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Algal bloom and its economic impact

Isabella Sanseverino, Diana Conduto, Luca Pozzoli, Srdan Dobricic and Teresa Lettieri

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Contact information
Name: Teresa Lettieri
Address: European Commission, Joint Research Centre
Institute for Environment and Sustainability
Water Resources Unit TP 121
Via E.Fermi, 2749
21027 Ispra (VA)
Italy

E-mail: teresa.lettieri@jrc.ec.europa.eu
Tel.: +39-0332789868

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Abstract

Harmful algal blooms (HABs) represent a natural phenomena caused by a mass proliferation of phytoplankton (cyanobacteria, diatoms, dinoflagellates) in waterbodies. Blooms can be harmful for the environment, human health and aquatic life due to the production of nocive toxins and the consequences of accumulated biomass (oxygen depletion). These blooms are occurring with increased regularity in marine and freshwater ecosystems and the reasons for their substantial intensification can be associated with a set of physical, chemical and biological factors including climate changes and anthropogenic impacts. Many bloom episodes have significant impacts on socio-economic systems. Fish mortality, illnesses caused by the consumption of contaminated seafood and the reluctance of consumers to purchase fish during HABs episodes represent only some of the economic impacts of HABs. The aim of this report is to evaluate the economic losses caused by HABs in different sectors. This was achieved by collecting data that exist in the technical literature and group them into four categories: (1) human health impacts; (2) fishery impacts; (3) tourism and recreation impacts; (4) monitoring and management costs. The data analysed refer to both marine and freshwater HABs. Among the sectors examined in this study, human health impacts appear less investigated than the other three categories. This is probably caused by the difficulty to assess the direct effects of toxins on human health because of the wide range of symptoms they can induce. Looking at the data, the interest in mitigating the economic losses associated with blooms is particularly demonstrated by studies aimed to develop monitoring and management strategies to reduce HABs episodes. Indeed, the water monitoring, when accompanied by appropriate management actions, can assure the mitigation of ongoing HABs and the reduction of negative impacts. During data collection, it has been more difficult to find economic data about blooms in Europe than in United States of America (USA). A reason may be the lack of European reports or publically available data about HABs and their socio-economic impacts. Much studies still have to be performed in this field, but the reported increase in HABs frequency will surely increase not only scientific analysis about HABs but also economic studies to report whether safeguards taken have succeeded in mitigating the economic impact associated with blooms.

1. Introduction

Harmful algal blooms (HABs) represent a natural phenomena caused by a mass proliferation of phytoplankton in waterbodies. The main groups of organisms generating HABs are diatoms, dinoflagellates and cyanobacteria. While diatoms and dinoflagellates are principally associated with blooms in seawater, cyanobacteria are most common in freshwater. All phytoplankton photosynthesize and their growth depends on different factors such as sunlight, carbon dioxide and the availability of nutrients, in particular nitrogen and phosphorus [1]. Additional factors influencing their life are water temperature, pH, climate changes, salinity, water column stability and anthropogenic modifications of aquatic environment including nutrients over-enrichment (eutrophication) [2, 3]. Eutrophication can result in visible algal blooms which cause an increase in the turbidity of water and can create taste and odours problems. During a blooms, algae can also produce nocive toxins that can render water unsafe and cause fish mortality or can impact human health through the consumption of contaminated seafood, skin contact and swallow water during recreational activities. Diatoms and dinoflagellates are involved in the production of toxins responsible for different poisoning in humans which interest mainly the nervous and the intestinal system [4]. Toxins produced by cyanobacteria pose also risk to human health in particular when water is used for recreational activity or for drinking [5, 6]. For this reason, globally, many countries have adopted standard measurements for limiting the presence in drinking water of Microcystin-LR, the most toxic and widespread hepatotoxin produced by cyanobacteria [7]. Sectors such as commercial fishery, tourism and recreation can be severely impacted by blooms [8-10]. Shellfish closure, the suspension of water recreational activities and monitoring and management plans adopted to reduce blooms are well-recognised impacts of HABs. They are also responsible for substantial economic losses which are likely to increase due to the reported intensification of HABs manifestations. In this report we have collected data about the economic impact of HABs on the following sectors: (1) human health; (2) fishery; (3) tourism and recreation; (4) monitoring and management. We reviewed the literature to identify scientific reports, papers and books about monetary data relevant to understand how HABs impact the economy. An internet search was performed using websites such as Google Scholar, consulting institutional websites like the European environmental protection agencies or obtaining data by economic journals (e.g. Ecological Economics). From all sources analysed we extracted monetary data and reported these values on our report. Most of the data referred to United States of America (USA), but we also found some information about Europe even if concerning only monitoring and management costs.

Estimates of expenditures caused by HABs can be useful to understand the effectiveness of protective measures taken to reduce HABs events. This means they can help to evaluate the cost of actions adopted to assure a good water quality and to identify which are the most effective ones to use. Our overview, including only studies that specifically address the economic impacts of HAB, can be therefore a valid support to scientists to evaluate the more appropriate method for estimating the economic effects of algal blooms and correlate this analysis with the cost-effectiveness of different approaches to reduce ongoing HABs and the subsequent negative impacts.

2. Algal blooms

Harmful algal blooms (HABs) refer to a rapid proliferation of phytoplankton species such as dinoflagellates, diatoms, and cyanobacteria in aquatic ecosystems (Figure 1). HABs are natural phenomena which pose serious risks to human health, environmental sustainability and aquatic life due to the production of toxins or the accumulated biomass. Dinoflagellates in particular may be responsible for the formation of the so-called “red tides” (Figure 1A). Nowadays there are about 90 marine planktonic microalgae capable to produce toxins and most of them are dinoflagellates, followed by diatoms. Harmful impacts attributed to toxins have for many years led to poisoning in humans consuming contaminated seafood or in livestock. Toxins can accumulate in shellfish and filter feeding bivalves and their consumption by human populations may cause damage to different system of the human body such as the nervous and the intestinal system [4]. HABs can also be caused by non-toxic species going through high-biomass blooms. The algal biomass accretion may discolour the water and may produce harmful effects and cause reduction in biodiversity due to shading of the benthos and oxygen decline after the bloom dies offs. Low oxygen levels caused by the decay of the algae have in-turn an impact on plant, animal and fish life (Figure 1C) [11, 12]. During respiration, fish may ingest algal-rich water which enters fish system and induces the production of Reactive Oxygen Species (ROS) with a resulting increase of oxidative stress and fish death [13]. At the same time, algal cells are themselves able to produce ROS as causative factor leading to fish mortality underlying the important role of oxidizing compounds in bloom toxicity [14]. Another mechanism by which algal bloom may kill fish and other organisms includes physical damage to the gills caused by the spines of diatoms. Indeed, when gills are damaged by spinous diatoms, the epithelium shows lesions and produces excessive mucus that lead to asphyxiation [15, 16].

Even if exact causes of HABs are still unclear, human impacts combined with climate changes have contributed to the recent increase in HABs incidence. HABs can affect large or smaller areas either in freshwater or in marine ecosystem and their dynamics are influenced by a set of physical, chemical and biological factors. These include seasonal variability in temperature, nutrients and water column stratification [17, 18]. In particular, the stability of water column is instrumental in determining the establishment of HABs. Given the important interactions among different processes in HABs formation, it seems clear that a multifaceted approach and interdisciplinary studies are required to fully understand ecological systems and all other factors which influence HABs dynamics. This information can contribute to a more complete assessment of the impacts of HABs on the ecosystems and human health and suggest what can be done to alleviate these impacts.

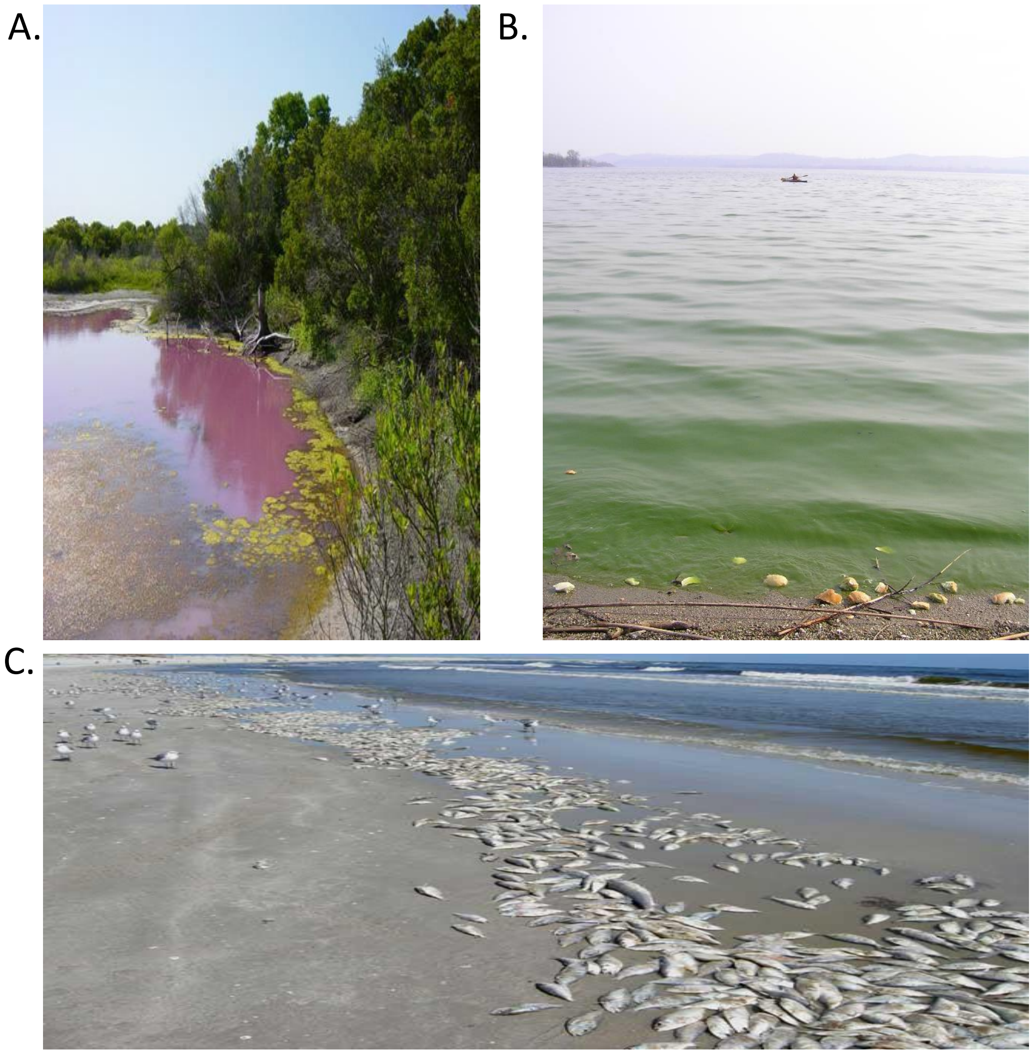

Figure 1: Harmful Algal Blooms (HABs) episodes and effects on fish

A. A discoloration of water caused by a red tide (Photo credit: Steve Morton and the "National Oceanic and Atmospheric Administration") **B.** Cyanobacterial scum during a bloom in Lake Varese (Italy) **C.** Fish kill caused by a bloom episode (Photo credit: Steve Morton and the "National Oceanic and Atmospheric Administration")

2.1 Principal groups of organisms generating Algal Blooms

2.1.1 Diatoms

Diatoms are unicellular, photosynthetic eukaryotes and include about 100 species spreading worldwide in both marine and freshwater. Marine diatoms play a central role in aquatic environment, contributing to 40% of primary productivity in marine ecosystems and 20% of global carbon fixation [19]. They also contribute to the ocean carbon, nitrogen and silica cycles. Diatoms have developed sophisticated strategies to adapt and respond to environmental stress factors such as nitrogen and phosphate limitation. In particular, regulation at proteasome level is essential for diatoms to modify their metabolism in response to environmental changes and to enhance stress tolerance [20].

