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Harmful Algae

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Abstract :

This chapter provides the first overview of the disruptive impacts of HABs on the blue economy, with a particular focus on the application of science and technology in their management and mitigation. We present case studies of HABs in five different locations as examples of their effects on different sectors of the blue economy. We also review the main technological advances in recent decades, and current needs for improved understanding of HAB dynamics, monitoring, and forecasting. An evident gap in dealing with HABs in the frame of the blue economy is the inequity in resources available for monitoring worldwide. While developed countries count on advanced (and even impressive) tools for monitoring and early warning (e.g., automated tools, oceanographic moored instruments, forecast models), efficient monitoring in most developing countries is still missing and, when performed, mainly focused on seafood products intended for export. Basic research on HABs in these countries is also frequently deficient, with modeling capabilities for early warning virtually non-existent. Considering that many (truly) sustainable blue economy activities are developed precisely in vulnerable areas with low economic power, the need for the development of affordable and sustainable technologies becomes critical, allowing for the efficient monitoring of HABs.

Keywords : HAB, Fisheries, Aquaculture, Human health, Early warning systems, Observations, Monitoring, Impact on Blue Economy

1 Introduction

The blue economy concept is increasingly becoming the new paradigm for exploitation of the ocean and coastal areas. Based on the three dimensions of sustainable development (i.e., economic, social, and environmental), it "*seeks to promote economic growth, social inclusion, and the preservation or improvement of livelihoods while at the same time ensuring environmental sustainability of the oceans and coastal areas*" [1]. The blue economy idea encompasses many established ocean industries, such as fisheries, aquaculture, tourism, maritime transport, as well as emerging activities, including offshore renewable energy, seabed extractive activities, and marine biotechnology. It also comprises ecosystem attributes lacking tangible monetary value but with many socio-economical impacts on human activities such as biodiversity, natural coastal habitat, and carbon sequestration.

The term harmful algal bloom (HAB) applies to the proliferation of micro- or macroalgae perceived as harmful by humans [2]. Given that there is no consensus on what a harmful bloom is, the best definition would be a sufficiently high concentration of an algal species causing adverse effects, either from microalgal-derived toxins (i.e., phycotoxins) or due to adverse effects caused by high algal biomass [3]. HABs are broadly considered as natural events known from historic times, with many examples reported between the 1200s and the 1700s [4-6], with a perceived global increase in their frequency and geographical distribution in recent decades linked to the effects of human activities such as eutrophication, ballast waters, coastal urbanization, ocean acidification and global warming [7-10]. While a recent analysis of the global HAEDAT database (http://haedat.iode.org) suggested that intensified monitoring efforts associated with increased aquaculture production are responsible for the perceived worldwide increase of HABs [11], there are documented increases in some HABs regionally [12], frequently linked to different pressures such as excessive nutrient loading [8,13-16]. Similarly, the analysis of long-term regional time series shows an increasing number of extraordinary HAB events associated with extreme weather conditions [17-20]. A general consensus thus exists that HABs will continue to expand and/or intensify in at least some regions due to global climate change induced by both natural and anthropogenic forcing [9,21].

Much scientific effort has been exerted in recent decades to estimate the socio-economic impact of HABs [e.g., 22,23]. Most of these studies have been mainly focused, however, on sectors of society for which the economic losses are relatively more evident, such as fisheries, aquaculture, and human health, with very few assessments so far accounting for possible interactions across these sectors and how they can affect and be affected by the well being of coastal communities and/or ecosystem services (e.g., [24-26]). Although HABs are broadly identified as one of the major threats to the ocean and human health as well as to the development of sustainable activities [27-29], up to now, no review has been entirely focused on HABs as deterring agents of the blue economy. This chapter aims to provide the first overview of the disruptive impact of HABs on sustainable development, with a particular focus on the application of science and technology advancements in the management and mitigation of HABs to facilitate the implementation of blue economy goals.

2. Impacts of HABs on the blue economy: case studies

The number of potentially harmful algal species is remarkable: about 200 species (from the several thousand described phytoplankton species) belonging to different phylogenetic groups and exhibiting diverse physiological and ecological characteristics [30,31]. The diversity of hazardous impacts they have on the social, economic, and environmental dimensions of the blue economy is also remarkable (Fig. 10.1). The successful management and mitigation of HAB threats and, in some cases, the efforts to prevent their occurrence are thus fundamental for achieving several indicators related to the Sustainable Development Goals (SDGs) of the Agenda 2030 (related to the 2021-2030 United Nations Decade of Ocean Science For Sustainable Development) that are closely related to the blue economy [32], such as food security (SDG 2), human health (SDG 3), water supply (SDG 6), sustainability (SDG 11), climate change (SDG 13), and aquatic ecosystems (SDG 14).

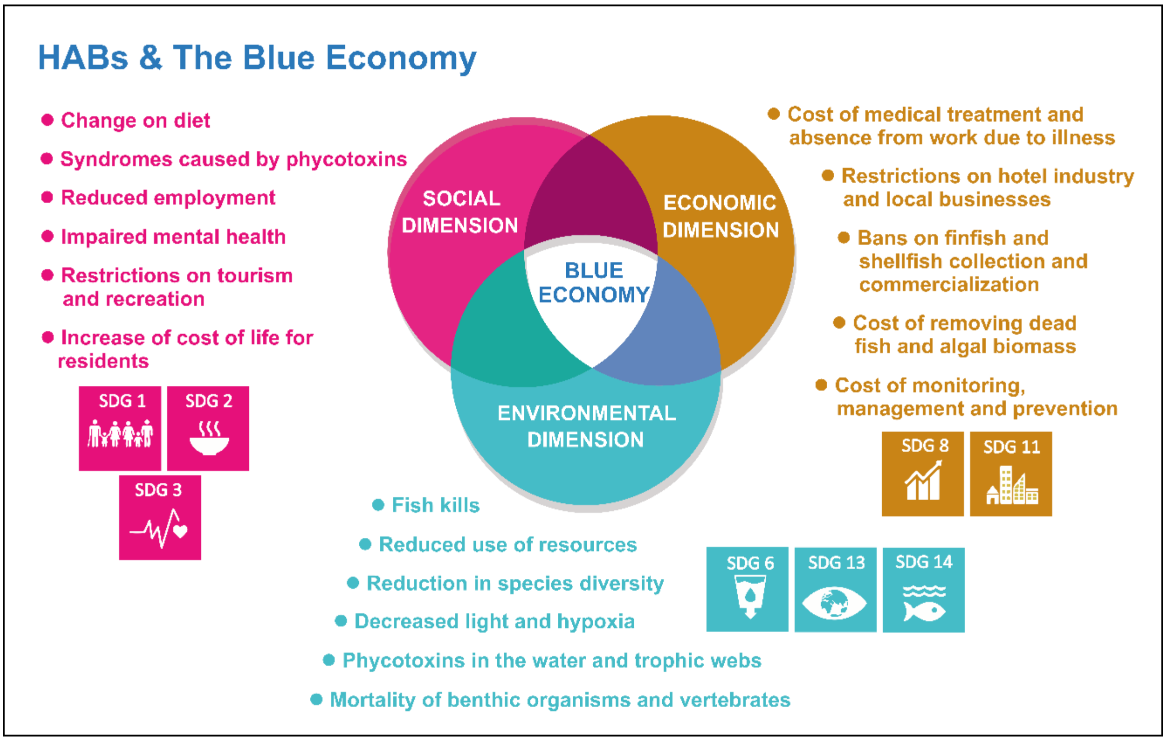

Fig. 10.1. Negative effects of harmful algal blooms (HABs) on the economic, social, and environmental dimensions of the blue economy and their interactions to some indicators of the Sustainable Development Goals (SDGs) of the United Nations Agenda 2030.

