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Human induced harmful algal blooms

The occurrence of coastal harmful algal blooms (HABs) over the last several decades has become a worldwide environmental concern. Some of these HABs are caused by anthropogenic nutritient pollution and can harm whole marine ecosystems which, in the worst cases, may become devoid of life. Aside from biodiversity impacts, they can also menace coastal economies.

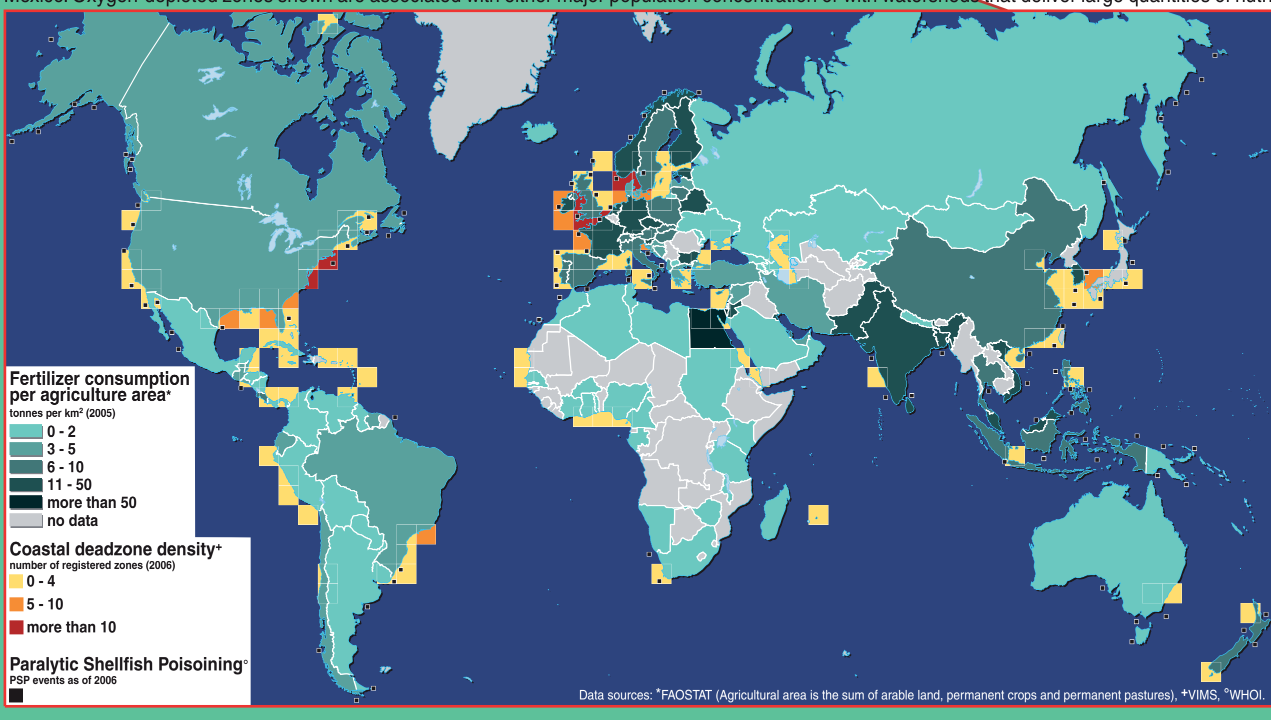
The threats to coastal and marine ecosystems are numerous today but one of the most widespread environmental problems is caused by an excess of nutrients[1] (Fig.3). Over the last century, intensification of agriculture, waste disposal, coastal development and fossil fuel use has substantially increased the discharge of nitrogen, phosphorus and other plant nutrients into the environment. Transiting via streams, rivers, groundwater, sewage outfalls and the atmosphere, these nutrients eventually end up in the oceans.