Diatoms are characterised by a siliceous cell wall (frustule) and most of them display spines which can physically clog and damage fish gills, leading to death. Diatoms of the genus *Pseudo-nitzschia* produce domoic acid, a neurotoxin structurally related to glutamic and kainic acid (Table 1). It enters into food chain through filter feeding organisms such as shellfish or finfish and it has a negative impact on growth rate of scallops besides being involved in toxicity occurring in wild animals such as California sea lions [21, 22]. Domoic acid cause Amnesic Shellfish Poisoning (ASP) in humans consuming shellfish or crustaceans and the effects include confusion, short-term memory loss, headache and in severe cases, death (Table 1) [23, 24]. Cases of human intoxication and global alteration of the marine food chain reveal, therefore, how risk assessment of domoic acid is directly connected to the need to safeguard food safety and human health.

2.1.2 Dinoflagellates

Dinoflagellates are microalgae forming a significant part of primary planktonic production in waterbodies and mainly responsible for harmful algal blooms (HABs) episodes occurring worldwide. Dinoflagellates species can be heterotrophic, autotrophic or combine heterotrophy with photosynthesis (mixotrophic dinoflagellates) [25]. Their structure is characterised by the presence of two flagella providing them the propulsive force to move in water and hold position in the water column according to nutrients' availability. Like other phytoplankton species, dinoflagellates use inorganic nutrients such as nitrate and phosphates and convert them into the basic building blocks of living organisms (carbohydrates, proteins, fats). Dinoflagellates usually reproduce by asexual fission but sexual reproduction also occurs in some species determining the formation of dormant cells called cystis. Cystis, settle to the bottom sediments, can persist for years and they are considered an effective strategy for survival through environmental or nutritional stresses. When favorable environmental conditions, such as warmer climate and nitrogen runoffs, occur, cystis germinate to produce HABs [26].

Dinoflagellates produce toxins that may affect public health through the consumption of contaminated seafood or direct human exposure to HABs. Toxins can cause significant diseases in man. These illnesses include Paralytic Shellfish Poisoning (PSP), Diarrhetic Shellfish Poisoning (DSP), Neurotoxic Shellfish Poisoning (NPS) and Ciguatera Fish Poisoning (CFP) (Table 1) [27].

Bloom released toxins are also responsible for shellfish toxicity, as observed along the coast of the Gulf of Maine and Pacific Northwest where toxins are produced by the dinoflagellate *Alexandrium fundyense* and *Alexandrium catenella* respectively [28, 29]. Example of blooms caused by a massive growth of dinoflagellates have been also reported in the Gulf of Mexico and in the east coast of Florida [30] while, in Europe, recent blooms phenomena have been described in countries like Greece and France [31, 32].

2.1.3 Cyanobacteria

The cyanobacteria or "blue green algae" comprise a diverse group of oxygenic photosynthetic bacteria with the ability to synthesise chlorophyll-a and other accessory pigments like phycobilin, phycocyanin and phycoerytrin proteins. The cyanobacteria have been studied since the seventies when the first acute cyanotoxin poisoning of domestic animals was documented in the scientific literature [33]. Ever since, scientific efforts have been done to better understand their biological characteristics. The majority of cyanobacteria are aerobic photoautotrophs and for their reproduction they need only water, carbon dioxide, inorganic substances and light. Their photosynthetic apparatus is similar, in the structure and in the function to that of the eukaryotic chloroplasts and for this aspect, as for their algal morphology, cyanobacteria are taxonomically classified by using the International Code of Botanical Nomenclature (ICBN). Moreover, considering the prokaryotic nature of cyanobacteria, their nomenclature is also governed by the provisions of the International Code of Nomenclature of Bacteria (now: International Code of Nomenclature of Prokaryotes; ICNP). Cyanobacteria taxonomy was traditionally based on morphological characteristics but, at present, molecular methods represent the more reliable and resolutive approach to identify the cyanobacteria species [34, 35]. A significant contribution to the update of the taxonomic status of cyanobacteria is given by two public databases on the web: AlgaeBase and CyanoDB [36, 37]. In particular, AlgaeBase includes, in addition to the taxonomic classification, other information such as geographical distribution, molecular sequences and bibliographic data.

Cyanobacteria are widely spread in many freshwater and marine ecosystems. Their long evolutionary history, started 2,5-3 billion years ago, enabled them to adapt to climatic, geochemical and anthropogenic changes. Cyanobacteria can colonize water that is salty, brackish or fresh and are able to survive extremely low and high temperatures [38, 39]. Cyanobacteria are also inhabitants of infertile substrates like desert sand and rocks [40, 41]. Freshwater is the prominent habitat for cyanobacteria and different species are able to spread along the water column dominating the epilimnion or deeper water layers.

The photosynthetic apparatus of the cyanobacteria includes two kinds of reaction centers, Photosystem I (PSI) and Photosystem II (PSII), and the accessory pigments mentioned above allow to optimize the light absorption and most efficiently catch the light in differentially illuminated habitats [5, 42]. The vertical movement of many species of cyanobacteria along the water column are guaranteed by the presence of gas vesicles. These cellular structures are cytoplasmic inclusions impermeable to liquid water, but highly permeable to gases normally present in the air. Gas vesicles are important to optimise the cyanobacteria vertical position in the water column and thus to find a favorable habitat for survival and growth. Environmental stimuli such as photic, physical, chemical and thermal factors can also influence the buoyancy of cyanobacteria, enabling them to adjust their position in water column.

Cyanobacteria are able to perform the dinitrogen fixation, a remarkable metabolic process to convert atmospheric nitrogen directly into ammonium by using the enzyme nitrogenase. Atmospheric nitrogen or dinitrogen comprises about 80% of the Earth's atmosphere. This element can enter and exit water in different forms: ammonium, nitrate, nitrite and organic nitrogen. Aquatic plants and algae can use all inorganic forms of nitrogen, but not dinitrogen, underlying the key role of organisms like cyanobacteria in fixing dinitrogen, a process which nutritional requirements of all living organisms are dependent on. Therefore, nitrogen is often the limiting factor for biomass production in environments where there is suitable climate and availability of water to support life. Nitrogenase is inactivated by oxygen and it is for that reason that in most cases, dinitrogen fixation occurs in heterocysts, cyanobacterial vegetative cells which are capable of blocking entry of oxygen [43, 44]. However, there are examples of dinitrogen fixation among cyanobacteria not forming heterocysts [43]. Under nitrogen limited conditions and when other nutrients are available, cyanobacteria may be advantaged in growing. This phenomenon can induce a massive growing of the cyanobacteria, the so-called "blooms", mainly in freshwater but also in marine environments. Cyanobacterial bloom formation and persistence is influenced by light intensity, water temperature, pH, climate change, water flow, water column stability and anthropogenic modifications of aquatic environment including nutrient over-enrichment (eutrophication). Cyanobacterial blooms can be harmful to the environment, animals and human health. Bloom senescence depletes oxygen from water, causing hypoxic conditions and the subsequent death of both plants and animals. In addition some species of cyanobacteria can be stimulated to produce a variety of toxic secondary metabolites (cyanotoxins) (Table 2). How environmental factors influence cyanotoxin production is under investigation but light, temperature and in particular nutrient input (both nitrogen and phosphorus) are surely involved [45]. The release of cyanotoxin into drinking and recreational water supplies has important repercussions on human health and the environment. Management approaches aimed to limit cyanobacterial biomass from our waterways are therefore necessary to reduce health risks and frequencies of hypoxic events.

2.1.3.1 Eutrophication and cyanobacteria growth

Eutrophication, a process whereby water bodies receive excess nutrients that stimulate blooms of algae has been recognized as a widespread problem since the 1970s. Nutrients can come from many sources, such as urban and rural wastewater, fertilizers applied to agricultural fields, combustion of fossil fuels, erosion of soil containing nutrients and sewage treatment plant discharges. Inorganic nitrogen, phosphorous compounds and carbon are involved in eutrophication process and human activities can accelerate the nutrient rate entering into ecosystems. Cyanobacteria are able to exploit anthropogenic modification of aquatic environment as evidenced by their higher affinity for nitrogen or phosphorus compared to other photosynthetic organisms [5]. Many cyanobacteria have the ability to fix dinitrogen and they have a substantial storage capacity for phosphorus, in addition they can sequester iron and a range of trace metals [46-48]. Phosphorus occurs naturally in rocks and other mineral deposits. Sediments show the capacity to take up and release phosphorus, thereby contributing to determine phosphorus levels in aquatic environment. In contrast to nitrogen pool that includes gaseous forms in addition to dissolved and particulate forms, the phosphorus pool is characterised by non-gaseous dissolved and particulate forms. Cyanobacteria show a storage capacity for phosphorus, useful for performing two to four cell divisions with a corresponding 4-32 fold increase in biomass. High phytoplankton density leads to high turbidity, low light availability and cyanobacteria can growth best under these conditions. Cyanobacteria can also escape to nitrogen limitation by fixing atmospheric nitrogen, therefore they can out-compete other phytoplankton organisms under nitrogen or phosphorus limitation. Changes in the nature of human activity (from agricultural to industrial water use) resulted in increased pollution of water resources. The consequent water eutrophication can cause visible Harmful Cyanobacteria Blooms (CyanoHABs), surface scums, benthic macrophyte aggregation and floating plant mats. The bloom decay may lead to the depletion of dissolved oxygen in water, release of toxins, loss of water clarity and disruption of food webs. In addition, phosphorus released from sediments can accelerate eutrophication.

Phosphorus has traditionally been considered the major nutrient controlling the manifestation of CyanoHABs in freshwater ecosystem, while nitrogen’s role in eutrophication has long been more controversial [49]. This has led to the control and reduction of phosphorus inputs in lakes and consequent improvements in water quality [50]. When, during the 1970s, there was an increase in the use of nitrogen-fertilizers and in fossil fuel emissions, a rise in nitrogen loading was reported in water bodies. Nevertheless it tooks times to recognize the key role of nitrogen in control of coastal water productivity and the observation that phosphorus reduction programs did not always improve water quality in estuaries and coastal marine ecosystem, pointed to the possible role of nitrogen in water eutrophication [45, 49, 51-53]. A reason to warrant also the reduction in nitrogen loading as a means of decreasing eutrophication, is the evidence that in freshwater and oligohaline ecosystems characterised by excessive nitrogen inputs, phytoplankton may be dominated by cyanobacteria, in particular non-dinitrogen-fixing cyanobacteria such as *Microcystis*, *Planktothrix*, *Aphanocapsa*, *Raphidiopsis* and *Woronichinia*. The ammonium seems to be the favorite nitrogen source for non-dinitrogen-fixing cyanobacteria and may represent an important factor for their dominance [54]. Moreover different studies reveal that excessive nitrogen inputs can be involved in CyanoHABs both in freshwater than in marine ecosystems, despite dinitrogen fixation by cyanobacteria is much less likely in estuaries and costal environment than in lakes [1, 55].