Thirty-four major phycotoxin groups have been described to date [33], with about 600 toxins produced by marine microalgae estimated so far (P. Hess, pers, comm.). Toxic microalgae have severe adverse effects, varying from fish kills and wildlife deaths to human syndromes caused by consumption of seafood contaminated with phycotoxins accumulated throughout the food web, as well as by direct contact with phycotoxins in the water or aerosol in the air (see [34] for a review of all human syndromes caused by phycotoxins and their symptoms). Proliferations of non-toxic algal species can cause fish kills by mechanical damage of gills or the production of reactive oxygen species [35]. Blooms of non-toxic algae can harm other aquatic organisms by decreasing sunlight penetration in the water column or causing anoxic conditions as a result of the degradation of high algal biomass [29,36,37]. HABs also impair ecosystem services by decreasing species diversity, resulting in reduced operationally defined resource use efficiency (defined as the ratio of phytoplankton biomass to total phosphorus) in coastal plankton assemblages [38].

Adverse effects of HAB organisms have significant socio-cultural and economic consequences resulting from bans on finfish and shellfish collection and commercialization, restriction of tourism and leisure activities due to the closure of beaches, as well as additional costs related to medical treatment of the human syndromes caused by phycotoxins and increased monitoring activities [39]. The proliferation of certain macroalgae has emerged as a problem for tourism, maritime activities, aquaculture, and artisanal fisheries in the last two decades. Examples are the massive proliferations of green algae (*Ulva prolifera*) in the Yellow Sea [40], mainly related to coastal eutrophication, and the influx of *Sargassum* spp. in the Caribbean Sea and Atlantic coasts of Africa [41]. In the open ocean, pelagic *Sargassum* species (*S. natans* and *S. fluitans)* serve as critical habitats for numerous species of fishes and invertebrates. However, since 2011, massive proliferations of *Sargassum* species have occurred in the Atlantic basin, from the Gulf of Guinea, throughout the North Equatorial Recirculation Region (NERR), including the Caribbean Sea and the Gulf of Mexico (42). These “brown tides” accumulate in bays, shallow waters and beaches, causing extensive near-shore “dead zones,” wildlife mortalities, economic losses to coastal fisheries and tourism, and human health impacts associated with hydrogen sulfide toxicity (42-43). Some uses of *Sargassum* biomass have been proposed, from fertilizers to papers, bioplastics, and cosmetics (44).

In addition to economic losses, fishery bans reduce employment opportunities and impair cultural identity as well as the physical and mental health of individuals [45]. Adverse effects of HABs on desalination plants may also potentially have severe socio-economic impacts, particularly in many arid and island countries, where desalination of seawater makes a significant contribution to the drinking water supply [46].

The nature of blue economy activities and the magnitude of HAB impacts have one thing in common: they depend strongly on the local environmental and socio-cultural context. As a consequence, the negative effects of HABs on the blue economy must be assessed locally (Fig. 10.2), as they depend on the interplay of several factors defined on a regional scale such as the characteristics of the individual HAB species, oceanographic features, economic activities, and socio-cultural practices. The next sections present some case studies to illustrate the effects of HABs on the blue economy.

Fig. 10.2. Examples of local blue economy activities affected by harmful algal blooms (HABs). Bloom (A) and salmon mortality (B) caused by *Heterosigma akashiwo* in a fjord in Southern Chile; Bloom of *Ostreopsis* covering benthic organisms in the Mediterranean Sea (C); Fisherman communities affected by HABs in the Frech Polynesia (D) and Philippines (E). Photo credits: (A) Fundación Huinay; (B) Álvaro Vidal; (C) Elisa Berdalet and Magda Vila; (D) Mireille Chinain; (E) Aletta T. Yñiguez

2.1 Chilean fjords

Shellfish and finfish farming are the main aquaculture activities in Chile traditionally threatened by HABs [47]. In the case of shellfish aquaculture, total mussel production reached ~370,000 t in 2018, equivalent to USD $7,000 M in exports [48]. Thus, phycotoxins that are potentially bioaccumulated in the seafood not only pose human health risks, but also result in important economic losses for the industry due to commercialization bans. Patagonian fjords are a hotspot for salmon aquaculture, positioning Chile as the world's second-largest producer of farmed salmon, after Norway [49], a condition that highlights the need to develop strategies for sustainable aquaculture improvement and management. This productive activity has greatly suffered from the effects of recurrent and intense HAB events in Chilean fjords in recent decades, with annual losses running into millions of dollars [50].

Four known and monitored human health syndromes related to phycotoxin ingestion are found in Chile: diarrhetic shellfish poisoning (DSP), amnesic shellfish poisoning (ASP), azaspiracid shellfish poisoning (AZP), and paralytic shellfish poisoning (PSP) [50]. The latter, caused by blooms of the dinoflagellate *Alexandrium catenella*, has caused 35 fatal cases and about three hundred human intoxications since its first detection in 1972 in southern Chilean Patagonia. The length of shellfish farm closures due to PSP toxins has varied with the intensity of HAB events. These events have negatively affected the value of these aquaculture products in several ways [50]: 1) reduced demand by consumers due to fears about seafood safety, 2) delay of the harvest to a point where shellfish are larger than their optimal marketable size, 3) inability to supply during peak demand periods, and 4) effects on the ability to use gear and space to begin growing new cohorts.

Although HABs have been recorded in the Chilean fjords since the 1970s, an apparent increase in the intensity and distribution of some HAB species has been observed in the last decade. Eutrophication resulting from aquaculture has been proposed as the principal causative factor of this increase. Intensive aquaculture activities (i.e., salmon cage-farming) may produce an inevitable rise in nutrient loading (and changes in nutrient ratios) through the addition of food and salmon excretions. The overall effect of high nutrient loads can be made worse by global warming, which has triggered a dramatic decrease in precipitation and streamflow in southern Chile during the last decade [51,52]. Drastic and sustained reductions in precipitation and river discharges alter the nutrient stoichiometry by reducing surface silica loading into the fjords, which have been proposed as a cause of increased HAB species occurrence in Chilean fjords [52-54]. Of significant concern for the scientific community is the fact that several of the recent HAB events occurred in sounds and fjords with longer retention times (121 to 200 days), where nutrients and phycotoxins can persist for more extended periods [17].

