P. maximus* when DA levels were above regulatory thresholds in the gonad tissue. This meant that closures of offshore scallop fishing areas were greatly reduced. Since 2004, only a small number of closures for ASTs have been enforced, the majority of which have been in Scotland (Bresnan et al., 2021, Rowland-Pilgrim et al., 2019). The main causative organisms of ASTs in Scotland are *P. australis* and *P. seriata* (Fehling et al., 2004) while *P. mulitseries* has been identified as a DA producer from the south coast of England (Percy 2006). A recent study suggests that the incidence of ASTs may be underreported. During the summer months, shellfish harvesting areas in the Shetland Islands are frequently closed due to high levels of DSTs and thus there is no monitoring for ASTs as human health is already protected. Whyte et al., (2023) showed that levels of DA can exceed regulatory limits during periods of high levels of DSTs, highlighting the limited understanding of the accumulation of ASTs in shellfish during the summer months in this area.

3.5 AZAs and *Azadinium*

Dinoflagellate species within the genus *Azadinium* produce the lipophilic toxins Azaspiracids. This new dinoflagellate genus was described from water samples collected near Stonehaven in Scotland (Tillmann et al., 2009). There have only been a very small number of closures of shellfish harvesting areas in the UK due to levels of AZAs above regulatory thresholds (Dhanji-Rapkova et al., 2019). The very small size of this species (5 – 10µm diameter) makes it difficult to identify and count routinely and little is known about its ecology in Scottish waters. There have been incidents of AZAs being detected in larger dinoflagellates (e.g., *Protoperidinium crassipes*, James et al., 2003) and ciliates (e.g., *Favella ehrenbergii*, Krock et al., 2009) presumably from having consumed *Azadinium.* Thus, the absence of this species from a particular area does not imply an absence of risk.

3.6 Yessotoxins

Yessotoxins (YTXs) are lipophilic shellfish toxins that to date, have only caused two closures of shellfish harvesting areas in the UK (Dhanji-Rapkova et al., 2019). Produced by the dinoflagellates *Protoceratium reticulatum*, *Lingulodinium polyedra, Gonyaulax grindleyii* and *G. tayloriii* there are doubts about its oral toxicity. As a result, the maximum permitted levels were increased in 2013 from 1 mg KG^{-1} shellfish tissue to 3.75mg KG^{-1} shellfish tissue. In the UK *P. reticulatum* and *L. polyedra* have been associated with the detection of YTXs in shellfish (Dhanji-Rapkova et al., 2019).

3.7 Farmed fish

The number of mortality events of farmed fish associated with HABs is likely underreported in the [IOC-ICES-PICES HAEDAT]() database, as fish farming companies are not required to formally report mortality events from HABs and often regard such information as commercially sensitive (GlobalHAB 2023). Unexpected mortality events in Scotland between 1979 and 1983 were ascribed to 'Flagellate 'X'', a small cell which at the time could not be identified but now is thought to have been a raphidophyte (type of phytoplankton) (Tett et al., 1980, Ayres et al., 1982, Gowen et al., 1987). The dinoflagellate *Karenia mikimotoi* has caused mortalities of farmed fish both in Scotland and along the south coast of England (Jones et al., 1982, Davidson et al., 2009, Baptie and Swan, 2017, Bresnan et al., 2021). Physical abrasion due to the spikey setae from diatoms (Bruno et al., 1987, Treasurer et al., 2003) and isolated incidents of potential deoxygenation caused by blooms of the dinoflagellate *Heterocapsa triquerta* and the haptophyte *Phaeocystis* (Bresnan et al., 2021) have also caused mortalities of farmed fish. There have also been verbal reports from industry of *Pseudo-nitzschia* blooms impacting fish welfare (Morro et al., 2022). Fish Farm (freshwater trout) mortalities have been reported associated with the 2023 Lough Neagh cyanobacterial blooms, pathology indicting irritation and damage to the gills.

Many fish farms perform their own phytoplankton monitoring daily to identify the risk from HAB events. Since the advent of amoebic gill disease in Scottish salmon farms, the industry has been reporting an increased incidence of impacts from algal blooms (Morro et al., 2022). This contributed to the establishment of the Farmed Fish Health Framework with a number of follow-on workshops to establish industry focused Standard Operating Procedures, training material and courses for the identification of harmful algal species (Weeks et al., 2022).

To date there have been no socio-economic studies performed to investigate the financial losses from farmed fish mortality events associated with HABs in Scotland. In 2015, a bloom of the haptophyte *Prymnesium parvum* resulted in fish kills in the Norfolk Broads (Wagstaff et al., 2021). In 2019, a bloom of the haptophyte *Chrysochromulina leadbeateri* in northern Norway was estimated to have killed 8 million salmon, totalling 14,000 tonnes, with a direct value of over 850 million NOK (~ £60million). The final figure was calculated to between 2.3 and 2.8 billion NOK (approx. £160 -£195 million) which included the revenue from the sale of the fish when fully grown, and additional societal costs associated with the clean-up and mitigation, loss of tax income and the funding of unemployment/social benefits (Kontali, 2020).