High nutrient concentrations stimulate the growth of microscopic algae called "phytoplankton". There is a clear connection between eutrophication (excessive nutrient load) and two significant environmental concerns: HABs and hypoxia (lack of dissolved oxygen in bottom waters) or "dead zones"[2, 3]. The effects of both HABs and hypoxia may be felt throughout coastal ecosystems, with direct and indirect effects on the environment and human health, food supplies and recreation[4]. HABs and hypoxia are natural and known since geologic times, but their increase in the last decades, mostly in coastal areas is, in some cases, clearly related to human development[5, 6, a].

Phytoplankton have colonised all fresh, brackish and salty waters. As there are usually only transient blooms in the upper ocean where the supply of nutrients is not sustained, coastal blooms are the topic of this note. The coastal environment is the most important area in terms of biodiversity and the most productive portion of the world's oceans. It also is the most affected by human activities.

Many countries have developed research plans dealing with the different aspects of harmful phytoplankton blooms[7, 8, 9, b, c]. One of the difficulties in studying HABs is that there are no standard blooming mechanisms or processes for different locations or regions[10]. HABs are sometimes revealed through satellite imaging (chlorophyl anomalies indicate phytoplankton dynamic[11]) (Fig.4), collection of water samples (enumeration of toxic algae), hydrodynamic and climatological studies (plankton and nutrients are transported by ocean currents that are in turn influenced by climatic factors[11]), and by measurements of HAB toxins in shellfish and other vectors.

Fig. 1 2006 Global dead zones



The number of coastal dead zones has doubled every decade since 1960[12]. Many are seasonal, but some of the low-oxygen areas persist year-round. More than 100 000 km² of marginal sea are affected, plus numerous bays and estuaries which are the most altered[13, 6]. The world's largest dead zone is found in the Baltic Sea, and the second is the Gulf of Mexico. Oxygen-depleted zones shown are associated with either major population concentration or with watersheds that deliver large quantities of nutrients to coastal waters (such as fertilizers). Out of 350 areas spotted in 2006, 175 are of concern, 161 are documented and only 13 have shown improvement.

Even if the increase of detected paralytic shellfish poisoning (PSP, one of many toxins linked to algal blooms - others include DSP, NSP, CFP, AZP, ASP) around the world seems clear, scientists often call it "apparent" because of the poor historic data available and the improvement of the detection methods during the last decades. The fact that part of the expansion may be the result of increased awareness should not negate human concern[d].

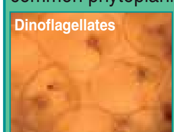
What leads to HABs?

Nutrient over-enrichment

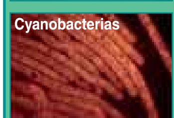
As the physical and biological processes involved are not well understood, and long-term observations are still lacking, it is difficult to assess the precise way in which human activities influence the occurrence and severity of HABs[4]. There is a clear connection between nurient levels and primary production (photosynthesis) and the most evident human influence on coastal productivity is due to pollution coming from river outflow and sewage. The growth of human activities (agriculture, aquaculture, industry, urbanization, recreation, etc.) has drastically increased the amount of nitrates and phosphates flowing into coastal waters[1, 2, 10].

Fig. 2 Microscopic images of potentially harmful phytoplankton

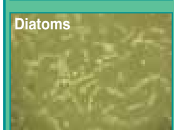
Phytoplanktonic algae are photosynthetic organisms that combine energy from the sun, carbon dioxide, and nutrients (nitrogen, phosphorus) to grow. Algae vary from small, single-celled species to complex multicellular forms, each one playing a significant role in aquatic ecology and oxygen supply to the atmosphere. They are the base of the marine food web, serving as the ultimate source of food and energy for even the largest fishes and mammals, through food-web transfer. Amongst the thousand of species of phytoplankton, about one hundred are known as potentially dangerous. The most common phytoplankton organisms forming HABs are:



Some of these unicellular organisms can form a cyst that remains dormant on the ocean bottom for years, waiting for favourable conditions to germinate again.