CyanoHABs principally affect nutrient-enriched water body, in particular if they have extended low-flow periods during a hot season and persistent vertical stratification that enable them to grow and fix atmospheric nitrogen under optimal conditions. Estuarine and coastal waters are environmental zones badly affected by turbulences as wind and tidal mixing, rendering these waters suboptimal to dinitrogen fixation. Nevertheless some cyanobacterial species are able to grow during periods of calm, warm and stratified conditions in coastal and open ocean conditions (*Nodularia*, *Aphanizomenon*, *Anabaena*, *Trichodesmium*). Selective grazing, salinity and the deficiency of metals (in particular iron), required for the activity of nitrogenase enzyme, represent additional limiting factors on the presence of dinitrogen fixers in coastal ecosystems. Policies aiming only to limit phosphorus without controlling nitrogen inputs can result in phosphorus limitation in freshwater fallowed by grater nitrogen export downstream where it can cause eutrophication problems in estuarine and marine ecosystems. The involvement of both nitrogen and phosphorus inputs in algal productivity observed in eutrophic lakes, estuarine and coastal waters suggest that nutrient impact on eutrophication need to be evaluated along the entire freshwater-marine continuum and that the reduction of both nutrients additions are required for significant improvement of water quality. A strategic approach focused on only nitrogen and phosphorus should not be adopted unless there is clear evidence that the removal of one nutrient will not influence downstream ecosystems. Therefore a dual, as opposed to single nutrient reduction strategies should be adopted in order to contribute to resolution of eutrophication problem [45].

2.1.3.2 Cyanobacteria and climate changes

Notwithstanding the link between the increase in exogenous nitrogen and phosphorus inputs and the augmented incidence of eutrophication, climate changes represent additional factors influencing the frequencies and magnitudes of cyanobacteria blooms. The impact of climate changes on water resources includes warming of air and water, changes in pluviosity, increased storm intensity and rising of salinity level in waterbodies. The rise of greenhouse gases from man's activity represents one of the main causes of global warming [56]. Since the industrial age begun, human emissions have added gases like carbon dioxide and methane in the atmosphere, so enhancing the natural greenhouse effect and contributing to an increase in Earth's temperature and climate changes. A direct consequence of warmer air temperature is a warmer water temperature. Higher surface water temperatures have important impacts on aquatic species distribution, dissolved oxygen levels, concentration of pollutants and algal bloom manifestation. Increasing temperatures can directly favor bloom-forming cyanobacteria because the maximum growth rates are achieved by most cyanobacteria above 25° [57]. Whereas the cyanobacteria growth faster at high temperatures, growth of other eukaryotic phytoplankton classes like *Chlorophytes*, *Dinoflagellates* and *Diatoms* decay in response to warming [18, 58]. Therefore in waters with high surface temperatures, cyanobacteria have better probabilities of out-competing other species. This competitive advantage is also supported by vertical stratification of water in hot periods. Increases or decreases in the turgor pressure of cells, obtained by regulating the function of gas vesicles, influence cyanobacterial buoyancy and regulate their location in the water column depending on light intensity and on the presence of nutrients [59]. Cyanobacteria can grow under very poor nutritional conditions and their ability to modify their vertical position in water allows them to occupy optimum depth for their growth.

When an intense cyanobacterial growth occurs on the surface water, turbidity due to blooms suppresses the development of many species of eukaryotic taxa not displaying buoyancy regulation and which, therefore, can be only passively entrained in the euphotic zone [60-62]. Global warming will also favor the spread of tropical/subtropical species to temperate regions. This is the example of *Cylindrospermopsis raciborskii* which was originally found in Australia and Central Africa while at present it has been observed in Europe and in United States of America (USA), suggesting a link between eutrophication and warmer temperature [63, 64]. Cyanobacteria are photosynthetic organisms able to harvest light in the green, yellow and orange part of the spectrum thanks to the presence of accessory pigments. Light energy absorption induce also an increase in surface water temperature interested by blooms and this mechanism further support their growth as reported in the Baltic Sea [65]. An increase in the average global temperature is strongly linked to changes in precipitation due to the rises in water vapour and alterations in atmospheric circulation. Intense rainfall events could increase pollution due to runoff or transport contaminants and an excess of nutrients into waterbodies. In this way, nutrients can accumulate in waters and can influence cyanobacteria growth in particular when water bodies with vertical stratification and long water resident time are involved. This correlation between precipitation patterns and cyanobacterial dominance has been observed worldwide with examples in China, USA, and Australia [66]. However, periods of dryness may influence cyanobacterial proliferation too. When a dryness period occurs, water evaporation induces a higher concentration of nutrients and increases the area of still water where cyanobacteria can easily grow. Situations in which rainfall follows period of dryness are particularly dangerous because the rain can transport cytotoxins released from cyanobacteria into groundwater so contaminating key sources of drinking water [67]. The atmosphere is also an important source of trace metals such as iron which is directly involved in promoting primary production and cyanobacteria growth [68]. Industrialized regions (Europe, China, Japan, North America) are usually impacted by iron-enriched rainfall rising the iron loading in coastal, ocean and offshore waters and this phenomenon should be considered when a bloom occurs [69, 70]. With regard to rising of salinity level in water bodies, one of the main causes is the warmer temperature and the consequent increased evaporation of water and reduced rainfall. Different cyanobacterial genera are able to withstand relatively high concentration of sodium chloride and it has been observed that both dinitrogen-fixers (*Anabaena*, *Anabaenopsis*, *Nodularia*, *Lyngbya*) and non dinitrogen-fixing cyanobacteria (*Microcystis aeruginosa*) can tolerate saline environment. Bloom-forming cyanobacteria genera has been observed worldwide at high salinities (up to 10 for *M. aeruginosa* or beyond 20 for *Nodularia spumigena*) pointing out how salinity tolerance constitute a significant factor governing blooms [71, 72]. Another symptom of climatic changes caused by fossil fuel emissions and potentially impacting Harmful Cyanobacteria Blooms (CyanoHABs) is an increase in atmospheric carbon dioxide concentration which causes additional carbon dioxide dissolution in waterbodies. This is predicted to lead to lowering of pH and carbonate ion concentration in aquatic systems. The availability of carbonate is important because some marine organisms use it to produce shells of calcite and aragonite and a possible effect of ocean acidification is the inhibition of the biological production of corals and calcifying phytoplankton and zooplankton. Nevertheless, cyanobacteria grow is favorite by high CO_2 concentration that may promote the intensification of blooms in eutrophic and hypertrophic waters [73].

3. Algal Blooms and toxins

When favorable environmental and climatic conditions concur to induce harmful algal blooms (HABs), phytoplankton species (Figure 2) have the capacity to produce hazardous toxins that can find their way through levels of food chain (crustaceans, molluscs) and are subsequently consumed by humans causing diseases or in the most serious cases, the death. Different physical, chemical and biological factors are responsible for HAB manifestation and the resulting toxins production (Table 1, Table 2). These factors include a growth in temperature, an increased incidence of rainfall events and an excessive nutrient discharge in the waterbodies. Toxins are usually released when an algal bloom dies off. The cell membrane rupture causes the spread of produced toxins in waterbodies and their absorption by organic material in the water column. However, toxins can also be released into the water by live algal cells [74]. When HABs happen, the presence of toxic algae is not always directly correlated to the effective production of nocive toxins. Moreover, a specific toxin can be produced by different algal species and a single algal specie is able to produce multiple types and variants of toxins. Low cell densities are often sufficient to reach dangerous toxicity levels of toxins. In addition, water or seafood contaminated with toxins are odorless and tasteless and toxins can not be destroyed by cooking or freezing.

Marine toxins have been classified in five groups according to the effects they cause to organisms which include: Paralytic Shellfish Poisoning (PSP), Diarrhetic Shellfish Poisoning (DSP), Amnesic Shellfish Poisoning (ASP), Neurotoxic Shellfish Poisoning (NSP) and Azaspiracid Shellfish Poisoning (AZP) (Table 1). PSP, DSP, NSP and AZP have been all associated with human consumption of shellfish contaminated with toxins produced by dinoflagellates while ASP is caused by ingesting toxins released by diatoms [75-77]. Other potent marine toxins are Ciguatoxins. They are responsible for Ciguatera Fish Poisoning (CFP), an illness induced by consumption of tropical/subtropical marine carnivorous fish contaminated with ciguatera toxins (Table 1) [77]. Yessotoxin poisoning, palytoxin poisoning and pectenotoxin poisoning are additional diseases associated with toxins produced by dinoflagellates (Table 1) [77]. Yessotoxins and pectenotoxins were initially classified within the DSP group but have been successively included in a distinct group because these toxins have not been shown to cause diarrhetic effects.

Cyanobacteria, principally responsible of HABs in freshwater and at lesser extent in marine environments, are able to produce toxins which are classified in: i) hepatotoxins that act on liver ii) cytotoxins that produce both hepatotoxic and nefrotoxic effects iii) neurotoxins that cause injury on the nervous system and iv) dermatoxins that cause irritant responses on contact (Table 2) [78, 79]. At present, the most severe episode in human associated with cyanobacteria occurred in Brazil, where kidney dyalisis patients were exposed to toxins microcystins in the water used for dyalisis. At least 50 deaths were caused by use in dyalisis the water contaminated by cyanobacteria toxins [80]. Another human fatalities regarded a woman who died after the chronic consumption of Blue Green Algae Supplements (BGAS) [81], food supplements containing blue-green algae and generally used as natural products for their purported beneficial effects such as losing weight during hypocaloric diets or elevating mood for people with depression. Blue Green Algae mainly used in BGAS production are *Spirulina* spp. and *Aphanizomenon flos aquae*. They are usually collected from water where potentially toxic cyanobacteria can be present and cause BGAS contamination. In the reported case, the death was probably caused by the contamination of BGAS by microcystins but a clear link was not demonstrated in the study [81]. However, in general, data about the effects of cytotoxins on human are very scarce. Most of the studies have not sufficient data to directly correlate harmful effects in human with the exposition to cyanobacteria, making difficult to evaluate the risk associated to cytotoxins. It is therefore necessary to study thoroughly the health impact of cyatotoxins on human, also considering that the exposure to cyanobacteria can be possible through different routes like potable water, recreation water, dyalisis and food supplements.