4. Cyano HABs

Cyanobacteria cause problems in freshwater and brackish systems (Lawton and Codd, 1991) however on occasion they can be transported downstream and cause problems in transitional or coastal waters. Some cyanobacteria species have the ability to fix nitrogen from the atmosphere which gives them a competitive advantage in environments when phosphate is in excess (Stal 2015). During the summer and autumn of 2023, widespread blooms of *Microcystis* spp. occurred in Lough Neagh causing dense accumulations of foul-smelling buoyant mats in areas of the lough, some of which caused concerns for human and animal welfare with acute economic impacts (Reid et al., 2024). Biomass from this freshwater HAB impacted the marine environment when it moved downstream from the lough to the coast causing the closure of businesses and beaches in the peak summer season. Water samples tested from the lough, estuarine and fully marine locations showed levels of *Microcystis* cells and cyanotoxins orders of magnitude above the World Health Organisation guidelines on several occasions. The extent of the blooms both spatially and temporally had a significant impact on businesses, tourism, potable water supply (>40% of NI drinking water) and amenity value (DAERA 2023, 2024).

5. HABs and eutrophication

In some instances, HABs and HAB events may be indicators of 'poor' or 'bad' water quality via the introduction of anthropogenic nutrient enrichment or chemical pollution, however direct attribution of this anthropogenic pressure to an increased frequency of HAB events has been difficult (Davidson et al., 2012, 2014). This is of particular relevance to policy makers as nutrient enrichment and nutrient balance are pressures that can respond to management measures. HAB events resulting from poor water quality often have a high profile with ministers and in the media due to resulting social upset. Thus, there is an onus on managers and policy makers to provide appropriate advice and to appear responsive to HAB events by employing effective management actions.

Between 2000 and 2006, there were several calls to investigate the relationship between fish farming and shellfish toxin producing HABs in Scotland. In 2000, a petition (PE96) by a member of the public to the Scottish Parliament called for an independent public inquiry into the adverse environmental effects of sea cage fish farming. In response, a review commissioned by SEPA (Tett & Edwards, 2002) distinguished algae associated with 'Red Tides' driven by nutrient input and certain physical and hydrological conditions, from shellfish-toxin producing species, for which explanations were more speculative. It was concluded that nutrient enrichment by fin-fish farming did not automatically lead to a greater risk of accumulation of algal toxins in shellfish flesh. In 2001, Scottish inshore waters were identified as potentially sensitive areas by the OSLO/PARIS (OSPAR) Commission Eutrophication Task Group due to increasing levels of fish farm activity. As a result, Scotland was required to undertake a eutrophication assessment of aquaculture 'hotspots' following the Harmonised Assessment Criteria of the Comprehensive Procedure (OSPAR Commission 2003). Two reports by independent experts were commissioned (Rydberg et al., 2003, Smayda, 2006) alongside a series of four cruises to examine environmental variables in sea lochs where fish farms were located (Gubbins et al., 2003). These three initiatives found no relationship between fish farms and shellfish toxin producing species in Scottish waters. A recent statistical based study also found no relationship between stock density in salmon farms in Scotland and closures of shellfish harvesting areas due to toxin producing HAB species (Gianella et al., 2023).

Improved understanding of the dynamics of shellfish toxin producing HAB species, revealed that their life history strategies, modes of nutrition, relationship with physical conditions and the influence of weather meant that a universal relationship between nutrient levels/ratios and the presence of HAB and HAB impacts in UK waters was not possible to attain (Gowen et al., 2012). In particular, the complex feeding mechanism of the dinoflagellate *Dinophysis* impacting community ecology (Park et al., 2006, Mitra, 2024, Reguera et al., 2024), as well as studies that highlight the role of physical processes, transport and wind-driven advection in the accumulation of high cell densities of harmful species (Whyte et al., 2014, Gillibrand et al., 2016, Brown et al., 2022, Dees et al., 2023) makes a straightforward relationship between nutrients and the presence of HAB species and in particular harmful algal events difficult to ascertain. In the recent OSPAR Quality Status report, chlorophyll 'a', used as a proxy for high phytoplankton biomass, and dissolved oxygen, a potential indicator of microbial activity during bloom die off, were the only HAB based indicators used in the eutrophication assessment (Devlin et al., 2024). Currently, discussions are underway to investigate plankton biodiversity indicators (McQuatters-Gollop et al., 2019) to support eutrophication assessments. While the direct link between eutrophication and toxin forming HABs is difficult to identify, there is no doubt that an increase in nutrients can lead to an increase in phytoplankton abundance and potential impacts on the marine environment. Thus, reduction of nutrients is still a relevant and important strategy for the reduction of HABs, particularly high-biomass bloom forming HAB species.

6. HABs and climate change

The relationship between HABs and climate change in UK waters is complex and has been reviewed as part of the UK Marine Climate Change Impact Partnership (MCCIP) assessments (Bresnan et al., 2013, 2020). Initially it was thought that climate change would promote the incidence of HABs via increased stratification, and new HAB species would be detected in UK waters as they warmed, however the situation has proven to be more complex (Bresnan et al., 2017a). Over the last 20 years, several studies in the UK have flagged the importance of physical and oceanographic processes in the transport of HAB species in water currents to coastal areas where they can impact humans coastal ecosystems and associated industries (Davidson et al., 2009, Gillibrand et al., 2016, Brown et al., 2020, Brown et al., 2022). The physical transport of HAB species by oceanographic processes, along with the formation of thermal fronts to permit/restrict entry of HAB species into sea lochs (Paterson et al., 2017), and the role of wind driven advection transporting cells from offshore to coastal areas (Whyte et al., 2014, Dees et al., 2023) means a simple relationship between HABs and climate change is difficult to define. Studies using data from the Continuous Plankton Recorder (CPR) Survey have shown changes in the regional distribution of *Dinophysis* in the North Sea on a multi-decadal scale (Edwards et al., 2006) while Hinder et al. (2012) attributed an increase in *Pseudo-nitzschia* spp. in the North East Atlantic with increasing sea surface temperatures (SST) and wind speed, also observing a negative correlation between dinoflagellates and increasing SST. An investigation into the relationship between shellfish toxin producing species and environmental variables (SST, North Atlantic Oscillation (NAO) index and wind) in Scotland revealed a significant positive relationship between *Alexandrium,* PSTs and the NAO and a negative correlation between *Dinophysis* and wind (Gianella et al., 2021). This study also highlighted the difficulties in performing these analyses on a national level and flagged the requirement to study HABs on a regional scale.