Exceptional conditions in the coast and open ocean produced by the positive phase of the Southern Annular Mode (SAM) and an extreme El Niño event coincided with the 2016 'Godzilla-Red tide events' that included several successive HAB events, resulting in the most extensive fish farm mortality ever recorded worldwide and created a vast socio-environmental impact in the region by affecting artisanal fisheries (blue mussels, oysters, clams) [21]. The first HAB caused by the dictyochophyte *Pseudochattonella verruculosa* killed farmed salmon, with losses for the Chilean salmon industry amounting to USD $800 M [17]. Subsequently, an *A. catenella* bloom affected 600 km of benthic artisanal fisheries due to a 4-month closure of 200 shellfish farms (~15% reduction in harvest compared to 2015) [47]. Two years later, in summer 2018, a new outbreak of *A. catenella* involving an intense PSP event occurred, which resulted in world record PSP shellfish toxicity (143,130 μg STXeq. 100 g^{-1} shellfish) [50]. Moreover, the end of the La Niña event and a positive phase of SAM during summer-fall 2021 produced the second driest season in the last 70 years, which coincided with a massive *Heterosigma akashiwo* bloom (>70,000 cells mL^{-1}) in the Comau fjord (Fig. 10.2 A-B) that caused the mortality of more than 8,000 t of salmon (Mardones et al., unpub. data).

Climatic anomalies have also triggered 'super blooms' of opportunistic toxic dinoflagellates of the genera *Karenia* and *Karlodinium* in outer waters off Patagonia. Unlike known phycotoxins (e.g., PSP, ASP, and DSP toxins), the potent cytotoxins produced by these dinoflagellates affect the gill and other sensitive tissues of marine organisms [55] and can kill a wide variety of marine organisms, ranging from marine mammals (i.e., baleen whales) to small invertebrates [55,56]. Blooms of cytotoxic HAB species may produce severe effects on the recruitment and growth of juvenile and adult wild species, negatively affecting artisanal fisheries. No studies have measured the impact of these types of HABs on non-cultured marine wildlife.

2.2 **Ostreopsis** *spp. in the Mediterranean Sea*

Since the end of the 1990s, blooms of benthic dinoflagellates of the genus *Ostreopsis* have become recurrent in several Mediterranean beaches (Fig. 10.2C). Initially reported in tropical areas, *Ostreopsis* species have expanded their biogeographic distribution to temperate latitudes (recently reviewed by [57]). Blooms of these benthic dinoflagellates threaten human health and the environment. In the context of the blue economy, these blooms have direct costs related to human health assistance and can cause economic losses related to tourism activities.

Ostreopsis blooms have been associated with mild acute respiratory illness, and skin and mucosa irritation in humans [58]. Palytoxin-analogues produced by this dinoflagellate have been proposed as the causative agent of these problems, although their direct implication is yet to be demonstrated [59]. Previously, in the tropics, *Ostreopsis* toxins had been associated with rare, but dramatic, seafood poisonings. In the Mediterranean, respiratory irritations occurred massively in Genoa (Italy) when 200 people were reported to the hospital with symptoms of rhinorrhea, cough, wheezing, and fever [60,61]. Epidemiology studies [62,63], and the experience of researchers during sampling (e.g., [64]), indicate that direct exposure to high *Ostreopsis* cell concentrations in seawater or aerosols during blooms of these dinoflagellates can result in mild acute symptoms. The effects of chronic exposure to toxic *Ostreopsis* blooms are still unknown. The potential health risks posed by blooms of *Ostreopsis* species stimulated the regular monitoring of these events in some areas, leading to occasional beach closures [65,66]. Some blooms have also been linked to massive mortalities of benthic fauna [62,67].

The available evidence indicates that people experienced *Ostreopsis*-related symptoms mainly during a particular stage of the bloom period, suggesting that toxicity is related to specific physiological conditions of the blooming cells [62,63]. Based on that, alert thresholds of *Ostreopsis* abundances corresponding to high risk of impacts on human health have been established (5×10^5 cells g^{-1} of FW macroalgae and 3×10^4 cells L^{-1}, in the benthos and plankton, respectively) and used by French and Italian authorities. These numbers should be combined with other environmental conditions, such as wind direction and seawater temperature, as discussed by Funari *et al*. [67] and Giussani *et al*. [68] and health symptoms [63] in Catalonia, Spain. However, symptoms were also noticed with cell concentrations below these alert values, and thus, more studies are required on this aspect.

Although the implementation of beach monitoring and surveillance systems in summer constitutes an effective strategy to prevent *Ostreopsis* impacts on human health, it requires optimal coordination between health and environmental authorities and researchers. In France, the National *Ostreopsis* Surveillance Network established in 2006 aims to prevent human health problems by detecting and responding to *Ostreopsis* bloom events in recreational waters along the French Mediterranean coast [69]. This network operates on an active basis during the blooming period from early summer to early fall (June to September) in coordination with other environmental and health surveillance agencies to ensure appropriate recommendations regarding control and management. It encompasses a health surveillance system with clinical toxicologists and experts on natural toxins and environmental *Ostreopsis* monitoring. Since beaches on the French coasts are strictly supervised and closed during *Ostreopsis* blooms, poisoning of the general public is less frequent nowadays. This prevents collapsing hospital or primary health care emergency facilities from massive admittances, as observed in the past in Italy and Algeria.

In order to ascertain the socio-economic impacts that a potential increasing frequency and biogeographic expansion of *Ostreopsis* blooms might cause in the future, the first step consists of knowing which would be the behavior of tourists and residents concerning their recreational use of the affected beaches and localities. A recent survey conducted in Monaco [63] by the University of Nantes, within the European funded project CoCliME ("Co-development of Climate Services for adaptation to changing Marine Ecosystems", part of the ERANET for Climate Services; https://www.coclime.eu) and the RAMOGE Agreement (among France, Monaco, and Italy; https://ramoge.org), indicated that despite their present importance, the occurrence of *Ostreopsis* blooms and their effects seem to be still poorly known by the general public. In the hypothetical scenarios of future increase of *Ostreopsis* blooms, many people would stop or decrease beach use, resulting in impairment of a significant portion of coastal recreational and tourist activities. However, a substantial part of the tourist and resident populations would continue to go to the beaches and thus could be exposed to health risks, resulting in increased health care costs. Efficient communication with the public becomes thus essential, with warning signs informing beach users about the presence of *Ostreopsis*. However, the messages should not be alarmistic and should avoid unnecessary panic. Overall, it is presently challenging to precisely ascertain the economic impacts that a potential increasing frequency and biogeographic expansion of *Ostreopsis* blooms might cause in the future.

An open question is why *Ostreopsis* species seem to have expanded their biogeographic distribution from tropical to temperate waters and why the species are increasingly blooming. The answer seems to be partly found in global warming and species tolerance to highly urbanized and deteriorated coastal habitats, characterized by turf algal formations and eutrophic conditions [70]. However, the assessment of this issue requires further clarification on the species resolution in this genus. While the recent detection of *Ostreopsis* cf. *siamensis* in the Bay of Biscay in the Northeast Atlantic Ocean [71] seems to confirm this apparent expansion from tropical to temperate areas, a recent taxonomic study found that *O. siamensis* is a tropical species while *O.* cf. *siamensis* is a separate and almost certainly undescribed species [72].

2.3 Northeast Atlantic Ocean

European Union countries face regular occurrences of several toxic microalgal species in the northeast Atlantic Ocean region. More than any other industry, including tourism, shellfish farming is by far the most affected one [73]. The European Union food law imposes specific obligations resulting in trade bans and area closures when acceptable biotoxin concentrations are exceeded [74]. The shutdowns of shellfish farming and harvesting can last for a few days up to several weeks and occasionally even months [e.g., 74,75-78].