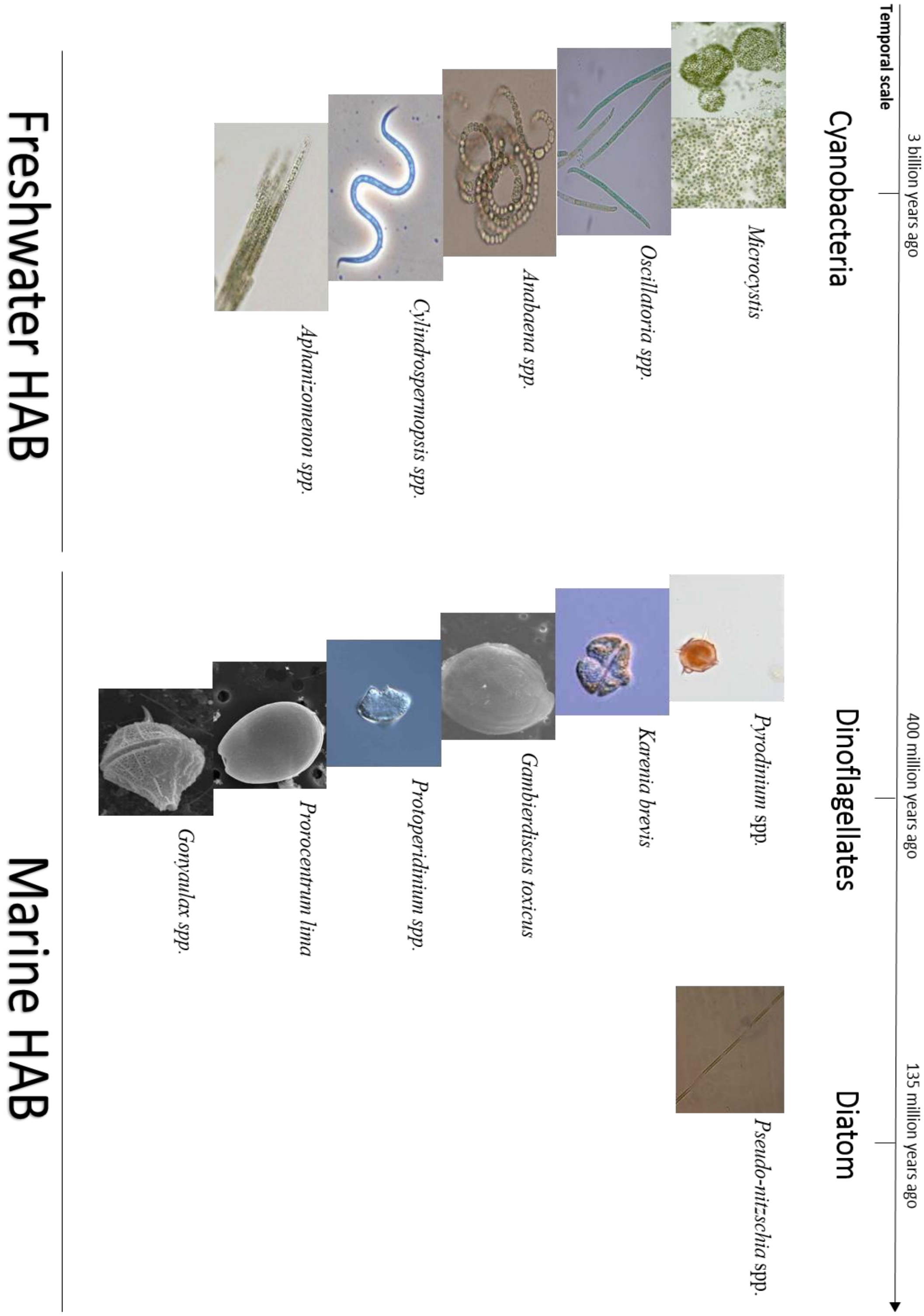

Figure 2: Phytoplankton species and organisms causing toxic Harmful Algal Blooms (HABs)

These photos represent some of the most common phytoplankton species and organisms involved in the production of nocive toxins. Cyanobacteria are principally associated with blooms occurring in freshwater while dinoflagellates and diatoms are common in seawater. Temporal scale indicates when cyanobacteria, dinoflagellates and diatoms appeared on Earth (Photo credit: Steve Morton and the "National Oceanic and Atmospheric Administration")

Table 1: Seafood poisonings caused by most common marine dinoflagellates or diatoms: their effects, primary targets and vectors

Poisoning	Main toxins	Most common organisms producing toxin	Effects	Main targets	Primary vector	Ref.
PSP*	Saxitoxins	*Alexandrium* spp., *Gymnodinium* spp., *Pyrodinium* spp.	Muscle twitching, burning, numbness, drowniess, headache, vertigo, respiratory paralysis leading to death	Sodium channels	Shellfish	[75, 82-85]
NSP*	Brevetoxins	*Kerenia brevis, Chattonella marina, C. antiqua, Fibrocapsa japonica, Heterosigma akashiwo*	Tingling, numbness, nausea, muscular pain, neurologic symptoms	Sodium channels	Shellfish	[86-88]
CFP*	Ciguatoxins	*Gambierdiscus toxicus*	Tingling, itching, hypotension, bradycardia, vomiting, diarrhoea, nausea	Sodium channels	Coral reef fish	[89-93]
AZP*	Azaspiracids	*Protoperidinium crassipes, Azadinium spinosum*	Diarrhoea, nausea, vomiting, stomach cramps	Calcium channel	Shellfish	[94-98]
DSP*	Okadaic acid, Dinophysis toxins	*Dinophysis* spp., *Prorocentrum* spp.	Diarrhoea, nausea, vomiting, abdominal cramps	Serine/ threonine protein phosphatases	Shellfish	[99-101]
Palytoxin poisoning	Palytoxins	*Ostreopsis siamensis*	Weakness, nausea, vomiting, myalgia, fever	Na^+-K^+ pumps	Shellfish	[102-105]
Yessotoxin poisonings	Yessotoxins	*Protoceratium reticulatum, Lingulodinium polyedrum, Gonyaulax spinifera*	Restlessness, dyspnea, shivering, jumping, cramps	Calcium/ sodium channel?	Shellfish	[106-108]
Pectenotoxin Poisoning	Pectenotoxins	*Patinopecten yessoensis*	Hepatotoxic effects	Na^+-K^+ ATPase	Shellfish	[101, 109, 110]
ASP*	Domoic acid	*Pseudo-nitzschia*	Amnesia, hallucinations, confusion, vomiting, cramping	Glutamate receptor	Shellfish, anchovies, crabs	[111, 112]

* (**PSP** stands for Paralytic Shellfish Poisoning; **NSP** stands for Neurotoxic Shellfish Poisoning; **CFP** stands for Ciguatera Fish Poisoning**; AZP** stands for Azaspiracid Shellfish Poisoning; **DSP** stands for Diarrhetic Shellfish Poisoning**; ASP** stands for Amnesic Shellfish Poisoning)

Table 2: Toxins produced by cyanobacteria: their effects and primary targets

Toxin classification	Toxins	Most common cyanobacteria genera producing toxins	Main organ affected	Effects	Main targets	Ref.
Hepatotoxins	Microcystins	*Microcystis, Anabaena, Anabaenopsis, Aphanizomenon, Planktothrix, Oscillatoria, Phormidium*	Liver	Diarrhea, vomiting, weakness liver inflammation, liver hemorrhage, pneumonia, dermatitis	Serine/ threonine protein phosphatases	[78-80, 113]
	Nodularin	*Nodularia, Nostoc*	Liver	Diarrhea, vomiting, weakness liver inflammation, liver hemorrhage, pneumonia, dermatitis	Serine/ threonine protein phosphatases	[78, 79, 113]
Cytotoxins	Cylindrospermopsin	*Cylindrospermopsis, Anabaena, Aphanizomenon, Raphidiopsis, Oscillatoria, Lyngbya, Umezakia*	Liver	Gastroenteritis, liver inflammation, liver hemorrhage, pneumonia, dermatitis	Protein synthesis	[113, 114]
Neurotoxins	Anatoxins	*Anabaena, Aphanizomenon, Planktothrix, Cylindrospermopsis, Oscillatoria*	Nervous system	Muscle twitching, burning, numbness, drowsiness, salivation, respiratory paralysis leading to death	Nicotinic receptors or acetylcholinesterase	[115, 116]
	Saxitoxins	*Anabaena, Aphanizomenon, Cylindrospermopsis Lyngbya, Planktothrix, Rhaphidiopsis*	Nervous system	Muscle twitching, burning, numbness, drowniess, headache, vertigo, respiratory paralysis leading to death	Sodium channels	[113, 117, 118]
	BMAA*	*Nostoc, Microcystis, Anabaena, Aphanizomenon, Nodularia*	Nervous system	No specific clinical symptoms, ALS/PDC with long-term consistent exposure	NMDA* excitotoxicity, ROS production	[119, 120]
Dermatoxins	Lypopolysaccharide	*Synechococcus, Microcystis Anacystis, Oscillatoria Schizothrix, Anabaena*	Skin	Skin irritation, eye irritation, headache, allergy, asthma, fever	Toll-like receptors	[121 - 123]
	Lyngbyatoxins	*Lyngbya*	Skin	Skin and eye irritation, respiratory problems	Protein kinase C	[124, 125]
	Aplysiatoxin	*Lyngbya, Schizothrix, Oscillatoria*	Skin	Skin irritation, asthma	Protein kinase C	[126]

* (**BMAA** stands for β-Methylamino-L-Alanine; **NMDA** stands for N-Methyl-D-Aspartate)

4. Algal Blooms incidence

Harmful algal blooms (HABs) events have been increasingly reported worldwide and the necessity to monitor their recurrence and impact on public health, fisheries resources and ecosystem health are some of the aims of the HABs research. The Harmful Algal Events Dataset (HAEDAT) is a database containing records of marine harmful algal events worldwide (Figure 3). In Europe, the single countries report HAB events to the HAEDAT inventory. The main institutions which provide data for the HAEDAT dataset and marine monitoring programs ongoing at national level are summarised in Table 3. HAEDAT contains records from the International Council for the Exploration of the Sea (ICES) area (North Atlantic) since 1985, and from the North Pacific Marine Science Organization (PICES) area (North Pacific) since 2000. Figure 4 shows the number of events currently contained in HAEDAT for different countries. Intergovernmental Oceanographic Commission (IOC) in South America, South Pacific and Asia, and North Africa are preparing to contribute. For every harmful algae event in the dataset a large number of information are provided, such as the location, the date of occurrence and duration, the causative species, the associated syndrome and toxins involved, the nature of the event and the resources involved. Figure 5 shows the total number of Harmful Algae events contained in the dataset depending on their associated syndrome, such as Diarrhetic Shellfish Poisoning (DSP), Paralytic Shellfish Poisoning (PSP), cyanobacterial and aerosolised toxin effects. The largest majority of events are related to seafood toxins, DSP, PSP, Amnesic Shellfish Poisoning (ASP), while only a small number of cyanobacteria events are reported so far. Figure 6 shows the total number of events according to their nature, most of the reported events are associated to seafood toxins, probably also due to higher monitoring of sea food for public health issues. A large number of events is also reported for high phytoplankton concentrations and water discoloration, less for fish mass mortality due to anoxic conditions.