Long term prediction of HAB species abundance and impact is difficult (Gobler et al., 2020). Gobler et al. (2017) predicted an increase in the growth rate of *D. acuminata* in the North-East Atlantic and North Sea modelling growth rates derived from laboratory-based experiments, however using data from the CPR Survey, Dees et al. (2017) showed that peak *Dinophysis* spp. abundance in the waters around the UK was observed in the 1970s/80s and has since shown a subsequent decline.

A focus on HABs and climate change should be considered in the context of the changing plankton communities in the North East Atlantic. In the North Sea, three ‘regime shifts’ in the phytoplankton community have been identified since the 1960s; in the 1960s (with the least data) associated with changes in the seasonality of the diatom genus *Chaetoceros*; during the 1980s characterised by an increase in phytoplankton biomass circa 1984 (Beaugrand et al., 2004) driven by a period of rapid warming; and from 1996 – 2003, where a declining phytoplankton biomass has been associated with the combined effects of increasing temperatures and declining river flow (Djeghri et al., 2023). This highlights the complex influence of climate change on the phytoplankton and mixoplankton communities over multidecadal scales. Recent studies and assessments have flagged the decline in diatom abundance in the waters to the west of the UK, while increasing in the North Sea (Bedford et al., 2020a, Edwards et al., 2022, Holland et al., 2023). CPR Survey data also shows a decline in abundance of thecate dinoflagellates, potentially due to warming and ocean circulation processes (Bedford et al., 2020a, Holland et al., 2023, Kléparski et al, 2024), however this trend has not been observed at coastal fixed-point stations in the UK (Bedford et al., 2020a, Holland et al., 2023). (Thus, HAB species are components of a plankton community experiencing changes at a community level, and changes at the HAB genus/species level must be considered in this context.

Ocean acidification (OA) is causing a decline in pH in surface waters of the North Atlantic (Findlay et al., 2022). While empirical studies suggest that the chemical processes involved in increased CO_2 uptake by the oceans may influence the competitiveness of some phytoplankton and HAB species (Raven et al., 2020, Wells et al., 2020) there have yet to be any dedicated studies performed on HABs and OA in UK waters.

7. HABs and higher trophic levels

Records of PSTs impacting marine mammals and other components of the food web in the UK are scarce. The 1968 PST event in the Northeast of England was associated with mortalities of seabirds (Coulson et al., 1968) and potentially sand eels (Adams et al., 1968). Since then, no animal mortalities had been associated with PSTs until Dec 2017 – Jan 2018, when a number of canine fatalities occurred in the Southeast of England. The dogs had consumed dead star fish, flat fish and crabs that had been washed ashore during a winter storm (Turner et al., 2018). This incident is considered unusual, as *Alexandrium* is only observed occasionally in the area during routine phytoplankton monitoring, the event occurred in winter when *Alexandrium* does not bloom, and PSTs have not been recorded in shellfish from this region since routine chemical testing began in 2008. A recent study has found PSTs in a diverse range of benthic animals in the North Sea from the Southern Bight to the Shetland Islands including starfish, brittlestars, sea urchins and byrozoans, with the sea star *Crossaster papposus* found to contain detectable PSTs in samples collected around the English coast and Oban, Scotland (Dean et al., 2020, Dean et al., 2021), however, the relationship with *Alexandrium* abundance in these areas has yet to be fully investigated.

Declines in populations of Scottish harbour seals have also been linked to the presence of PSTs and ASTs in clinical samples and excreta, evidencing animal health impacts in marine mammals following consumption of contaminated fish and/or shellfish (Hall and Frame 2010, Jensen et al., 2015). A small study investigating the presence of ASTs in copepods at Stonehaven in the Northeast of Scotland found them in every sample analysed suggesting that algal toxins are readily passed through the food web (Cook et al., 2020). This is supported by an *ad hoc* study of algal toxins in fish from Scottish waters which has shown the presence of DSTs, PSTs and ASTs in fish, including areas such as Orkney and the east coast of Scotland where there is little shellfish toxin monitoring (Kershaw et al., 2019). A recent modelling study in Scotland showed the potential for amnesic shellfish toxins in fish prey to represent a risk to harbour seals (Hall et al., 2024). The role of algal toxins as an additional pressure in recent 2021 Guillemot mortality event in Scotland (Fullick et al., 2022) is currently being reviewed.

8. HABs and natural capital

As previously discussed, ‘harmful algae’ and HABs are not discrete entities within nature, but human-centred categories for ecological processes that adversely impact human welfare. Thus, they may appropriately be considered, using both monetary and physical accounting, in a natural capital framework:

- **Effect of HABs on ecosystem services:** HAB events cause biophysical and psychosocial harms, some of which should be costed as distinct items in national accounts, while others are already included as they have reduced the calculated value of ecosystem services.
- **HABs and natural capital:** whereas the monetary value of natural capital is calculated from the net present value (NPV) of ecosystem services, the physical value of natural capital assets might be altered by changes in the frequency and intensity of HAB events; increases in such events might be symptomatic of anthropogenically disturbed ecosystems and might themselves cause further disturbance.