The French Institute of Marine Research (Ifremer), in close collaboration with the French government and other stakeholders, has implemented the French monitoring program for phycotoxins in marine organisms (REPHYTOX), a rapid alert system that transmits the results of toxic phytoplankton and phycotoxins in shellfish weekly. Special emphasis is given to the dinoflagellates *Dinophysis acuminata* and *A. catenella*, and the diatoms *Pseudo-nitzschia* spp., the toxin producers associated with the DSP, ASP, and PSP syndromes in this area, respectively. In France, toxic outbreaks are more prevalent in the northern Atlantic coastline, when compared to the south. *Dinophysis* outbreaks in the northern region are recurrent and cyclical, while only one toxic event caused by *Pseudo-nitzschia* has been observed in 40 years all along the Atlantic French coastline. More recently, in the last decade, blooms of the dinoflagellate *Lepidodinium chlorophorum* caused significant events of shellfish mortality every summer (July-August), particularly in the Pen-Bé area. The exposure to risk for shellfish farmers and harvesters can also be recurrent in other countries on the northeast Atlantic coast. Alert systems have been implemented through the ASIMUTH project ("Applied Simulations and Integrated Modelling for the Understanding of Harmful Algal Blooms") [79] and applied to alert shellfish harvesters in Portugal, where blooms of *Pseudo-nitzschia* and dinoflagellates of the genera *Dinophysis*, *Gymnodinium*, and recently *Karenia*, are more frequently observed. From July 2013 to March 2014, this system performed 85% of correct one-week forecasts, with accuracy depending on specific areas (i.e., coastal, estuaries, and lagoons [80]).

The economic impact of HABs due to the closures of mussel farms was studied in Galicia (Spain) between 1990 and 2008, with an incidence rate (i.e., the proportion of closing days per annum) varying between 2% and 47% [75]. This survey demonstrated that administrative closures can be anticipated by farmers to mitigate the economic losses by harvesting prior to the shutdown and marketing mussels when the measure is repealed. The economic impact of these HAB events is therefore limited, except when the incident rate is exceptionally high, as observed in 2005, or if the event takes place during the last months of the year corresponding to the peak of demand [75]. A similar trend was observed in Greece, where public authorities may prohibit harvesting mussels for periods that may vary from one to six months during HAB events, with profit reduction ranging between 4% and 38% when HAB-related events last between 6 weeks and half a year, respectively [81]. Additional costs are incurred by farmers when the closure takes place in August (e.g., storage, meshbags, loss of seeds), but the usual spring occurrence of HAB events can be anticipated by mussel producers and cause limited impacts. When closures last less than 30 days, which represents the great majority of cases, there is no economic loss at all [81]. Alternatively, it has been proposed that the timing of trade restrictions during peak market seasons matters more than the length of the ban. For instance, a 3-week closure in the peak season in Greece (May to August) was observed to have greater consequences than a trade ban occurring in springtime for periods of more than six weeks [77].

HABs may represent a loss of turnover in the short term during the closure period. Although the losses are not irretrievable, they induce short-term cash flow problems related to the shift in the timing of sales. For instance, the economic consequences of trade bans and closures in France proved to be reasonably limited. Between 2004 and 2018, in the regions of south Britanny and Pays de la Loire, 432 prefectural bylaws of closures were promulgated, with an average length of 30 days and more than two-thirds concerning DSP outbreaks [73]. Because 82% of trade bans concerned the spring months between April and June, they were anticipated by shellfish farmers. For some producers, the management of HAB events is done by purchasing mussels not contaminated with phycotoxins from stocks harvested by other professionals. Other practices include the management of human resources, such as the assignment of staff to maintenance tasks during blooms or by requesting employees to take their annual leave during the blooms. These strategies allow producers to avoid overall economic losses. Nonetheless, the impact can be higher if HAB frequency and intensity increase over time, as in the case of Scottish shellfish farmers. An economic study based on a Cobb-Douglas function found that a 1% change in diarrhoetic shellfish toxins would reduce sales by 0.66% [78]. The annual loss from *Dinophysis*-generated biotoxins was estimated at 15% of total output (equivalent to GBP £ 1.37 M per year in 2015).

2.4 Ciguatera in the Caribbean and French Polynesia

Ciguatera Poisoning (CP) is caused by the consumption of marine fish and invertebrates contaminated with a suite of compounds, collectively known as ciguatoxins, produced by benthic dinoflagellates of the genera *Gambierdiscus* and *Fukuyoa* [82]. Ciguatoxins accumulate in coral reef food webs after herbivorous fish inadvertently ingest cells of these toxic dinoflagellates growing attached to their food source (e.g., macroalgae) or when invertebrates filter cells free-floating in the water column [83]. Poisoning includes various gastrointestinal, cardiovascular, and neurological symptoms, the latter of which may last from days to years and can be highly debilitating, complicated by the absence of a permanent cure [84]. While restricted to tropical and subtropical areas, CP is currently considered the most prevalent phycotoxin syndrome worldwide, estimated to affect between 10,000 and 500,000 people each year, although the real number of cases is not known, mainly due to misdiagnosis and underreporting [84].

The Pacific and the Greater Caribbean are endemic regions, hosting the highest incidence rates of CP cases [82]. This status results from the combination of favorable habitat and growth conditions for ciguatera causative dinoflagellates and the high dependence of local populations on marine food resources. CP represents 96% of seafood poisonings in French Polynesia, responsible for ~150 to over 700 cases every year since 2000 [82,85]. CP distribution in French Polynesia shows no significant evolution over time, but variability is apparent between the archipelagoes or islands from year to year. In the Greater Caribbean region, CP has been reported from most islands, with the highest incidence rates reported in Montserrat, Antigua and Barbuda and the British Virgin Islands (from 1996-2006, as reported by [86]), and lower prevalences occurring along continental margins (e.g., Colombia, Central America). Over the past decade, the geographic extent of CP appears to be expanding to some adjacent areas (e.g., northern Gulf of Mexico), while some endemic locations such as St. Thomas exhibited declines in incidence [87].

The full scope of CP impact on coastal communities is challenging to understand and quantify due to the high degree of underreporting and lack of tools and approaches needed to diagnose and treat this illness accurately. Indeed, only 10-20% of CP cases are estimated to be reported [88], which challenges the assessment of the true evolution of this illness in the Pacific and the Caribbean Sea. In both regions, CP is considered an almost inevitable risk associated with local fish consumption, and many affected by this poisoning do not seek medical help unless symptoms are critical, with only 0.1% or fewer intoxicated persons consulting a physician ([82] and references therein).

Although still a recent concept in both French Polynesia and the Caribbean, the blue economy is a substantial part of the economic and social web of their communities, as fishing and marine ecotourism are key sectors, with strong cultural and historical roots (Fig 10.2D). For example, a survey conducted on Moorea island in French Polynesia found that over 50% of households interviewed consumed fish six to seven times each week, with 76% of them having at least one member of the household actively involved in local reef fishing activity [89]. This heavy dependence on fish resources for subsistence explains why these communities are at such high risk of exposure to ciguatoxins, with fishermen being the first to suffer from the economic consequences of CP as the sale of toxic fish may decrease their income and exportation opportunities. In addition to the risk of losing customer confidence, fishermen are forced to avoid certain fish species and fishing areas known to be risky, leading to additional time and expenses (e.g., additional fuel cost) associated with accessing safer fishing areas.