These bacteria, often referred to as blue-green algae are found in almost every conceivable habitat, from oceans to fresh water and from bare rock to soil. Some produce potent toxins of various types.



The cell is encased within a unique wall made of silica that shows a wide diversity in form and beautiful ornamentations. Most diatoms are harmles and are impoartant contributors to oceanic productivity. A few species are toxic, however, and can affect human health and marine ecosystems.

Photo credits: Elisabeth Nezan (Ifremer), John Patchett (University of Warkwick), Mark Schneegurt (Wichita State University), Cyanosite (www-cyanosite.bio.purdue.edu)

Intensified agriculture and industrial farming are on the rise to cope with increased demand for food by an expanding global population. Nutrient over-enrichment of oceans from agricultral runoff (fertilisers) is amongst the greatest threat to the health of marine ecosystems[14, 15, 16]. This worldwide emerging problem leads to widespread changes in the structure and functioning of entire ecosystems. The largest source of nitrogen pollution comes from agriculture activities (for example, runoff from cropland and animal lots), which leak directly into water bodies or are volatilise into atmospheric ammonia[17]. Since 1800, nitrogen pollution has increased 5-10 fold and is still increasing[1]. Phosphates and nitrates are used in huge quantities to fertilize soils (Fig.3), and actually only a fraction of these ends up in crops - in some regions it is less than 20%[18]- the rest leaking into the environment where it may have serious impacts on air, land, freshwater and oceans.

Discharge of untreated domestic wastes linked with population growth and rapid urbanisation is also a major source of marine pollution. The effects of raw sewage discharge into water bodies are multiple, and eutrophication is often one. For many countries, the main constraint to progress in sewage treatment is not technical but financial[1]. While some countries can impose and afford the best available technology for wastewater treatment, big cities of emerging/developing countries often discharge more than 80% of their wastewater untreated (Fig.3). Besides domestic wastes, industrial sewage discharges are also noxious to the marine environment.

Blooms driven by other factors

Fossil fuel combustion[17] (deposition of oxidized nitrogen compounds from the air) and dispersion of harmful species via ballast water discharge[2] are also known mechanisms that can bring about some types of blooms.

Beside human-induced nutritional pollution, some areas of the oceans experience "natural" algal blooms. Oceanographic and climatologic processes lead to currents (driven by wind, storms, differences in water density, etc) that can bring up deep cool nutrient-rich waters to the shallow zones where photosynthesis take place. Better conditions for growth and reproduction of the phytoplankton are then available, favouring blooms.

Aftermaths of natural catastrophic phenomena such as abundant precipitation, floods, hurricanes and warm sluggish water runoff are also known to flush more fresh water and nutrients into the coastal region, sometimes leading to blooms.

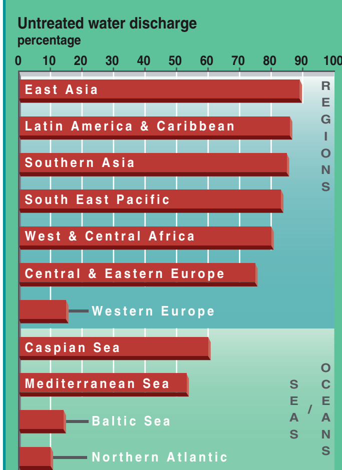
Impacts and consequences

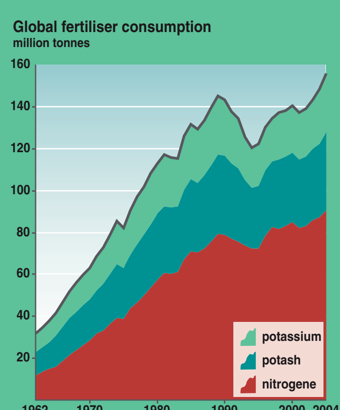
Estuaries and bays are most affected, but eutrophication is also apparent over large areas of semi-enclosed seas such as the Baltic, North Adriatic, Black Sea, the Gulf of Mexico or the Seto Inland Sea (Japan)[19]. Once conditions are favourable, cells of microalgae reproduce prolifically through asexual cell division leading to exponential growth. If unchecked by environmental conditions (grazing by animals or a shortage of