Currently the negative costs associated with HABs are not included in UK monetary accounting of ecosystem services made according to the UN System of Environmental-Economic Accounting (SEEA) (UN 2021). They are, however, deemed includable amongst 'Nature's Contributions to People' (NCP)(Diaz et al., 2018).

Drawing on Office of National Statistics sources, Tett et al. (2024) reported that plankton contributed positively towards the provisioning, regulating and cultural services provided by UK seas, with an annual value of £3.24 billion and a NPV of £152 billion in 2019 prices. Harms were not explicitly accounted.

A recent study showed that an increase of 1% in the incidence of *Dinophysis* would result in a cost of £1.37 million in enforced closures of harvesting areas in a Scottish industry annually turning over £10.1 million (Martino et al., 2020). Applying Martino's conclusions to the entire UK mussel-farming industry gave an estimated annual loss of £4.1 million, thus reducing by 15% the resource rent estimation of the ecosystem provisioning service provided to shellfish aquaculture by phytoplankton. Using estimates of HAB loss per kilometre of European coast (Hoagland & Scatasta, 2006) put the UK loss at £23 million per year in 2019 prices. The total economic impact of a fish kill in Norway by *Chrysochromulina leadbeateri* was estimated to be 2.3 – 2.8 billion NOK (approx. £160 – 195 million) once the full losses of revenue associated with the sale of the fish when mature and costs associated with clean-up and unemployment payments were included (Kontali, 2020).

Health costs need separate accounting. Extrapolating data from Hinder et al., (2011) on the estimated number of HAB illnesses a year in the UK and Guest et al., (2020) on NHS costs, the potential cost of HAB food poisoning to the NHS is estimated at ~ £300K per year. Losses associated with other shellfish toxins, public upset when seeing scums or foams or dead animals associated with HABs have yet to have a financial cost associated with them although the societal impact has been acknowledged (Willis et al., 2018). Some of these effects might be valued as a depreciation to cultural services.

While negative costs associated with HAB impacts may seem trivial in the context of total provisioning value that plankton provide, in some instances, impacts such as mortalities from fish farms are experienced in remote, rural locations with little other sources of employment and where fish farm employment present high value jobs for local communities (Krause et al., 2020). A recent global workshop on the costs of HABs flagged the financial burden currently carried by reinsurance industries and the collapse of a large company in Korea due to the volume of payouts to cover financial losses in the aquaculture industry due to HABs (Trainer et al., 2020). Gianella (2023) calculated a 'risk index' associated with HABs and fish farms for Scotland and identified the island regions, Shetland, Orkney, Western Isles as being at the highest risk due to their small populations and dependence on the aquaculture industry for local employment. There will be a benefit to policy makers from calculating the total cost of HAB impacts in UK waters, as it will identify the value of investment into management and mitigation measures to reduce the financial impact from HABs.

Finally, the topic of harms to ecosystems themselves needs more analysis. As already described, some algal blooms provide crucial inputs of food to marine food webs, and impacts of toxic algae on marine vertebrates, or of oxygen sag caused by bloom decay, are to some extent natural components of marine ecosystem functioning. What we need to know is to what extent increases in the frequency and intensity of HAB events (if any) are merely symptoms of anthropogenically disturbed marine ecosystems, or whether they contribute to this disturbance and thus decrease ecosystem resilience to the effects of human activity. It isn't obvious, how to quantify such effects in monetary terms. One approach, currently hypothetical, might be to evaluate the costs of insurance against greater volatility in ecosystem services.

9. HABs and environmental assessment indicators and impacts

There is no dedicated 'HAB' indicator in the statutory environmental assessment portfolio. The eutrophication assessment uses high biomass (as detected via chlorophyll 'a' or low dissolved oxygen values) as an indicator of accelerated phytoplankton growth resulting in a high biomass HAB or microbial activity during HAB decay (Devlin et al., 2024). Whilst data obtained using this approach is a key data source for eutrophication assessments, it does not provide enough detail on plankton community and species shifts (Kruskopf and Flynn, 2006). Current Pelagic Habitat biodiversity indicators use a plankton life form approach to investigate changes in plankton diversity which has the potential to detect shifts in high biomass HABs such as *Karenia mikimotoi* or *Chaetoceros* spp. but in its current form will not detect changes in low biomass shellfish toxin producing HABs such as *Alexandrium* or *Dinophysis*.

As stated in section 3.0, a HAB is not a biological entity and thus it is unlikely that one single HAB life form can represent the diversity of HAB species and impacts experienced by the UK. Many shellfish toxin producing HAB genera contain both toxin and non-toxin producing species. The limitations of routine monitoring using light microscopy means that it is not possible to identify these cells to species level and it is not known if toxin producing species are present. For example, the toxin producing *A. catenella* is morphologically identical to the non-toxin producing *A. tamarense,* both of which have been recorded in Scottish waters (Brown et al., 2010). Some toxin producing species may only produce toxins in response to specific environmental conditions or in the presence of grazers (Fehling et al., 2006, Lundholm et al., 2018) and so the presence or abundance of HAB species in a sample may not be representative of the associated toxin loading present. A range of individual HAB life forms based on their ecology, life history and mode of impact may need to be developed to encompass the range of potentially different pressures which influence the development of individual HAB events.