The financial losses caused by decreased harvests associated with these bans were estimated to be USD $1.1 M per year in French Polynesia and USD $10 M in the Caribbean [82]. In French Polynesia, hotels and restaurants are reluctant to serve reef fish to their customers, preferring to offer offshore products. Local restaurants in the U.S. Virgin Islands frequently choose to import fish rather than serving those caught locally due to the threat of lawsuits and risk of bad publicity [90], which may tarnish the destination image and desirability for a particular location. Some professionals also turn away from at-risk species to avoid insurance costs to cover potential ciguatera-caused damages [91]. This shift from locally caught to imported fish increases costs to restaurants and hotels, resulting in the loss of revenue, and also represents a loss of an important source of income for all businesses in the seafood supply chain. At the global level, CP may discourage hotelkeepers, restaurants, and consumers from purchasing marine products generally due to the perception of risk [92].

Beyond these economic consequences, CP may also have social and cultural impacts on coastal communities, including lifestyle, local food trade, dietary shifts, and loss of fishing as an occupation, as the local population may abandon the consumption of locally caught seafood in favor of imported and processed food [93]. In the long term, this situation may contribute to the increased occurrence of non-communicable diseases such as obesity, diabetes, and arterial hypertension, already prevalent in the Pacific region. In communities to which local fishing is culturally important, CP may also lead to a progressive loss of transmission of knowledge related to lagoon fishing techniques, and more globally, loss of local ecological knowledge to the younger generations [94]. Finally, lawsuits brought by fish consumers who have suffered CP can affect fishers, restaurants, hotels, and other markets that comprise the supply chain/dealers. Such an example of litigation has already been described after a massive poisoning in Australia in 1997 [95].

The effects of CP on human health and well-being pose a severe limitation on the development of blue economy activities in the Caribbean Sea and the Pacific, which are largely based on food supply from the sea and tourism revenue. However, it is critical to understand the factors favoring CP. Although this syndrome has been known in these areas for centuries, habitat destruction caused by both natural (e.g., tsunamis, cyclones) and anthropogenic sources (excessive building and ports) — as well as coral bleaching from ocean acidification and ocean heatwaves — seems to be fostering ecosystem disturbances favoring macroalgal communities where benthic *Gambierdiscus* thrive, therefore increasing the risk of CP. In addition, global warming also seems to be involved in the increase of biogeographical distribution of these species and their toxins [57].

2.5 PSP outbreaks and fish kills in the Philippines

Aquaculture production in Asia constitutes 89% of global production and has outpaced capture fisheries. Within this region, the Philippines was ranked 11th in the world in 2018 in terms of aquaculture production of fish, crustaceans, and mollusks [96]. Aquaculture now contributes 53% of the total fish harvest in this country. As the Philippines population keeps growing, there is a push to increase aquaculture of marine species (mariculture) activities across its many coastlines as a source of food and livelihood.

Beyond mariculture, the ocean-based blue economy significantly contributes to the country's economy (Fig 10.2 E) and has the potential to contribute more, despite historically being relatively marginalized [97]. Embayments are the prime sites for shellfish mariculture, as well as wild harvest. Mussels and oysters are cultured through different methods, such as stakes and long lines. These cultures tend to be based on small farms set up by one to several fisherfolks (e.g., through cooperatives). Gleaners in surrounding communities also harvest wild shellfish. Unfortunately, many of these embayments are affected by PSP outbreaks due mainly to the dinoflagellate *Pyrodinium bahamense*, while a few are caused by *Alexandrium minutum* or *Alexandrium tamiyavanichii* [98,99]. These embayments are typically characterized by high residence times at their head, with river run-off contributing to stratified conditions during rainy periods and increasing nutrient loading [100,101]. These conditions allow for the retention of dinoflagellate cysts within the bays, which contributes to recurrent HAB events when cysts germinate and cell densities increase, depending on the environmental conditions [100-102].

The Philippines currently has the highest worldwide number of PSP outbreaks, with 2,555 poisonings recorded between 1985 and 2018 [103,104], with 165 of these ending in deaths. Apart from health impacts, these HAB events have had substantial socio-economic implications. Shellfish farmers and gleaners, who are already the poorest in the country, are the most affected through the loss of their food source and livelihood due to shellfish harvest bans, with their annual net income decrease due to PSP outbreaks estimated to be on average 33% and 55%, respectively [97]. A more negligible impact (9% decline) is also felt by other industries, such as restaurants, that use shellfish as ingredients. Shrimp and krill are also included in harvest bans and would have further socio-economic impacts that have not been analyzed. In some sites, these shellfish harvest bans have extended for more than one year, thus amplifying the impacts of HABs.

Although PSP is by far the dominant HAB-related concern in the country, other toxic algal species have been observed in Philippine waters. The diatom *Nitzschia navis-varingica* (a domoic acid producer) has been reported in different areas [105,106], and high levels of domoic acid have been observed in the bivalve *Spondylus*, which are commonly consumed by people [107]. During a bloom of *Dinophysis caudata* and *Dinophysis miles* in the central Philippines, high levels of diarrhetic shellfish toxins were measured in the mussel *Perna viridis* [108]. So far, only one confirmed ASP case had been documented, and no DSP cases. The toxins for these syndromes are tested much less frequently compared to paralytic toxins in the national monitoring program. Only four CP events due to the consumption of reef fishes contaminated with ciguatera toxins have been confirmed, though there are several other suspected cases [99]. Thus, the occurrence and impacts of other toxic microalgae in the Philippines strongly need to be further assessed.

The expansion of mariculture parks is being promoted in the country as a means to enhance production, especially from fish farms. These fish-farming areas again tend to be located in embayments or channels, where they can overlap with other coastal habitats and uses such as capture fisheries and tourism. These sites can be vulnerable to HABs in addition to anthropogenic impacts [109]. Fish kill events in the Philippines occur sporadically in some areas and almost yearly in others [99]. A variety of algal species have been associated with these fish kill events. The first major fish kill occurred in 2002 due to a bloom of *Prorocentrum cordatum* in Bolinao-Anda, Pangasinan, at the northwestern portion of the country [110,111]. This led to the death of thousands of kilos of milkfish in fish pens and cages, and approximately USD $9 M in losses. As with most fish kill estimates in the country, this monetary figure does not include impacts on livelihoods revolving around the industry and is likely a conservative estimate of the actual impact. Other HAB species associated with fish kills in this same area are diatoms of the genera *Skeletonema* and *Rhizosolenia*, the raphidophyte *Chatonella subsalsa*, and the dinoflagellate *Takayama* sp.

HABs compromise the existing and potential blue economy in the Philippines. Although these events do not appear to be increasing in frequency and duration, more sites are being affected, and new harmful species are detected [99]. The occurrence of toxic HAB species in shellfish farms around the country, along with other considerations (e.g., water quality, sanitation, and management), limit the potential capacity of the country to supply its burgeoning population and also export these fisheries products. HABs leading to fish kills increase the uncertainties in fish farming and again restrict potential production. These aspects affect the sustainability of the different mariculture and fisheries activities and tend to have negative and inequitable impacts among the stakeholders.