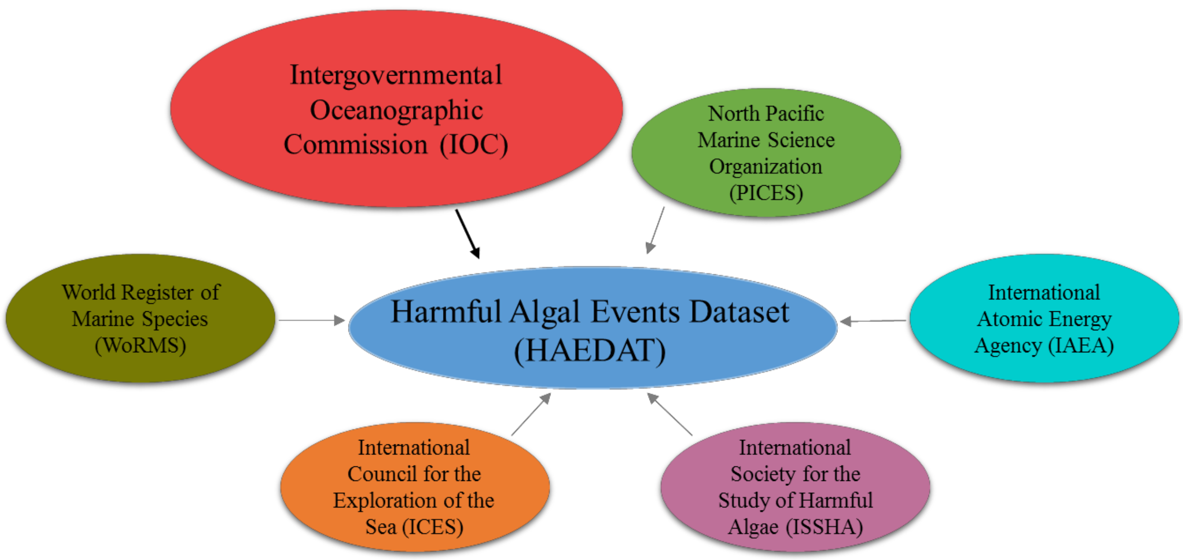

Figure 3: Harmful Algal Events Dataset (HAEDAT)

The figure shows the Commission (Intergovernmental Oceanographic Commission–IOC) which built the HAEDET and the other collaborating partners. HAEDET has been built within the "International Oceanographic Data and Information Exchange" (IODE) of the IOC of UNESCO, and in cooperation with the World Register of Marine Species (WoRMS), the International Council for the Exploration of the Sea (ICES), the North Pacific Marine Science Organization (PICES), the International Atomic Energy Agency (IAEA) and the International Society for the Study of Harmful Algae (ISSHA)

Table 3: Main countries and institutions who provide data for the Harmful Algal Events Dataset (HAEDAT) and the national marine monitoring programs about Harmful Algal Blooms (HABs) in Europe

Country/Region	Institutions/Monitoring Programs
Baltic Sea	Helsinki Commission (HELCOM)
	National Environmental Research Institute of Denmark
	Estonian Marine Institute
	Latvian Institute of Aquatic Ecology
	Swedish National Monitoring conducted by the Swedish Meteorological and Hydrological Institute (SMHI)
	German Marine Monitoring Program for the North and Baltic Seas (BLMP)
Norway	The Norwegian Food Safety Authority (NFSA)
UK	Food Standards Agency (England, Wales, N. Ireland)
	Food Standards Scotland
Ireland	Marine Institute of Ireland
France	Réseau d'Observation et de Surveillance du Phytoplancton et des Phycotoxines
	Suivi Régional des Nutriments
	Réseau Hydrologique Littoral Normand
Spain	Technological Institute for the Marine Environment Monitoring of Galicia
	Andalusian Monitoring Program
	Catalan Monitoring Program by Institut de Recerca I Tecnologia Agroalimentàries (IRTA)
Portugal	Portuguese Sea and Atmosphere Institute (IPMA)

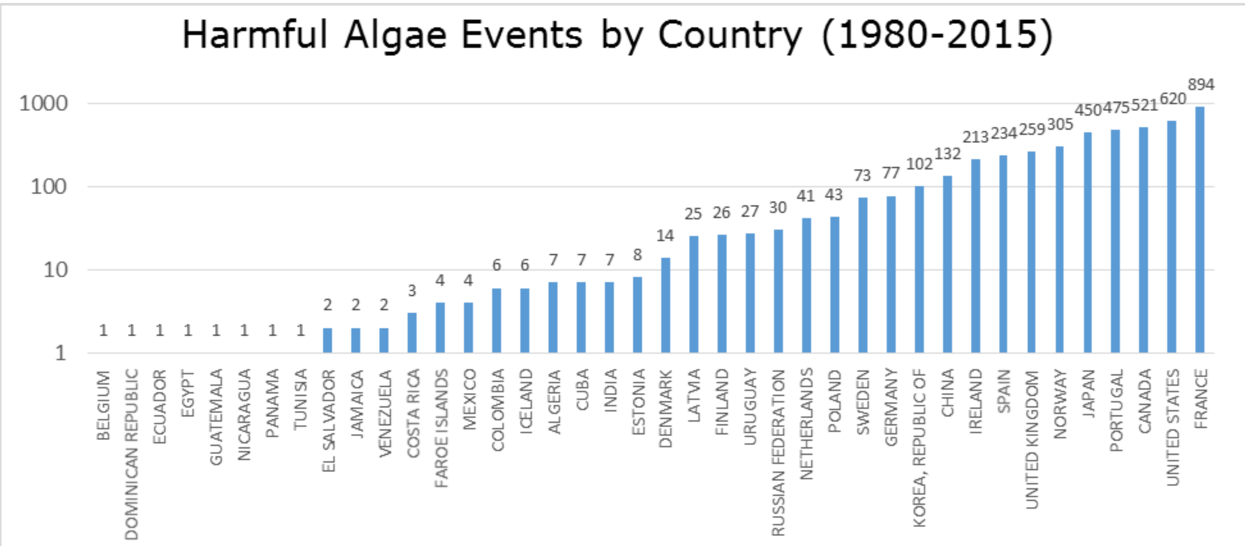

Figure 4: Total Number of Harmful Algae Events reported globally by single countries during the period 1980-2015 to the Harmful Algal Events Dataset (HAEDAT)

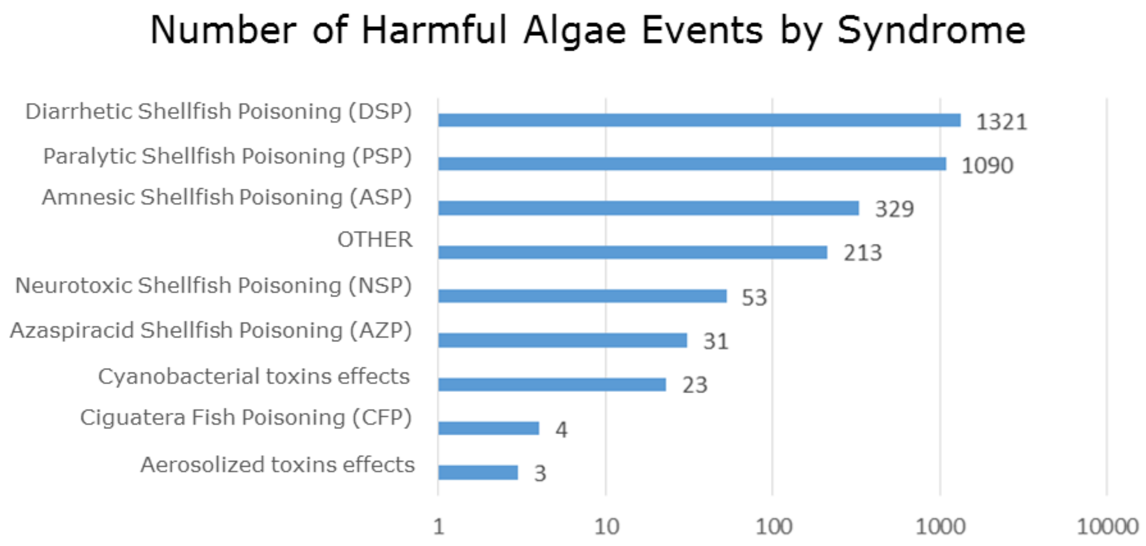

Figure 5: Total Number of Harmful Algae Events by syndrome reported globally during the period 1980-2015 to the Harmful Algal Events Dataset (HAEDAT)

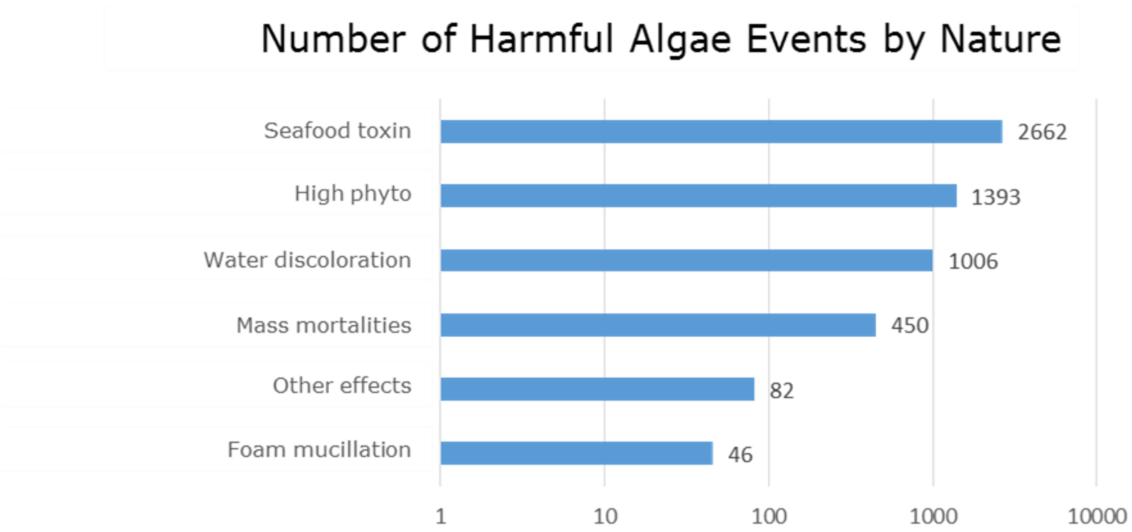

Figure 6: Total Number of Harmful Algae Events by nature reported globally during the period 1980-2015 to the Harmful Algal Events Dataset (HAEDAT)

5. Economic impacts of Algal Blooms

Harmful Algal Blooms (HABs) episodes represent a natural freshwater and marine risk and their manifestations are correlated to a significant impact on socio-economic systems and human health. Millions of people around the world need and depend upon freshwater or marine water for obtaining resources and services whose availability is strictly dependent on the protection of waterbodies. The impact of climate changes and anthropogenic factors synergize to negatively affect water environment causing alterations of their physical, chemical and biological properties. These changes may have significant socio-economic implications and the main sectors affected include public health, commercial fisheries, tourism, recreational activities, monitoring and management [8, 9].

HABs episodes are characterised by a rapid proliferation in algal population or by a production of harmful toxins. The biological impact of HABs includes fish mortalities, seafood contamination and illness in humans from the consumption of contaminated shellfish or fish. All these phenomena are responsible for direct or indirect economic impacts of HABs manifestations. Direct impacts include lost revenue in the marine business caused by shellfish closure, costs of medical treatments for cases of sickness in humans, expenses to remove algae from the water or dead fish from the beaches and investment costs in preventing and monitoring HABs. Indirect effects comprise a significant reduction in tourist flow to the areas affected by HABs, lost revenue from businesses that serve the hotel industry, a decrease in recreation use of lakes, sea and oceans and also an increase in spending of residents.

To date, not many studies have specifically addressed the economic effects of HABs, in particular when HABs were caused by cyanobacteria. The difficulty of conducting studies on marine HABs has been influenced by the lack of consistent data on market sectors, the low frequency of HABs, the number and dimension of area affected. Despite these limits, some analysis have been performed and probably they have been in part driven by the importance of toxins in commercial marine shellfish production. Far fewer data have been collected for HABs caused by cyanobacteria. The reason for this difference could be attributed to the spatially and temporally sporadic nature of these blooms. Anyway, the reported increase in HABs frequency will surely favor not only scientific studies to deeply understand factors concurring to generate HABs but also economic analysis to report whether safeguards taken have succeeded in mitigating the economic losses associated with blooms.

In this report, socio-economics effects caused by HABs are grouped in four main impacts: (1) human health impacts; (2) fishery impacts; (3) tourism and recreation impacts; (4) monitoring and management costs (Figure 7).