It is becoming clear that toxin producing HABs should be considered as a pressure for higher trophic levels in environmental status assessments. While the level of investigation in the UK to date has been *ad hoc*, there is sufficient evidence to confirm the presence of algal toxins throughout the food web with the likelihood of these are causing chronic impacts or acting synergistically with other pressures (e.g. lack of prey or habitat availability) on marine mammals and sea birds. This area is under-researched and aside from the UK studies cited in section 9.0, there is only one other study in Northern Europe which investigates the link between algal toxins and marine mammals. This study focused on an unusual mass mortality event of harbour seals in Denmark and Sweden in 2007. Mollerup et al., (2024) hypothesizes that this mortality event was caused by a combination of exposure to DST toxins and bacterial infection by *Klebsiella pneumonia.*

Our understanding of the toxicity of HAB species in UK waters is mainly driven by shellfish testing and toxin producing phytoplankton monitoring as part of the EU Shellfish Hygiene Directive. As this monitoring is driven by the location and intensity of aquaculture industry effort, it leaves large portions of the east coast of England and Scotland without proper monitoring for shellfish toxins (see Figure 2(h)) despite the presence of toxin producing species. Incorporation of passive sampling methods such as Solid Phase Absorption Toxin Tracking (SPATT) and subsequent toxin analysis (Bresnan et al., 2016) may provide a solution to fill the spatial gap in this information.

10. HABs and management measures

HAB events are high profile events which garner a lot of public interest due to potential loss of earnings from affected industries as well as society's connection with the ocean (Willis et al., 2018). HAB events are often reported in the media, with government asked to provide remediation measures, advice, or financial support when livelihoods are put at risk or lost (BBC Media 2000, DAERA 2023).

10.1 HABs and 'Good Environmental Status'

Saraminaga et al., (2023) collated first thoughts on the evaluation of HABs in the assessment of 'Good Environmental Status (GES)' for the MSFD and presents a decision tree, involving setting of thresholds using local expertise, which could be used as a tool to support decision making in the determination of GES (see Appendix 2). There is a complexity to this as some HABs are naturally occurring and may be indicative of GES even though they may negatively impact the marine ecosystem or associated industry. Each HAB incidence is likely to be contextually specific with regard to species, impact, location and potential drivers and thus rather than the development of standardized tools and assessments, assessment is likely to be conducted on a region-by-region/case-by-case basis.

From a management perspective there are clear actions that policy makers can take. If a HAB event is either driven by anthropogenic pressures that can be managed (e.g. anthropogenic nutrient enrichment, introduction of invasive non-native species, creation of hydrographic structures in the water), these can be targeted to ***prevent the HAB event*** . If the HABs are natural phenomena and will not respond to a management actions, measures must be directed towards protection of human health, society, marine ecosystems, or industry to ***prevent or mitigate the impact from the HAB event***.

HAB events which do not respond to management measures should be considered as a pressure and 'prevailing conditions' in the context of statutory status assessments. This is particularly relevant for shellfish toxin producing species, as current evidence suggests that these toxins can negatively impact higher trophic levels such as sea birds and marine mammals (see Section 9.0). Figure 3 summarises management options for HABs, with blue arrows highlighting areas where actions by policy makers can influence direct inclusion of HAB events in statutory environmental assessments. Green arrows show where policy makers can implement management measures to mitigate impacts from HABs.

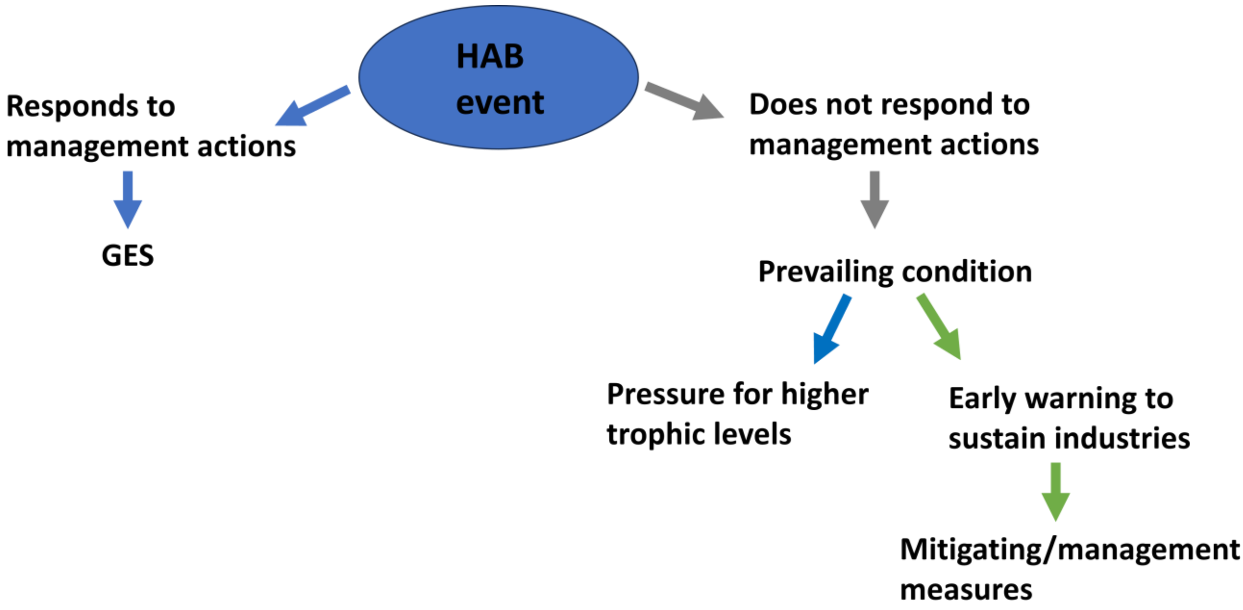

Figure 2: Summary of inclusion of HAB events in statutory environmental status assessments. Blue arrows show where management actions can influence inclusion in assessments via the development of assessment tools. Green arrows show where policy makers can implement management measures to mitigate impacts from HABs.