3. Role of science and technology in facing HAB-related challenges

The vast diversity of harmful algal species and phycotoxins, combined with the unpredictable nature of HABs due to complex biotic and abiotic ecological drivers, makes the complete prevention of these events an unrealistic goal. While some preventive measures such as the limitation of anthropogenic nutrient input in water bodies [112] and international ballast water regulation [113] may contribute to alleviating the problem in some areas, our ability to manage and mitigate the adverse effects of HABs still depends largely on the early detection of the causative species and their toxins [114]. The case studies described in the previous sections gave tangible examples of how both basic and applied research and monitoring have improved our understanding of HAB dynamics and risks, whereas Doucette *et al*. [115] and Stauffer *et al*. [116] provided comprehensive reviews on the methods and technological tools currently available for the monitoring of HABs. We will next discuss some of the main technical challenges faced by scientific and local community stakeholders in dealing with harmful algae from a sustainable perspective.

3.1 Increasing diversity of HAB species

The importance of correct species identification in HAB monitoring has already been addressed by Pitcher [117], and this issue has been further accentuated by the discovery of several cryptic species, strongly suggesting that some species may have been misidentified in the past. Proper identification at the species level is mandatory, as several genera include complexes of both toxic and non-toxic species, as well as species with populations from different geographic areas with different toxin profiles. Some representative examples of such HAB species complexes are found in the '*Alexandrium tamarense*-complex' [118], *Prymnesium parvum* [119], and *Pseudo-nitzchia* spp. [120,121], in which the species appear to be genetically independent, but distinguished by only minor and sometimes subtle ultrastructural details. To further complicate species' identifications, several nanoplanktonic HAB species (of difficult detection in routine monitoring analysis) have been described during the last few decades, including species of the dinoflagellate genera *Azadinium* [122] and *Karlodinium* [123].

Experience from training courses run by the UNESCO's Intergovernmental Oceanographic Commission (IOC) for the identification of HAB species from 1995 to 2020 shows that species identification in most monitoring programs is carried out on preserved material. It is estimated that only one-third (36%) of the species included in the IOC Taxonomic Reference List [31] can be reliably identified in preserved samples using light microscopy (LM). Species that cannot be identified using LM (Fig. 10.3) present a challenge for monitoring personnel, who do not generally have time or facilities to examine species in scanning or transmission electron microscopy (SEM/TEM) or carry out molecular analyses. Such species include:

- Naked or nanoflagellates, many of which cannot be identified correctly in preserved samples (in particular if fixed with Lugol's solution), for example, raphidophytes and dictyochophytes [124];
- Nanoplanktonic HAB species where morphological differences, albeit distinct, between species cannot be observed in LM due to their small size;
- Benthic dinoflagellates, mainly belonging to the genera *Gambierdiscus*, *Fukuyoa* and *Ostreopsis*, for which molecular analyses are needed for proper identification of most species [125];
- Diatoms of the genus *Pseudo-nitzschia*, where most diagnostic morphological differences between species can be observed only by SEM/TEM.

Molecular methods based on oligonucleotide probes (e.g., qPCR and DNA microarrays) have been successfully used in some developed countries to monitor HABs (e.g., [126-129]). However, this strategy only works well in locations where blooms of target species are recurrent and ignores the presence of putative emergent HAB species [130]. Massively parallel sequencing (MPS; also known as "metabarcoding") constitutes a powerful alternative that enables the simultaneous detection of many HAB species in monitoring programs [131,132]. While these molecular-based technologies are promising, most HAB monitoring activities still rely on the opportune detection of HAB organisms solely through LM. This is particularly true for developing countries where LM is sometimes the only available tool. Consequently, species requiring examination beyond observation in LM may be adequately identified only when they form blooms with severe impacts on human health or the marine environment. This means that occurrences of certain taxa (e.g., raphidophytes, *Prymnesium* spp., *Pseudo-nitzschia* spp.) without associated adverse effects can be assumed to remain unreported or reported only at the generic level, impeding further insight into the geographical distribution and seasonal occurrence of these species. Under a scenario of increasing frequency of emerging HAB events, this issue is expected to get worse with the future discovery of cryptic species, and increasing sea surface temperature may cause a shift in phytoplankton assemblages towards smaller species [133].

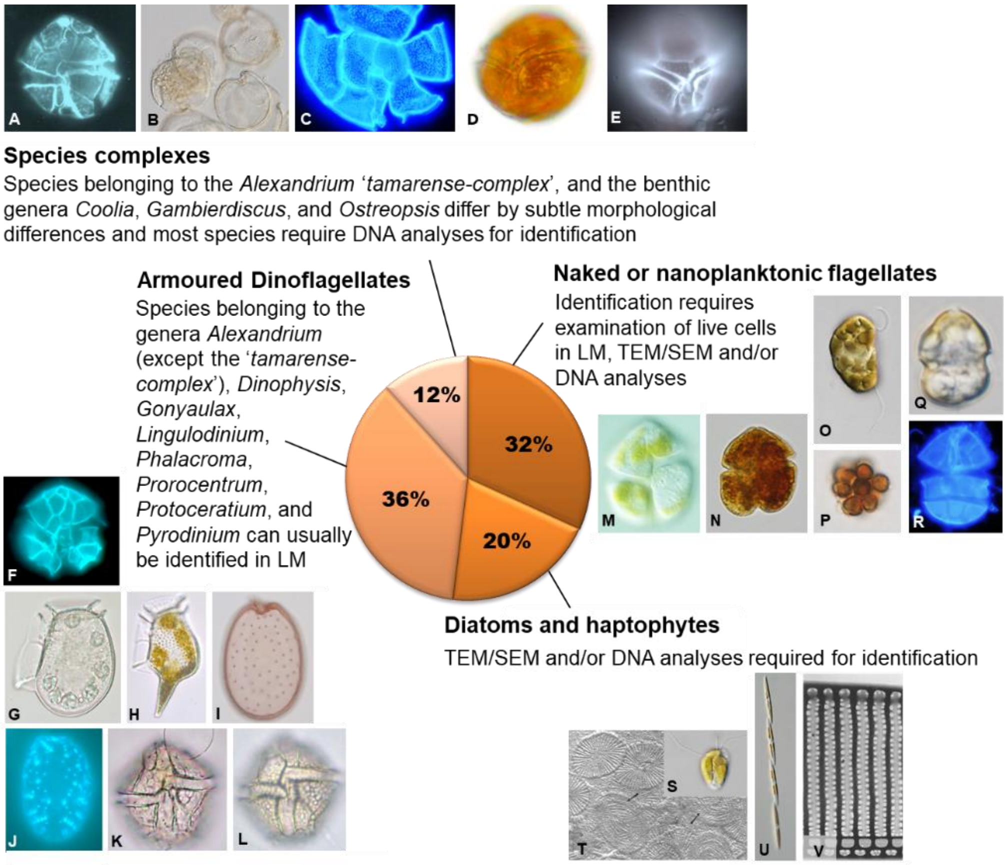

Fig. 10.3. Various types of potentially toxic, eukaryotic microalgae, grouped according to methodological requirements for identification to the species level. Percentages indicated of the total number of species (154) in the IOC Taxonomic Reference List (Moestrup et al., 2021). (A) *Alexandrium tamarense*, (B-C) *Gambierdiscus australes*, (D-E) *Coolia tropicalis*, (F) *Alexandrium minutum*, (G) *Dinophysis fortii*, (H) *Dinophysis caudata*, (I) *Prorocentrum lima*, (J) *Prorocentum rhathymum*, (K) *Protoceratium reticulatum*, (L) *Lingulodinium polyedrum*, (M-N) *Karenia mikimotoi*, (O-P) *Heterosigma akashiwo*, (Q-R) *Azadinium spinosum*, (S-T) *Prymnesium parvum*, (U-V) *Pseudo-nitzshcia* spp. Specimens documented under LM, except (T) and (V) for which SEM and TEM were used, respectively. Photos not to scale. Photo credits: J. Larsen, except by G. Hansen (G) and N. Lundholm (U-V).