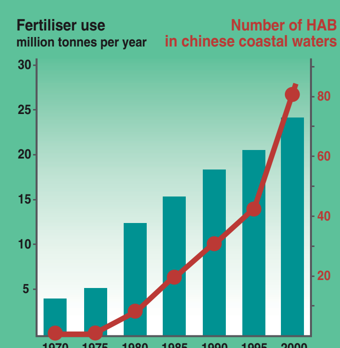
Fig. 3 Water conditions favoring some HABs

Marine water pollution has been identified as a factor in some HABs. Primary production, such as algal cell division, increases with eutrophication which is often fueled by untreated sewage water discharge. Notice on the graph how much water treatment needs improvment worldwide!

A link between the trends in fertilizer use and the number of red tides for Chinese coastal waters has been reported. Annual fertilizer use has climbed to 156 million tonnes, almost fivefold rise over the last 40 years. Stronger natural buffer zones (forest, wetlands) and diminished runoff of nutrients have the potential to decrease the number and intensity of HABs worldwide.







Data sources: The International Fertilizer Industry Association[h], Earth Policy Institute[i], UNEP 2006[1], Smil 2001[23], Zhang 1994[24]

Fig. 4 Satellite imagery detection

This SeaWiFS image acquired on April 16, 2001, shows the development of a highly reflective phytoplankton bloom (in green) in the Gulf of California. In addition to naturally high nutrient concentrations and productivity in this area, nitrogen-rich agricultural runoff fuels large (54 to 577km^2) phytoplankton blooms. Runoff exerts a strong and consistent influence on biological process, in 80% of cases stimulating blooms within days of fertilization and irrigation of agricultural fields[14].

Photo credit: NASA's visibleearth[j]

nutrients or light), the population can sometimes accumulate to visually spectacular (and environmentally catastrophic) levels. Discolouring the water (red, green, brown), these blooms cause problems even if composed of non-toxic algae. Sometimes harmful algae are dilute and invisible: the water seems clear, but still contain dangerous levels of highly potent toxins. These toxins enter the marine food chain when the producing algae are consumed by marine animals (zooplankton, fish or shellfish), accumulating in these consumers and passing up the food chain.

Impact on marine ecosystems

The connections between nutrients, eutrophication, HABs and hypoxia as well as their impact on the marine ecosystem itself are multiple and difficult to quantify.

"Dead zones" are defined as very low oxygenated (hypoxic) areas in the world's seas and oceans (Fig.1). Many of them are devoid of fish and other aquatic life, they are known all throughout the world and lead to a decline in biological diversity[14, 23]. After dying, microalgae sink to the bottom where they are decomposed through bacterial action which use up most of the oxygen dissolved in the bottom waters. As summer ocean waters are stratified, bottom waters become isolated and oxygen-depleted, resulting in inhospitable conditions. In some cases, oxygen depletes so quickly that it cuts off escape routes and results in fish kills.

Coastal biodiversity is the highest compared with all other ocean biotopes, but also the most affected by pollution. Coastal HABs thus can have a noteworthy deleterious effect on the most important marine ecosystems – an impact that is not quantifiable in terms of money. Through the food web, toxic blooms also affect seabirds and marine mammals such as whales, dolphins, sea lions and manatees[3, 20, 21]. It is however clear that losses of non-commercial marine resources can have severe consequences. Prolonged high biomass blooms damage seagrass and coral reef communities through the reduction of light penetration, and by depleting the oxygen in the environment. Macroalgal (seaweed) HABs have affected reef habitats in many parts of the world.