Figure 7: Economic impact of Harmful Algal Blooms (HABs)

Figure shows four sectors affected by HABs episodes and lists, for each of them, the main causes of economic losses

5.1 Human health impacts

When toxins are released in water during harmful algal blooms (HABs), their toxic effects in humans are believed to occur through different routes: consumption of contaminated seafood, inhalation via aerosols or wind dispersed particles of dried algal material, ingestion of water or scum and direct contact with skin or conjunctiva. The main illnesses caused by marine toxins in humans include the above mentioned Amnesic Shellfish Poisoning (ASP), Paralytic Shellfish Poisoning (PSP), Diarrhetic Shellfish Poisoning (DSP), Neurotoxic Shellfish Poisoning (NSP) and Ciguatera Fish Poisoning (CFP) (Table 1). These diseases may occur in humans with varying degrees of severity and the treatment of symptoms exhibited by affected people represent a cost for the healthcare sector. Hospitalization and sickness due to intoxication incidents result in the costs of medical treatments, illness investigation, emergency transportation and are also responsible for the loss of individual productivities.

A study published in 1995 showed the economic impact of toxin related diseases in Canada (Table 4) [127]. This study focused on the evaluation of their societal costs, defined as the sum of medical costs and individual expenses. The first included medical cares and medical investigations while the latter comprised lost wages, lost vacation time and transportation of patients to the hospital. The reported annual cases were 525 and the annual costs of diseases was overall estimated at $670,000. Data on monitoring costs of PSP was also included and they were valued to cost $3.3 million per year. A first effort to collect data about economic losses caused by HABs in the United States of America (USA) was done in a report focused on the period between 1987 and 1992 (Table 4) [128]. A review of HABs literature combined with the opinion of experts from coastal states and with calculations performed by the authors showed an expenditure of $20 million annually for public health due to seafood poisonings, about 42% of nationwide average expenditure. Another study analysed the expenses of respiratory illnesses such as pneumonia, bronchitis and asthma related to the occurrence of *Karenia brevis* bloom in Saratosa Country (Florida) (Table 4) [129]. *Karenia brevis* is a harmful marine algae responsible for the production of neurotoxins known as brevetoxins (Table 1). When humans come into contact with brevetoxins, they have a high probability of developing NSP [130]. However, brevetoxins may also be incorporated into marine aerosols and thus cause damage to the human respiratory system [131]. Weather conditions such as wind can furthermore spread toxins onshore where human may be exposed. In that study, a statistical model was used to correlate *Karenia brevis* episodes with the cost of respiratory visits to hospital emergency departments in a period of time ranging from October 2001 to September 2006. The hospital chosen was the Saratosa Memorial Hospital, a health facility located near the coast. Authors showed a direct relationship between *Karenia brevis* cell counts, pollen counts, influenza virus outbreaks, tourist visits and low temperature. These data was obtained by adding costs of medical services and lost productivities during the illness period and multiplying the result by the days of hospital visits. Costs of emergency department visits were evaluated to be $24 for nonurgent treatments, $67 for semiurgent treatments and $148 for urgent treatments. The total emergency departments visit charges was estimated to range from $252 and $1,045 while lost productivity was obtained by determining a weighted average median personal income of $38,589. Authors then conclude that the annual costs of respiratory illnesses associated with *Karenia brevis* blooms in Saratosa Country ranged from $0.02 to $0.13 million, depending on the severity of the bloom. One more recent study analysed the literature and surveillance/monitoring data in order to estimate the annual incidence and cost of marine borne diseases caused by marine pathogens in the USA (Table 4) [132]. It is well known that the consumption of seafood contaminated by toxins and beach recreation activities are the main causes of poisoning in humans. Authors estimated that the annual economic impact of marine borne diseases in USA was on the order of $900 million. Of these, a charge of $350 million was principally correlated to seafood-borne diseases due to pathogens and marine toxins, $300 million were associated to seafood diseases with unknown etiology and finally $30 million and $300 were linked to direct exposure to the Vibrio species and to gastrointestinal illnesses from beach recreation, respectively. As regards studies about the economic effect of HABs caused by cyanobacteria on human health, we did not find related monetary data.

Table 4: Estimated economic impacts of Harmful Algal Blooms (HABs) on human health

Article	**Ref.**	**Place of study**	**Sector affected**	**Estimated economic losses**	**Predicted range of time**
Estimated Costs of Paralytic Shellfish, Diarrhetic Shellfish and Ciguatera Poisoning in Canada	[127]	Canada	Public health	$670,000	Annual
The Economic Effects of Harmful Algal Blooms in the United States: Estimates, Assessment Issues, and Information Needs	[128]	USA	Public health	$20 million	Annual
The costs of respiratory illnesses arising from Florida gulf coast Karenia brevis blooms	[129]	Saratosa Country (Florida)	Public health	$0.02-0.13 million	Annual
An estimate of the cost of acute health effects from food- and water-borne marine pathogens and toxins in the USA	[132]	USA	Public health	$900 million	Annual

5.2 Commercial fishery impacts

Harmful algal blooms (HABs) episodes are strongly correlated to economic losses in fish market. During HABs, toxins released by algae may be absorbed by fishes causing closure of fish trade while algae proliferation may cause an oxygen depletion in waterbodies leading to fish mortality. The consequent increase in the cost of fish and the decline in consumer demand due to the reluctance to purchase fish at a high price and in particular during HABs manifestations, represent only some of the economic impacts of HABs in the commercial fishery field. A halt in commercial fishery involves a direct economic effect on producers and when harvested fishes are prevented from reaching the market due to high toxicity levels, the economic impact must also take into account harvest costs. HABs may also affect aquaculture facility that must invest additional money to safeguard the commercial activity. Because of the high public interest in seafood safety, the economic impact of commercial and recreational fishery represents an important point to understand the response of people to the troubles caused by HABs. However, economic studies about the impact of HABs on the commercial fishing sector are mostly referred to seawater with respect to freshwater. A study, in particular, recorded a monetary loss of about £29-118,000 per year in the United Kingdom due to a HABs in freshwater (Table 5), but unfortunately we failed to find other studies investigating similar impacts [133].

Focusing on marine HABs, a study performed in Southwest Florida analysed the economic effects of the red tide bloom in 1971. Authors calculated the amount of lost revenue in the commercial fishery industry at approximately $1,5 million while the total losses, obtained by including also tourism variable, was $20 million (Table 5) [134]. An estimate of economic effects caused by brown tide in commercial bay scallop industry in New York was shown to be around $2 million (Table 5) [135]. In this study, published in 1988, there was only a preliminary evaluation of economic data but this work was followed by more accurate studies about the relationship between marine HABs and economic aspects. Data from the Division of Marine Fisheries was used in a study conducted in North Carolina to monitor the economic impact of the two week Neuse River closure due to the bloom of dinoflagellate *Pfiesteria* in 1995 [136]. The survey focused on purchases and sales of seafood and interviews of dealers were also conducted to calculate the amount of economic loss incurred. The main impact was reported to occur at the dealer level where a 30% reduction in purchase of seafood products were recorded. To evaluate sales losses due to HABs episodes, many studies consider also the effects of public announcements warning of the dangers of consuming contaminated shellfish in addition to standard economic parameters. Consumers may be influenced by the media reporting the presence of poisonous shellfish in a particular area and their fear to eat a certain food can spread to other related products. Consumer worries about HABs and their possible consequences on human health may also be amplified by inaccurate and aspecific news from the media. In addition, the inability of consumer to distinguish between safe and unsafe products may induce them to suppose that all supplies are unsafe. A potential result of this phenomenon is a decrease in fish demand that can also be extended to uncontaminated products as reported in a study on the impact of demand for mussels in Montreal dating back on 1987 [137]. In this study, a domoic acid contamination of Prince Edward Island, Canada, was correlated to a significant sales losses incurred by Great Eastern Mussel Farms, one of the United States of America (USA) producers supplying the Canadian market. Shellfish produced by this firm recorded a decline in sales even if products were unaffected by the contamination and plastic bags of mussels had a logo with guarantees of freshness and quality. Authors found that demand for mussels was affected by information conveyed by the media and underlined the importance for states affected by blooms to provide a public education about these events.

The impact of media and in particular of negative publicity on seafood industry was analysed during a Pfiesteria bloom that occurred in Maryland in 1997 [138]. The economic loss was estimated at $43 million and it was mainly attributed to the effect produced by misinformation on consumers (Table 5). A more recent study used a contingent behavior analysis to measure the effects of a hypothetical *Pfiesteria* bloom on individual's perception of health risks related to consuming seafood [139]. A survey consisting in contacting consumers by email and by phone was performed with the aim to ameliorate the impact of negative public information about fish kills on seafood market. Individuals recruited for the survey were asked to respond to questions about the knowledge of *Pfiesteria* and regarding personal consumption of seafood, both with and without fish kills. Some individuals were sent materials describing health risks associated with *Pfiesteria* in order to reassure consumers that seafood is safe even during a fish kill episode. A pamphlet containing information about a new seafood inspection program were also provided to a group of respondents. Results showed a hypothetical decrease in seafood sales despite information assured they had no impact on human health. It was also displayed that customers were quite responsive to seafood inspection program and that actions by authorities could influence customer decisions. The economic loss due to avoidance costs to inform consumers of *Pfiesteria*-related fish kill was in the order of $100 million per month (Table 5). When this article was published, it was thought that *Pfiesteria* had not harmful effects on human health and until now no direct link with negative effects on humans has been clearly demonstrated [140, 141]. The economic impact of HABs on commercial fishery may also be avoided by elaborating prediction models useful to guide management actions. In a study focused on a bloom occurring in 2005 in the Gulf of Maine, a prediction model was correlated to the economic value of predictions [142]. This approach is useful because when a bloom is expected it will be possible to take strategic measures, such as the closure of fishing areas, to prevent economic losses. Another article analysed the effects of the 2005 bloom described in Maine and reported a loss of about $6.0 million in sales of mussels, mahogany quahogs, and clams caused by the closure of shellfish harvesting areas (Table 5) and a total economic impact of red tide event was estimated at $14.8 million for Maine businesses [143]. Recently, a short communication evaluated the potential economic loss to the oyster marker in Texas during the 2010-2011 season [144]. Texas is considered a primary supplier of oyster in USA and various algal bloom in 2011 caused a closure of several harvesting areas. The economic impact to the fisherman was calculated at the first level of impact: sacks of oyster, their value, landed on the local docks. The harvesting season for oyster is generally from November to the end of April and not considering expenses, losses calculated during the first three months were $8,515.67 per vessel, $8,515.67 per captain and $5,677.11 per deckhand (Table 5). Water closures in response to blooms were also reported in Galveston Bay (Texas) where they impacted the economy with estimated losses of $167,588 in the oyster industry (Table 5) [145]. Still, an extensive bloom occurred in New England in 2005 was declared to be a disaster in particular for the economic impact to shellfish harvesters. In the State of Maine waters were closed during the period of the bloom (from April to August) and caused estimated losses of $2 million in soft shell clam harvests and $400,000 in harvests of mussels (Table 5) [146]. Oxygen depletion, a phenomenon characterizing HABs episodes, was correlated to a decrease in the brown shrimps harvest in North Carolina. In particular, during the period 1999-2005, two adjacent areas, the Neuse River and the Palmico Sound experienced an economic loss of about $32,000 and $1,240,000 respectively [147].