3.2 Toxin detection

While the detection of potential HAB organisms is critical for the early warning of bloom development, the toxicity of algal species can vary markedly due to the interplay between their genetic makeup and physiological responses to multiple environmental factors [134]. This frequently results in potential uncoupling of cell and toxin concentration, with under- or overestimation of the adverse effects of a bloom event [115]. The simultaneous detection of HAB organisms and phycotoxins in seafood is thus required to protect consumers from poisoning without causing losses due to unnecessary fisheries closures [114]. While shellfish phycotoxin monitoring is implemented by public and private resources in many countries, international coordination for the establishment of standard analytical procedures and regulations is still an urgent need [34]. A critical aspect concerns the maximum amount of toxins in shellfish intended for human consumption, that is, the toxicity equivalence factors that apply to commercialized products [135].

The overwhelming diversity of algal toxins and toxic mechanisms involved in their harmful effects on humans and marine organisms pose a challenge for monitoring agencies and managers. LC-MS/MS is currently considered the most reliable method for the precise determination of phycotoxins. However, this tool is mainly used for basic research and is rarely used in monitoring programs due to elevated equipment cost, required high professional expertise, and lack of toxin analytical standards [129]. Routine detection of phycotoxins in many countries is still based on mouse bioassay [34], the latter presenting several drawbacks such as its qualitative nature, delays for results, and high incidence of false positives, in addition to ethical issues [33]. Thus, much effort has been made in recent years to develop functional and structural assays that would also be low-cost, user-friendly, and provide high-throughput analyses (reviewed by [136]). Although these methods still have some limitations (e.g., lack of sensitivity or specificity and poor understanding of toxic mechanisms), they represent promising alternatives for the sustainable monitoring of HAB toxins. ELISA kits (nowadays available for many phycotoxins) have been used in monitoring programs and by fishermen to test shellfish and other commercial products themselves, resulting in the more efficient management of shellfish harvest [113]. Still, the main gap in this regard is the lack of a reliable kit-based assay for ciguatoxins, as CP remains the most serious of all phycotoxin-related human poisoning syndromes worldwide.

3.3 Observing systems

The early detection of HAB events depends on obtaining timely information about the presence of harmful algal species and the environmental conditions favoring their growth. HABs are complex oceanographic phenomena affected by a broad range of physical processes (e.g., turbulence, upwelling, local retention) and characterized by episodic occurrence over a broad range of temporal and spatial scales varying from days to months and meters to kilometers, respectively [137]. However, the collection of samples for phytoplankton counting and phycotoxin analysis in monitoring programs rarely takes place more than weekly (frequently monthly in developing countries, if performed at all) and/or with proper spatial resolution, with undersampling becoming even more critical in remote areas [34]. Thus, much effort has been applied in recent decades to integrate these routine monitoring activities with complementary oceanographic approaches and predictive models in coordination with key stakeholders such as local communities, fishers, managers, and scientists (e.g., [79,138]).

Available ocean observational technologies for real-time (or nearly) detection of HABs include remote satellite detection [139] as well as automated instruments that can be deployed on moored, ship-based, or autonomous mobile platforms [see 116 for a review]. Examples of such automated approaches are PhycoProbeTM and Optical Phytoplankton Discriminator (OPD; also known as BreveBuster). The former leverages multichannel excitation and fluorescence to discriminate among different pigment signatures to detect main microalgal groups [116], while the latter focuses on the optical pigment signature of the dinoflagellate *Karenia brevis* [140]. Recent development in imaging flow cytometry also allows the implementation of this observing capability in deployable instruments such as Imaging Flow Cytobot (IFCB; [141,142]) and Cytobuoy [143], while the Environmental Sample Processor (ESP; [144]) uses molecular and enzymatic assays to detect the presence of toxic cells and toxins in the water, respectively. Although these instruments are still viewed mainly as research tools, they are useful for understanding HAB dynamics and are increasingly becoming incorporated into monitoring programs.

Anderson et al. [145] provided meaningful examples of HAB observing systems that integrate routine monitoring of harmful algal species and phycotoxins with complementary oceanographic approaches. One of the main conclusions presented by these authors is that there is no universal solution that fits the needs of monitoring programs in all regions. As a matter of fact, while automated instruments play significant roles in some regional programs on the West Coast of the United States [146] and France [147], good results have been obtained with satellite remote sensing in China [148], Korea [149], Iberian Peninsula [150], Scotland [151], Ecuador [152], and Chile [153]. Citizen science programs are also increasingly becoming critical to improving the spatial and temporal coverage of regional HAB monitoring programs, as observed in some areas in the United States (e.g., Alaska and Gulf of Mexico [154,155]) and France [157].

The improved resolution obtained with these HAB observing systems has supported predictive models in some regional programs allowing for short-term early warning (days to months). Examples of such forecast approaches based on cell/cyst counts coupled with remote satellite data and hydrodynamic models are carried out in the Gulf of Maine [157] and California [154] to predict cell concentration and spatial distribution of toxic blooms. More recently, the ASIMUTH project (mentioned previously in section 2.3.) developed a prototype HAB alert system allowing for the forecast of phytoplankton and biotoxin data using satellite remote sensing and other information on current, past recent, or future modeled oceanographic conditions ([151] and reference therein). The potential of these models to increase our forecast capacity for risk assessment depends on obtaining a better ecophysiological understanding of the growth dynamics of toxic algal species such as loss processes, life cycle (e.g., encystment and excystment), and species-specific environmental conditions promoting toxicity [159].