Actions to ***prevent the HAB*** can be factored into tools and thresholds for statutory environmental assessment, as per Saraminaga et al., (2023) (Appendix 2). Investigation of the plankton life form approach, developed for statutory biodiversity assessments (McQuatters-Gollop et al., 2019) to incorporate HABs, will support the development of relevant tools and thresholds to implement this.

Actions to ***prevent or mitigate HAB impact*** involve the development of tools to improve management decisions by industry in response to HAB events to mitigate impact. One example, promoted globally, is the development of early warning systems to warn of the potential for HAB events (FAO, IOC and IAEA, 2023). In the UK, a successful example of this is the HAB reports system employed in Shetland (Davidson et al., 2021; www.HABreports.org). This approach uses a 'traffic light approach' based on expert interpretation of current and recent cell and biotoxin concentrations and other environmental indicators such satellite derived chlorophyll and modelled current velocities. Where appropriate alerts trigger high-resolution mathematical modelling of cell advection to provide short term forecasts of bloom advection. This allows industry to make informed management decisions and implement mitigation measures should a HAB event become imminent. In the English Channel, a web-based portal tool has also been developed for the French scallop fishing fleet to highlight which fishing areas are open and closed (Chenouf et al., 2020).

New approaches can support early warning systems or provide information about HAB impact. Satellite imagery has the potential to provide wide scale spatial data to identify the extent of HABs. This has been used to identify *Karenia mikimotoi* in Scotland and the English Channel and to identify *Phaeocystis* in the southern North Sea (Davidson et al., 2009, Kurekin et al., 2014). Advanced modelling can also provide support to industry during spatial planning applications to improve locational guidance to reduce impact from HABs (Stoner et al., 2023). Further information can be found in Fernandes-Salvador et al. (2021).

Development of industry practices may help avoid impacts from HABs. Offshore locations for fish farms present opportunities to avoid competition for space in the near shore environment as well as the potential to reduce other welfare issues (Morro et al., 2022). In this context the suitability of species to the harsher offshore environment requires consideration, as does the associated increase in operational costs.

Industry reports a lack of mitigation options while experiencing impacts from a HAB. Fish farmers have limited choices: most prevalent is the reduction of feeding to reduce oxygen demand and encourage fish to disperse within the sea cages. Curtain tarpaulins and bubble curtains have had success in some regions but not others and, towing of cages to other locations if forewarned of HAB events can sometimes be implemented, however these actions do not guarantee avoidance of welfare impacts (Morro et al., 2022). Clay dispersal has had some positive results in Asia in response to high biomass blooms of *Cochlodinium polykrikoides* (now *Margalefidinium polykrikoides*) (Seger et al., 2017, Song et al., 2021) however this has yet to be investigated in European waters due to its potential environmental impacts.

Some HAB impacts, particularly visual disturbances from high biomass blooms tend to be underreported. Establishment of citizen science networks such as trialled in the *Phenomer* project in France (Siano et al., 2020) and the 'Bloomin' Algae app (CEH 2024) can provide support to monitoring agencies to identify the diversity and impacts of these HAB events, including on public perception. Citizen science can also contribute to the formal reporting of these events to dedicated databases such as IOC-ICES-PICES HAEDAT (Zingone et al., 2022).

10.2 HABs and extreme events

HABs can also cause extreme events with a wide regional range of impact such as the PST/ *Alexandrium* events in the 1960s and 1990s (Ayres 1975, Joint et al., 1997, Brown et al., 2001) and the extensive *Karenia mikimotoi* bloom in 2006 and can be natural events (Davidson et al., 2009). During 2023, blooms of *Noctiluca scintillans* in the southern North Sea were reported using satellite imagery and caused water discolouration (LabPlas 2023). Extreme mass mortality events such as the unusual crustacean mortalities in the north east of England in 2021 (Henderson et al., 2023) and guillemot mortalities in Scotland in 2021 (Fullick et al., 2022) generate a very high media profile and require an immediate response to provide advice to ministers and public. Thus they fall outside of environmental assessment reporting time frames. While informal networks spring into action when these events occur, in some instances when HABs may not be the initial consideration, there can be a delay before collecting relevant plankton samples and the chance to identify relevant HAB species may be missed.

11. Forward Look

The HAB/plankton monitoring and research communities in the UK are very active and the understanding of changes to the pelagic habitat, the dynamics of HABs and HAB events have significantly improved over the last two decades. New technologies that are currently being tested or incorporated into monitoring systems such as automated imaging technologies (Imaging FlowCytobot, FlowCam), molecular methods (qPCR and eDNA) (Campbell et al., 2010, Hatfield et al., 2023, McQuillian et al., 2023), remote sensing and advanced modelling methods are providing new insights into drivers of HABs and HAB events. These will provide valuable resources to policy makers to improve provision of advice in response to HAB events and also to improve forecasting power to mitigate impacts (Fernandes-Salvador et al., 2021, Ruiz-Villarreal et al., 2022).