Table 5: Estimated economic impacts of freshwater Harmful Algal Blooms (HABs) and marine HABs on commercial fishery

Article	Ref.	Place of study	Sector affected	Estimated economic losses	Predicted range of time
Environmental costs of freshwater eutrophication in England and Wales	[133]	United Kingdom	Commercial fishery	£29-118,00	Annual
The economic effects of the 1971 Florida red tide and the damage it presages for future occurrences	[134]	Southwest Florida	Commercial fishing industry /businesses that supply the hotel industry	$20 million	Annual
Measuring The Economic Effects of Brown Tides	[135]	New York state	Bay scallop fishery	$2 million	Annual
Pfiesteria's economic impact on seafood industry sales and recreational fishing	[138]	Maryland	Commercial fishery	$43 million	Annual
The Welfare Effects of Pfiesteria-Related Fish Kills: A Contingent Behavior Analysis of Seafood Consumers	[139]	Mid-Atlantic region, USA	Welfare (avoidance costs to avoid losses on the sale of fish)	$100 million	Monthly
Economic losses from closure of shellfish harvesting areas in Maine	[143]	Maine	Commercial fishery	$6.0 million	Annual
Potential economic loss to the Calhoun Country oystermen	[144]	Calhoun Country, Texas	Oyster industry	$22,708.45	Three-monthly
Economic Impact of the 2000 Red Tide on Galveston County, Texas: A Case Study, in Texas Parks and Wildlife	[145]	Galveston Bay (Texas)	Oyster industry	$167,588	Four-monthly
Economic impact of the 2005 red tide event on commercial shellfish fisheries in New England	[146]	Maine (New England)	soft shell clam harvests harvests of mussels	$2 million $400,000	Five-monthly

Article	Ref.	Place of study	Sector affected	Estimated economic losses	Predicted range of time
Quantifying the Economic Effects of Hypoxia on a Fishery for Brown ShrimpFarfantepenaeus aztecus	[147]	North Carolina	Fishery for brown shrimp	$32,000-1,240,000	Seven-yearly

5.3 Tourism/recreation impacts

Economic effects reported during harmful algal blooms (HABs) episodes are influenced by different variables, one of which is the tourism/recreation impact. The economic damage caused by blooms comprises losses due to fishing closures applied to recreational fishers, reduction in amusement and recreational experiences of visitors near the beaches and a drop in attendance in hotel, restaurants and in the number of rented holiday homes. The tourism and recreation effects on the economy are influenced by the change in the coastal or freshwater environment triggered during a bloom. These changes include the discoloration of water, the accumulation of dead fish on beaches and the smell coming from algae decomposition. When a local economic impact in these two sectors is estimated, it should be take into account a redirection of tourism business because other activities may benefit from HABs manifestations. This entails that, in many cases, an economic effects of HABs, extended to a state or a nation, could be difficult to quantify. A study that records the economic losses in tourism/recreation sector due to eutrophication of freshwater estimated at $1.16 billion the annual value loss in the United States of America (USA) (Table 6) [148].

Still, in a period of time ranging from 1987 to 1992, the economic loss reported in recreation and tourism sectors was estimated at $7 million per year (Table 6). These data refer, in particular, to the impact on tourism caused by the red tide in North Carolina in 1987 and the effect on recreational shellfishing for razor clams in Oregon and Washington in 1991 and 1992 [128]. Recreational razor clam fishery is an important touristic attraction for visitors of Washington's Pacific coast and during razor clam harvest opening, clammers give a significant contribute to the coastal economy. By calculating the total expenditures by clammers during the clamming season 2007-2008, an estimate of economic losses due to a whole season closure was about $20.4 million (Table 6) [149].

Most of the studies analysed the economic impact of HABs in Florida. HABs episodes are frequently reported in this state where coasts are principally affected by the dinoflagellate *Karenia Brevis*. This alga is responsible of producing brevetoxins, harmful neurotoxins which are released in the water column and can become airborne (Table 1). The presence of wind can favor the contact between neurotoxins and humans and can induce in them eye, nose and respiratory irritations. In addition, brevetoxins can render fish unsafe for consumption, cause fish mortality and the possibility of Neurotoxic Shellfish Poisoning (NSP) in humans if contaminated shellfish are eaten [87, 88]. Losses to restaurant and lodging sectors caused by HABs were studied in a small geographical area including Fort Walton Beach and Destin, both located in the Northwest part of Florida, from 1995 through 1999 when two red tides events were reported [150]. These two business sectors were selected because they were particularly vulnerable to red tide related losses. Considering only business activities located closest to the beaches and using a time series of reported taxable income from business sectors, this study quantified the economic impact of red tide events in a reduction of restaurant and lodging revenues of $2.8 million and $3.7 million per month, respectively (Table 6). Authors also verified that the passage of a tropical storm (hurricane) had a minor effect on the economy respect to a bloom, with an impact of $0.5 million per month. The influence of HABs on the behavior of people that decided to change their plans instead of going to beachfront restaurants was also assessed in a period from 1998 to 2005 [151]. Proprietary data was used to estimates sales reductions in three restaurants located directly on the Gulf of Mexico in Southwest Florida. Managers of the restaurants were asked to provide information about environmental conditions that were considered to influence sales like the presence of red tide, rainfall or storm episodes. A red tide event was reported by managers when there was a visible discoloration in the water, dead fish onshore or if physical symptoms caused by aerosolized toxins were observed. The accuracy of recorded data was assured by determining cell counts which represent a measure of the density of a bloom. Study results were found by correlating daily sales with environmental parameters (temperature, wind speed, rainfall, red tides, and storm conditions) and in the case of red tides, two restaurants out of three incurred a decline ranging from $868 to $3,734 for each day that blooms were detected (Table 6). Marine-based recreational activities are also affected by HABs. A study based on probability models performed a telephone survey in order to understand behavior of 894 residents of Saratosa and Manatee countries (Southwest Florida) relative to four activities: beach-going, fishing from boat, fishing from a pier and patronage of coastal restaurants. Results showed that residents affected by red tide ranged from a low of 37% for restaurant patronage to a high of 70% for beach-going [152]. The ability of HABs to influence individual behavior was also observed in changes in work habits of lifeguards employed in Saratosa country [153]. The survey was conducted during two different periods of time: from March 1 to September 30 in 2004 when HABs were not observed and from March 1 to September 30 in 2005 when HABs occurred. The absenteeism of lifeguards, defined as work absences attributable to an illness, caused a loss of about $3,000 in 2005 (Table 6). This value was calculated including the costs of medical expenses and lost labor productivity. Estimating the frequency of absenteeism, 56,25% percent of lifeguards were reported to take vacation time to reduce exposure to aerosolized toxins. Moreover the number of vacation days taken by lifeguards were more during a bloom than other periods of time.

Table 6: Estimated economic impacts of freshwater Harmful Algal Blooms (HABs) and marine HABs on tourism/recreation impact

Articles	**Ref.**	**Place of study**	**Sector affected**	**Estimated economic losses**	**Predicted range of time**
Eutrophication of U.S. freshwaters: analysis of potential economic damages	[148]	USA	Tourism/ recreation sector due to eutrophication of freshwater	$1.16 billion	Annual
The Economic Effects of Harmful Algal Blooms in the United States: Estimates, Assessment Issues, and Information Needs	[128]	USA	Recreation and tourism	$7 million	Annual
Regional economic impacts of razor clam beach closures due to harmful algal blooms (HABs) on the Pacific coast of Washington	[149]	Pacific and Grey Harbor counties (Washington)	Razor clam fishery	$20.4 million	Annual
Harmful Algal Blooms and Coastal Business: Economic Consequences in Florida	[150]	Northwest Florida	Restaurant revenue Lodging revenue	$2.8 million $3.7 million	Monthly Monthly
Firm-level economic effects of HABS: A tool for business loss assessment	[151]	Southwest Florida	Restaurant revenue	$868-3,734	Daily
Changes in Work Habits of Lifeguards in Relation to Florida Red Tide	[153]	Saratosa Country (Florida)	Lifeguard services on the beaches	$3,000	Seven-monthly

5.4 Monitoring and management impacts

Monitoring programs for harmful algal blooms (HABs) refer to strategies adopted by different countries worldwide to control hazards from toxic algae in order to protect public health, fisheries and minimize ecosystem and economic losses caused by blooms (Table 6) [154-156]. The water monitoring, when accompanied by appropriate management actions can assure the mitigation of ongoing HABs and the reduction of negative impacts. However, monitoring and management programs may alleviate future HABs episodes if preventions methods would have adopted. In that regard, the reduction in nutrient load in waterbodies may help to prevent certain types of HABs as observed when sewage or waste discharges are deeply monitored [157]. The economic effects of HABs on monitoring and management programs include costs for water sampling to assess the presence of nocive toxins when the count of algal cells exceeds the limit values. The presence of nocive toxins is also tested on shellfish products in order to prohibit their placing on the market in case of contamination. Other costs refer to expenses for water treatment required to remove toxins if a public water supply is expected, costs for actions to remove odor compounds associated with blooms or to identify the factor causing blooms and again expenses due to actions taken to destroy HABs during the bloom process [10, 158]. An efficient monitoring programme may include a regular qualitative and quantitative sampling of phytoplankton cells. Many states have adopted specific strategies to prevent blooms in coastal waters and have instituted specific action plans to safeguard fish mariculture [154]. In the case of Norway, this state accounts for 50% of the world production of farmed salmon and invests about $300,000 per year in monitoring actions against blooms (Table 6) [154]. Sampling campains are organized weekly and fish farmers along with the State Food Authority have a key role in the monitoring program. Other approximated annual costs of monitoring HABs in different states are included in a document published by the Asia-Pacific Economic Cooperation (APEC) in 2011 [154]. Looking in particular at the European data about annual monitoring plans against HABs, Denmark and Portugal spent about $500,000, France $800,000 and Spain (Galicia) $1114,000 (Table 6) [154]. A study reported an annual expenditure of $2 million associated to monitoring and management programs in the United States of America (USA) (Table 6) [128]. However, this cost is an underestimated value because it does not take into account many states which do not have regular HABs monitoring programs. In Massachusetts, Paralytic Shellfish Poisoning (PSP) tests on shellfish cost $7,000 per annum while in Florida, an expenditure of about $170 thousand per year is applied to the beach cleanup of dead fish due to a bloom (Table 6) [128]. An overview on the monitoring and management economic impact of HABs in the USA can be found in the document published by the Environmental Protection Agency (EPA) in 2015 [159].

Eutrophication is considered a major problem for water environments and the high levels of phosphorous and nitrogen inputs from different sources are among the principal causes of degradation of lacustrine and marine ecosystems. Baltic Sea is an example of eutrophication, indeed anthropogenic impacts and annual atmospheric depositions of dissolved inorganic nitrogen have led to an increase in nutrient concentration in the water mass associated with more frequent HABs episodes [156]. Baltic Sea is particularly subjected to eutrophication because it is a semienclosed sea where nutrients are carried in the water via rivers and atmospheric depositions. The concentration of nitrogen and phosphorus have significantly increased during the last century and since 1974, the Helsinki Commission (HELCOM) adopted investment programs to promote the protection of the Baltic Sea [156]. A study analysed cost-effective solutions in the agricultural sector to nutrients load reductions (nitrogen and phosphorus) to the German Baltic Sea region [160]. The analysis considered data about land use and nutrient emission from 19 river catchments with the aim to find the most cost-effective measures to reduce nutrients loads from agriculture. The abatment measures included the reduction use of fertilizers, the conversion of the land use to reduce the nutrient emissions and the advisory service to inform the farmers about the optimal solutions to be adopted for water protection. Whit this predictive model, the author estimated a cost of €9-34 million and of €12-35 million per annum to achieve the 25% nitrogen or phosphorus nutrients reduction, respectively (Table 6). Still, a recent study based on an assessment model to evaluate the economic impacts of climate changes on nutrient input to the Baltic Sea, estimated an annual value of 15 billion euros under certainty in climate prevision and forecasted additional costs under uncertainty ranging from 90 million euros to about 7900 million euros according to the adopted management actions in case of blooms (Table 6) [161]. A detailed review of the literature about cost evaluations of nutrient reduction policies for the Baltic Sea has been published by Halkos and Galani in 2013 [156].