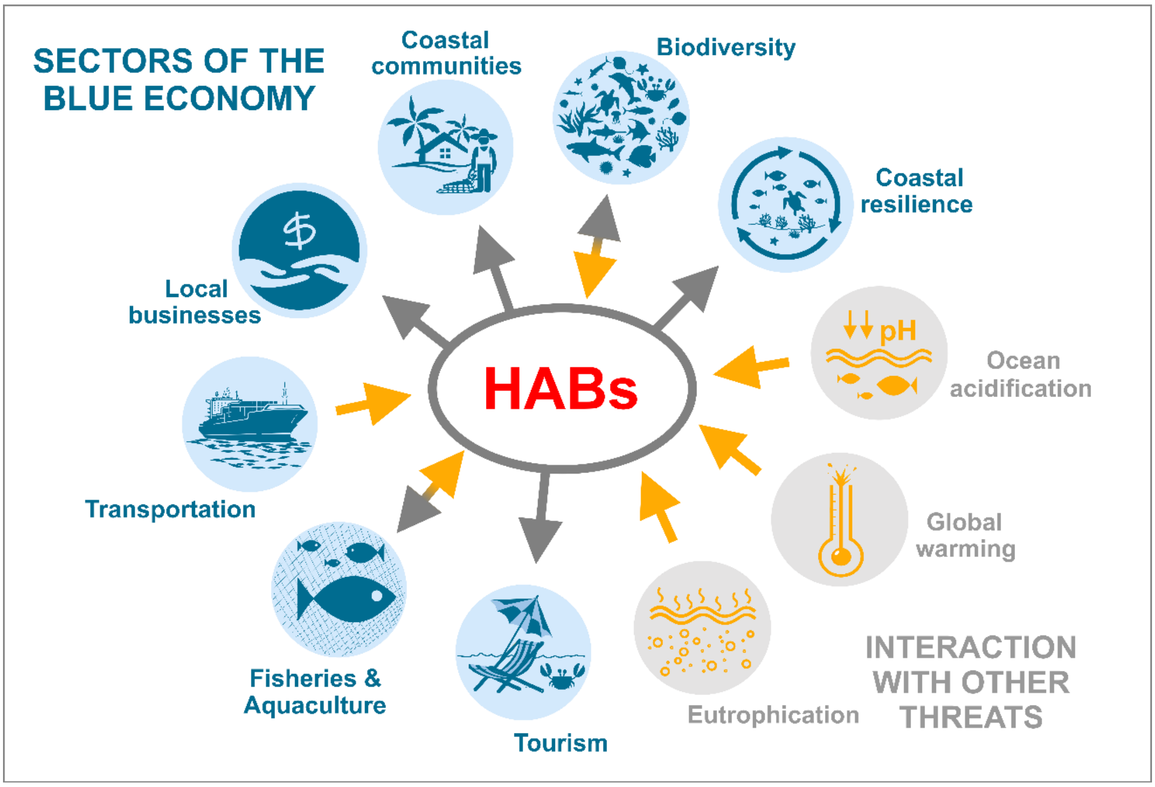

Fig. 10.4. Interactions of harmful algal blooms (HABs) with different sectors of the blue economy and other environmental threats. Sectors negatively affected by HABs are indicated by grey arrows, whereas orange arrows indicate factors promoting these events.

4. Concluding remarks and perspectives

The main sectors of the blue economy affected by the negative impacts of HABs and examples of their economic losses are shown in Fig. 10.4 and Table 10.1, respectively, whereas the case studies presented in the previous sections provide examples of these effects. Aquaculture is by far the blue economy sector most affected worldwide by phycotoxins and fish kills caused by high microalgal biomass/ichtyotoxins [159]. Indeed, it was the most impaired sector in three of the five regions described in this chapter (i.e., Chile, North Atlantic, and the Philippines). However, effects on other sectors — such as fisheries, tourism, local businesses, and coastal resilience — are also illustrated by the case studies describing *Ostreopsis* blooms in the Mediterranean Sea and CP in

French Polynesia and the Caribbean Sea. In all of these areas, HABs also affect the well-being of local communities either by directly impairing their health (e.g., consumption of phycotoxins in shellfish and/or aerosols) or the way they economically support themselves. In this regard, a better epidemiological assessment of the effects of HABs on human health is desperately needed as chronic impacts due to the repeated exposure to low toxin levels are still largely unknown [161]. Some sectors of the blue economy can, in turn, also favor the prevalence of HABs (Fig. 10.4). One example of that is the introduction of harmful algal species in new areas through oceanic transportation (e.g., ballast water) and/or aquaculture activities [162]. Another important aspect to consider is that the frequency and magnitude of HABs will likely increase in response to other blue economy environmental threats such as eutrophication, global warming, and ocean acidification. As a matter of fact, changes in the amount and stoichiometry of nutrients in incoming freshwater to estuaries are expected to promote HABs in the future ([163]; See also Chapter 5 in this book).

Table 10.1. Examples of financial losses and costs caused by harmful algal blooms (HABs) on different economic sectors.

Economic Sector	Country	Period	Annual loss/cost (USD $)	Source
Commercial fisheries	Maine (US East Coast)	2008-2011	~3.47 – 10.4 M	[22]
	U.S. West Coast	2015	43.7 M	[22]
	Korea	2010-2018	0 –126,900	[22]
	Southern Chile	2016	2 M	[22]
Recreational fisheries	Korea	2010-2018	0 – 37.7 M	[22]
	U.S. West Coast	non-specified	10.6 M	[22]
Aquaculture	Scotland	2009-2018	~1.31 M	[22]
	Korea	2010-2018	0 – 20.8 M	[22]
	Southern Chile	2016	800 M	[89]
Tourism	Korea	2010-2018	0 –19 M	[22]
Human Health	U.S. Southeast	non-specified	60,000 – 700,000	[22]
	Moorea Island (French Polynesia)	2007-2013	6,452 – 51,616	[89]
	Southern Chile	2014-2018	6,621 – 93,119	[22]
Monitorig	Southern Chile	2019	6.91 M	[22]
	Korea	2010-2018	0.9 – 6.2 M	[22]
R&D	Korea	2013-2018	0.83 – 4 M	[22]

Significant progress has been achieved in the last four decades in understanding HAB dynamics, improved taxonomy, toxin detection, monitoring, and forecasting. At this point, it is important to consider that the blue economy "seeks to promote economic growth, social inclusion, and the preservation or improvement of livelihoods *while at the same time ensuring environmental sustainability of the oceans and coastal areas*" [1]. The blue economy is based on fisheries and aquaculture to provide food for humans, but also tourism and leisure, transport of goods and people, generation of clean and renewable energy and minerals, drinking water, and new drugs. However, conducting the activities to obtain these benefits entrains risks for the environment that, in some cases, are also direct or indirect factors fostering HABs [9]:

- Eutrophication caused by intensive aquaculture, agriculture, or urban run-off;
- Excessive use of the coastal zones favoring water retention and thus the accumulation of a high number of HAB organisms;
- Ballast water, plastics, and transport of aquaculture organisms facilitating the spread of harmful species to new habitats;
- Fisheries exploitation causes biodiversity loss and food web disruptions.

An evident gap in dealing with HABs is the difference in the resources available for monitoring in the different areas of the world. While developed countries count on automated tools, oceanographic moored instruments, and forecast models based on hydrographic conditions to provide early warning, robust monitoring in most developing countries is still missing and, when performed, mostly focused on seafood products aimed for exportation to developed countries [34]. Most developing countries still rely solely on microscopic analysis and, depending on the type of harmful algae, occasionally on remote satellite data, with toxin analysis seldom performed. As basic research on HABs in these countries is frequently also deficient, modeling capabilities for early warning are virtually non-existent.

There is an urgent need to implement blue economy practices, sustainable by definition, everywhere, as a tool to cope with the environmental threats and to achieve a more equitable planet. Indeed, many successful (truly sustainable) blue economy activities are precisely developed in vulnerable areas with low economic power [e.g., 164, 165]. Thus, it becomes critical that affordable and sustainable technologies be developed to allow the efficient monitoring of HABs. This need is reinforced by the fact that some HAB-related health issues (ciguatera being the most emblematic among those) occur mostly in developing countries in the tropical and subtropical areas, which poses constraints against the implementation of sustainable fisheries, aquaculture, and tourism in these areas. Scientific knowledge can undoubtedly support that by facilitating the development of low-cost and reliable monitoring tools for HABs. Minimizing the anthropogenic forcings that favor HABs occurrence, especially in the most vulnerable habitats and human communities, is one efficient way to protect the environment while promoting economic growth and social inclusion, and thus walking towards a blue economy-based system.

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