Benthic HABs are poorly studied in UK waters and there has yet to be a study to examine if benthic toxin producing species are a native part of the benthic phytoplankton community. In France, a study found the palytoxin producer *Ostreopsis* cf *siamensis* was present along the Atlantic coast of France from the Basque country to the Western English channel (Drouet et al., 2021). The first incidence of respiratory irritation by *Ostreopsis* cf *ovata* was reported from the Atlantic coast of France in 2021 (Chomerat et al., 2022, Paradis et al., 2024) suggesting the potential for new events which pose a risk to human health and impact recreational use of the oceans along the Atlantic coasts of Europe.

The seas around the UK will experience a significant increase in the number of offshore wind structures in the coming decades. These structures have the potential to alter the physical structure of the water column by increasing wakes of turbulence around wind turbine structures, or removal of wind energy from the atmosphere by the rotating turbines (Dorrell et al., 2022). Over a regional sea scale e.g. the North Sea, this has the potential to drive changes in bottom up (e.g. Orkney and Shetland) or top down (Southern North Sea) control of the ecosystem (Trifonova and Scott, 2023). There has yet to be a dedicated study on HAB species but changes in seasonal stratification will impact the preference of different HAB species (diatoms, increased turbulence), mixoplankton (decreased turbulence), with potential knock on impacts on community composition. Wind turbines also have the potential to act as habitat for benthic/epiphytic HAB species which are poorly studied in UK waters.

12. Recommendations

To date, a joined-up approach to address issues from HABs is lacking in the UK, with policy and legal thinking dividing HABs and their impacts into human health protection or local water quality issues. This has hampered the inclusion of HABs and impacts into statutory status assessments. In part, this has been due to the complexities around the concepts of different HAB types and the delineation between the status of HABs and potential negative impacts. Moving forward there are several recommendations to support the inclusion of HABs in statutory status assessments and management measures to support industries from negative HAB impacts;

12.1 Monitoring and assessment

- The current plankton life form approach used for the UK Marine Strategy and OSPAR Quality Status Assessment should be investigated to identify how best to include HABs into statutory status assessments. There is unlikely to be a single generic ‘HAB’ lifeform indicator. The presence of a HAB may still meet ‘good’ status despite the HAB having a negative impact.

- Toxins produced by HABs that accumulate in shellfish flesh are present within the marine food web and thus pose a threat to higher trophic levels (e.g. marine mammals, sea birds). Shellfish toxins should be included as a pressure for higher trophic levels in future environmental status assessments.

- Benthic HABs are poorly studied in the UK. There is merit in identifying which benthic HAB species are currently present to inform management plans should they begin to present problems.

- The freshwater cyanobacterial blooms in Lough Neagh, Northern Ireland have resulted in cyanotoxins being detected at unsafe levels in both estuarine and coastal locations on the Atlantic coastline. A joined up management approach between land use, freshwater and marine agencies is required to deal with this issue especially in areas with significant agriculture, wastewater or industry.

- Citizen science approaches to report the impacts from HABs should be explored and encouraged.

- Increased collaboration and data sharing with the fish farming industry is required to better quantify the HAB events occurring at salmon aquaculture sites in Scottish waters and the resultant health and economic impacts. This would allow the development of improved mitigation approaches, particularly given that HABs are likely one of several causes of complex gill disease and hence the relationship between HAB events and fish health is unlikely to be linear. Improved data sharing between aquaculture companies is also likely to provide a collective benefit, but requires approaches to its implementation that do not impact commercial confidentiality.

12.2 Management and measures

- Options to mitigate the impact from HABs are limited and confounded by climate change and ocean acidification. Accordingly, further investigation of mitigation measures is encouraged.

- A socio-economic study on the impacts from the different HAB types experienced across the UK needs to be performed to identify the value of investment in improving management and adaptation measures to reduce HAB impacts.

- The influence of offshore wind structures on HAB dynamics should be included in development plans.

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Appendix 1

Table A1.1 Toxin producing HAB species recorded in the UK (from Bresnan et al., 2021)