Regulations on drinking and recreational water quality regarding cyanobacteria and cyanotoxins are principally focused on microcystins produced by *Microcystis aeruginosa*. The reason is that microcystins are considered the most important cause of possible damage to human health. A recent progress in the perception of cyanotoxins as risk for human health has been demonstrated by different countries and even if not all of them have incorporated analyses of cyanotoxins as a routine, several guidelines mention the provisional value of 1µg/l for microcystin-LR (MC-LR) for drinking water as reported on the 2003 World Health Organization (WHO) guidelines [7]. Specific approaches adopted by different countries for cyanotoxins risk assessment and management are included in the document published in 2012 by the Umweltbundesamt (UBA), the main German environmental protection agency [155].

With regard to monitoring costs associated with Harmful Cyanobacteria Blooms (CyanoHABs), a study conducted in Australia fixed at $8.7 million the annual costs for monitoring and contingency planning for blooms caused by cyanobacteria (Table 6) [162]. The evaluation of economic costs of monitoring of CyanoHABs was also performed in the summer 2002-20003 in the Waikato River, an important drinking water supply for Hamilton City in New Zealand. The cost was estimated at $50,000 over three summer months (Table 6) [163]. The need to prevent HABs episodes by planning monitoring programs is also linked to the necessity to limit economic losses in different fields such as tourism and recreation sectors. In Germany, high microcystin concentrations reported in Lake Boehringen (Germany) was the cause of the closure of all water recreational activities in 2011 and 2012 and the country invested €10,000 per annum in monitoring the lakes for CyanoHABs [10].

The ecosystem's response to a reduction in nutrient loading, an important aspect influencing the eutrophication state of waterbodies, was analysed in the four biggest lakes of De Wieden wetland (Netherland). An ecological-economic model was used to provide information on the cost-effectiveness of different approaches used to rehabilitate the lakes to a clear water state. The authors founded that the most cost-effective way to reach this aim provided for a total costs of around 5 million euros/year (Table 6) [164]. The approach was based on the reduction in phosphorous loading associated with biomanipulation, a method useful in removing the benthivorous fish with the subsequent increase in daphnia concentration and the reduction in the number of algae followed by a better water transparency.

During HABs episodes, different methods are adopted to remove algae from water. Chemical methods include the use of copper sulphate, an algicide which may cause the complete lysis of the bloom population and the release of toxins into the water. An example of illness following the use of copper sulphate is the recorded case of hepato-enteritisis occurred in the community of Palm Island (Australia) [165]. A study conducted in Australia estimated the value of copper sulphate treatments within the reservoir and in the water treatment intakes at $1 million per annum (Table 6) [166]. Other compounds commonly used are permanganate, aluminium sulphate, activated carbon and zeolite (Aqual-P) [10]. The effect of all these treatments on the environment has not been clearly understood and many management authorities prefer to adopt physical methods for removing CyanoHABs. These methods include artificial destratification, mechanical mixing, hypolimnetic oxygenation and hypolimnetic syphoning. When waterbodies experience periods of warm stable conditions, one effect may be the stratification of water column. During stratification, the hypolimnion, the deepest layer of water, becomes depleted of oxygen and nutrients can be released from sediments. This increase in nutrients induce the proliferation of cyanobacteria and physical methods, acting on destratification, mixing and oxygenation of water, may limit the cyanobacteria proliferation because they act by impairing their ideal growing conditions. The approach of hypolimnetic syphoning is used to remove nutrient-enriched water from waterbodies and this method, used in Lake Varese (Italy) in combination with oxygenation, is reported to cost $150,000 per annum (Table 6) [167]. In addition, mechanical mixers, used in a small reservoir in Perth (Australia) was estimated to cost $30,000 per month (Table 6) [168].

Table 7: Estimated economic impacts of marine Harmful Algal Blooms (HABs) and freshwater HABs on monitoring and management

Articles	**Ref.**	**Place of study**	**Sector affected**	**Estimated economic losses**	**Predicted range of time**
Monitoring and Management Strategies for Harmful Algal Blooms in Coastal Waters	[154]	Norway Denmark Portugal France Spain (Galicia)	Monitoring and management	$300,000 $500,000 $500,000 $800,000 $1114,000	Annual
The Economic Effects of Harmful Algal Blooms in the United States: Estimates, Assessment Issues, and Information Needs	[128]	USA Florida Florida	Monitoring and management PSP tests Beach cleanup	$2 million $7,000 $170,000	Annual
Diffuse nutrient reduction in the German Baltic Sea catchment: Cost-effectiveness analysis of water protection measures	[160]	German Baltic Sea region	Nitrogen reduction Phosphorus reduction	€9-34 million €12-35 million	Annual
Value of adaptation in water protection. Economic impacts of uncertain climate change in the Baltic Sea	[161]	Baltic Sea	Management actions	€15 billion-7960 million	Annual
Cost of algal blooms	[162]	Australia	Monitoring and contingency planning	$8.7 million	Annual

Articles	Ref.	Place of study	Sector affected	Estimated economic losses	Predicted range of time
New Zealand risk management approach for toxic cyanobacteria in drinking water	[163]	Waikato River (New Zealand)	Monitoring	$50,000	Three months
Cost-efficient eutrophication control in a shallow lake ecosystem subject to two steady states	[164]	De Wieden wetland (Netherland)	Management	€5 million	Annual
Economic cost of cyanobacterial blooms	[166]	Australia	Management	$1 million	Annual
Hypolimnetic withdrawal coupled with oxygenation as lake restoration measures: the successful case of Lake Varese (Italy)	[167]	Lake Varese (Italy)	Management	$150,000	Annual
Mixing in a small, artificially destratified Perth reservoir, in Department of Environmental Engineering	[168]	Perth (Australia)	Management	$30,000	Monthly

6. Future Outlook

Molecular technologies exploiting health problematics are in constant development. Several works on the use of molecular techniques for detection of toxin producing microorganisms have been reported [169-172]. Most works are based on quantitative Polymerase Chain Reaction (qPCR) analysis, measuring the prevalence of a target organism (specific gene) or metabolite (messenger ribonucleic acids) at very low concentration. Although the use of such information for management purposes is yet to be refined [173, 174], it certainly gives an idea of the toxic potential of a bloom and enables mitigation measures. Furthermore, techniques such metagenomics coupled with physical-chemical data may contribute for a deeper knowledge of the microbial community and infer on its response to environmental pressures. Metagenomics allows the analyses of the all microbial community, in its complexity, by reporting the relative abundance of each organism. Understanding the equilibrium state of the microbial community allows potential determination of "biomarkers" for specific stresses, such as temperature or nutrient input variations. Once "equilibrium" and stress conditions are known, predictive models on bloom occurrence, and its potential harm, can be developed based on real time measurements of variables such as temperature, nutrients and oxygen availability, among others. Systems for in situ qPCR analysis are being developed [175], unfortunately it still requires the presence of a technician in the field.

As regards climate and physical-chemical parameters remote acquisition of data is already a possibility trough data logger systems coupled to multi-probe sondes and meteorological stations. Overall, the contribution of molecular techniques and physical parameters to understand and predict the blooms dynamics has high relevance, since it allows predicting potential harmful situation at a very early stage.

Conclusions

Harmful Algal Blooms (HABs), defined as a mass proliferation of toxic or non toxic phytoplankton species in aquatic ecosystems, are natural occurrences with important economic implications in different sectors. This technical report, after giving a description of the most common phytoplankton organisms causing HABs, compiles data from different sources including scientific reports, papers and books about the economic losses due to HABs. Data refer to both marine and freshwater HABs and are related to the impact of blooms on human health, fishery, tourism or to the monitoring and management processes for preventing HABs. Among all sectors examined in this report, economic losses associated to human health are surely the most complicated to determine, mainly for the difficulty to assess the direct effects of toxins on human health because of the wide range of symptoms they can induce. European data are not included in all categories analysed but only in the section about monitoring and management costs. A reason may be the lack of reports or publically available data on the economic impact of HABs in Europe. Cost estimates about HABs events in the United States of America (USA) are, on the contrary, well documented by scientific reports. The need for transparency in the economic data, linked to a good evaluation of the costs of actions adopted to assure a good water quality and to identify which are the most effective ones to use, may guarantee a clear evaluation of economic losses caused by HABs. The value of this report is to provide information about monetary losses that are needed in cost- benefit analyses for policy guidance about HABs. It can also be a support to familiarise readers with HABs events and to allow the scientific community to evaluate the methods for estimating the impact of HABs on the economy and also to identify the most-effective ones in terms of costs and benefits. Providing information to individuals about HABs and promoting management processes to reduce their manifestations are examples of measures useful to reduce negative impacts associated with blooms. It is therefore important to guarantee a greater public awareness of HABs episodes and foster the effective monitoring and management of HABs in order to recognise the phenomena, understand their causes, predict their manifestations, and mitigate their effects. Molecular–based technologies 'data and the integration into model for prediction will pave the way to accomplish this effort.

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List of abbreviations and definitions

APEC	Asia-Pacific Economic Cooperation
ASP	Amnesic Shellfish Poisoning
AZP	Azaspiracid Shellfish Poisoning
BGAS	Blue Green Algae Supplements
BLMP	German Marine Monitoring Program for the North and Baltic Seas
BMAA	β-Methylamino-L-Alanine
CFP	Ciguatera Fish Poisoning
CyanoHABs	Harmful cyanobacteria blooms
DSP	Diarrhetic Shellfish Poisoning
EPA	Environmental Protection Agency
HABs	Harmful algal blooms
HAEDAT	Harmful Algal Events Dataset
HELCOM	Helsinki Commission
IAEA	International Atomic Energy Agency
ICBN	International Code of Botanical Nomenclature
ICES	International Council for the Exploration of the Sea
ICNP	International Code of Nomenclature of Prokaryotes
IOC	Intergovernmental Oceanographic Commission
IODE	International Oceanographic Data and Information Exchange
IPMA	Portuguese Sea and Atmosphere Institute
IRTA	Institut de Recerca I Tecnologia Agroalimentàries
ISSHA	International Society for the Study of Harmful Algae
NFSA	The Norwegian Food Safety Authority
NMDA	N-Methyl-D-Aspartate
NSP	Neurotoxic Shellfish Poisoning
PICES	North Pacific Marine Science Organization
PSI	Photosystem I
PSII	Photosystem II
PSP	Paralytic Shellfish Poisoning
qPCR	quantitative Polymerase Chain Reaction
ROS	Reactive Oxygen Species
SMHI	Swedish Meteorological and Hydrological Institute
UBA	Umweltbundesamt
USA	United States of America
WHO	World Health Organization
WoRMS	World Register of Marine Species

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