Species	UK
PST events	
Alexandrium catenella (Whedon & Kofoid) Balech, 1985	◆
Alexandrium minutum Halim 1960	◆
Alexandrium ostenfeldii (Paulsen) Balech and Tangen 1955	●
DST events	
Dinophysis acuminata Claparède & Lachmann, 1859	◆
Dinophysis acuta Ehrenberg, 1859	◆
Dinophysis caudata Saville-Kent 1881	●[1]
Dinophysis fortii Pavillard 1924	●[1]
Dinophysis infundibulum J.Schiller 1928	●[1]
Dinophysis norvegica Claparède & Lachmann, 1859	●
Dinophysis ovum (F.Schütt) T.H.Abé	●
Dinophysis tripos Gourret, 1883	●[2]
Phalacroma rotundatum (Claparéde & Lachmann) Kofoid & J.R.Michener, 1911	●
Prorocentrum lima (Ehrenberg) F.Stein, 1878	●
AZA events	
Amphidoma languida Tillmann, Salas & Elbrachter, 2012	●
Azadinium poporum Tillmann & Elbrächter, 2011	●
Azadinium spinosum Elbrächter & Tillmann, 2009	●
YTX events	
Gonyaulax spinifera (Claparède & Lachmann) Diesing, 1866	●
Lingulodinium polyedra (F.Stein) J.D.Dodge, 1989	●
Protoceratium reticulatum (Claparède & Lachmann) Bütschli 1885	●
Other	
Prorocentrum cordatum (Ostenfeld) J.D.Dodge, 1975	●
AST events	
Halamphora coffeaeformis (C.Agardh) Levkov, 2009	●
Pseudo-nitzschia australis Frenguelli, 1939	◆
Pseudo-nitzschia caciantha Lundholm, Moestrup & Hasle, 2003	●
Pseudo-nitzschia calliantha Lundholm, Moestrup & Hasle, 2003	●
Pseudo-nitzschia cuspidata (Hasle) Hasle, 1993	●
Pseudo-nitzschia delicatissima (Cleve) Heiden, 1928	●
Pseudo-nitzschia fraudulenta (Cleve) Hasle, 1993	●
Pseudo-nitzschia multiseries (Hasle) Hasle, 1995	●
Pseudo-nitzschia plurisecta Orive & Pérez-Aicua, 2013	●
Pseudo-nitzschia pseudodelicatissima (Hasle) Hasle, 199	●
Pseudo-nitzschia pungens (Grunow ex Cleve) G.R.Hasle, 1993	●
Pseudo-nitzschia seriata (Cleve) H.Peragallo, 1899	◆
Pseudo-nitzschia subpacifica (Hasle) Hasle, 1993	●
Ichthyotoxins and other fish killing/benthic mortality mechanisms	

Karenia brevis (C.C.Davis) Gert Hansen & Moestrup, 2000	● [1]
Karenia mikimotoi (Miyake & Kominami ex Oda) Gert Hansen & Moestrup, 2000	◆
Karlodinium veneficum (D.Ballantine) J.Larsen, 2000	● [3]
Fibrocapsa japonica S.Toriumi & H.Takano, 1973	●
Heterosigma akashiwo (Y.Hada) Y.Hada ex Y.Hara & M.Chihara, 1987	◆
"Flagellate X"	●
Prymnesium calathiferum Chang & Ryan, 1985	
Prymnesium parvum N. Carter, 1937	●
Prymnesium polylepis (Manton & Parke) Edvardsen, Eikrem & Probert, 2011	●

◆ Dominant species associated with HAEDAT events
● Species recorded

[1] Recorded in Parke and Dixon, (1976)
[2] Infrequently observed
[3] Isolated by Parke, 1950 (Bergholtz et al., 2006)

Appendix 2

HAB decision tree for determining Good Environmental Stratus (GES) (from Sariminaga et al., 2023)

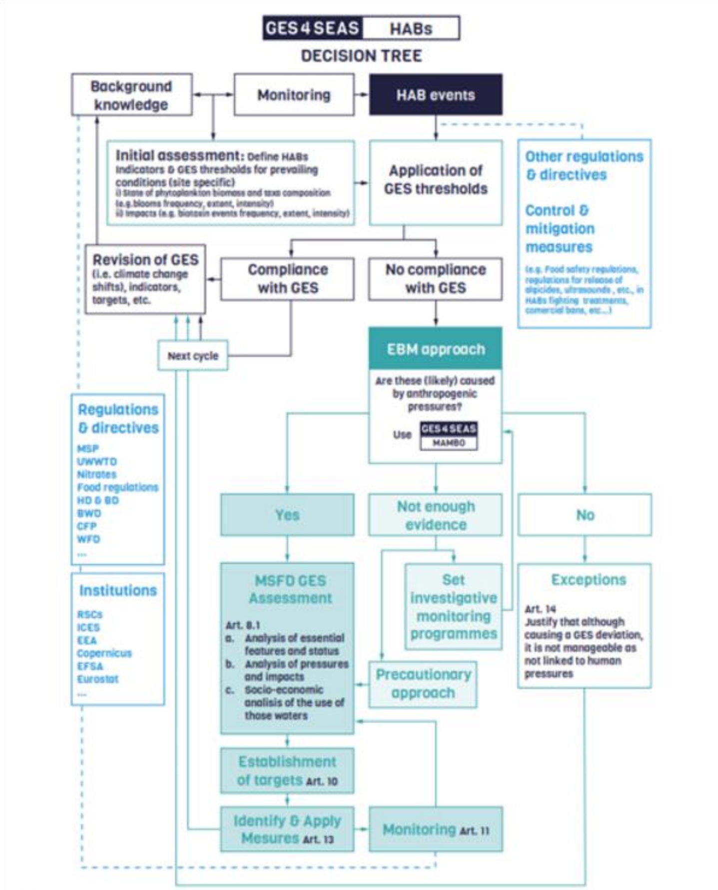

FIGURE 1
GES4HABs Decision tree to guide policy makers and Marine Strategy Framework Directive (MSFD) stakeholders on the steps and decisions to support management and MSFD reporting actions related to different Harmful Algal Blooms (HABs) in their jurisdiction areas. GES, Good Environmental Status; EBM, Ecosystem-Based Management; RSC, Regional Seas Conventions; ICES, International Council for the Exploration of the Sea; EEA, European Environment Agency; EFSA, European Food Safety Authority; Eurostat, Statistical office of the European Union; MSP, Maritime spatial planning; WFD, Water Framework Directive; UWWTD, Urban Waste Water Treatment Directive; Nitrates, Nitrates Directive; HD and BD, Habitats Directive and Birds Directive; BWD, Bathing Water Directive; CFP, Common Fisheries Policy; MAMBO, environMental mAtrix for the Management of BlOoms (see Figure 2).