Photo credit: NOAA's CSCOR[b]

Consequences for human society

In European marine waters, the annual socio-economic impact of HABs is estimated at around 850 million euros affecting mainly commercial fisheries (158 million euros) and tourism (687 millions euros)[22]. The country with the greatest losses appears to be Spain immediately followed by France and Italy[a]. In the USA, researchers estimate HABs' cost as being at least $50 million per year[2].

Public health is the sector most affected by HABs when people are exposed to toxins principally through the consumption of contaminated seafood products. Most shellfish filter seawater for food, sometimes consuming toxic phytoplankton. The toxins then accumulate in their flesh and can reach a threshold where they become dangerous (sometimes lethal) to humans and other animals, though not to the shellfish themselves. Syndromes[2] are gastrointestinal problems that might include nausea, vomiting, diarrhea, dizziness, disorientation, amnesia and permanent memory loss, and paralysis up to death in the worst cases. Among the five main toxins, *ciguatera* is responsible for more than half of all seafood intoxications (10 000 to 50 000 human illnesses anually[g]).

HABs can also threaten **aquaculture and fishing ressources**. In 2004, seafood production reached about 130 million tonnes globally, one quarter coming from aquaculture. About 20 million tonnes are farmed in freshwater and 15 million in salt waters[17]. Natural waste produced by the farmed animals, as well as excess feed can result in an over-abundance of nutrients in natural waters surrounding aquaculture areas. If this load exceeds certain limits, it can contribute to algal blooms[17]. Consequences are the closure of harvestable shellfish and fish stocks, and death of shellfish, as well as of wild and farmed fish (by hypoxia or by alteration of gill function). Even non-toxic, large biomasses of phytoplankton can prevent light from reaching seagrass beds and coral reefs which provide nurseries for commercially important fish.

Tourism and related business can suffer from HAB pollution. High-biomass HABs sometimes coat and foul beaches, making them inhospitable in appearance and smell, and interfering with recreational activities. Overgrown and turbid seagrass beds and coral reefs are no longer attractive for divers, and might not support the high diversity necessary for a healthy environment. Reductions in seafood sales, including the avoidance of "safe" seafood due to over-reaction to health warnings during HAB outbreaks can also be important.

Fig. 5 Fishkills linked to HABs worldwide as of 2006

Harmful algal blooms can result in extensive fishkills. For example, during the night of 19-20 August 2003, millions of young menhaden were killed on the west shore of Narragansett Bay, Rhode Island USA, probably because of oxygen depletion resulting from an algal bloom.

Below, a map showing the location where extensive fishkills were reported as of 2006.

Photo credit: Narragansett Bay Estuary Program, Narragansett, R. I. www.nbep.org
Data source: WHOI[g]

Some solutions exist

Some preventive solutions exist and direct bloom control strategies are under development, but the appropriate public policy response to eutrophication is complex, as many economic activities are involved in nutrient enrichment of the marine environment. Remediation is possible, as demonstrated by remarkable improvement of an oxygen-starved zone of the Black Sea, that disappeared within seven years following the decline of use of manufactured fertilizers in Central and Eastern Europe[25].

Preventive solutions

- Cut the use of eutrophic polluting substances upstream in the watershed (e.g. ecotaxes on these products).
- Curb the use of pesticides and their discharge in the rivers where they can contribute to eutrophication by killing certain classes of organisms.
- Better treatment and disposal of industrial, human and animal waste (develop waste treatment facilities and technology).
- Better use of fertilisers in farming (favour natural fertilizers, reduce excessive and poorly-timed application)[13].
- Reduce nitrogen and CO_2 emissions from fossil-fuel burning (using new technologies and/or alternative energy sources)[26].
- Avoid land conversion, and promote the restoration of wetlands and other natural buffers (forests, grasslands) that act as reservoirs of nutrients before they reach the ocean.
- Replace laundry soap phosphates by anti-calcareous agents that don't have impacts on the environment.
- Educate and sensitize people regarding the issue.

HAB and eutrophication control strategies

Secondary effects of bloom control strategies on the environment are often hard to predict, so the preventive strategies mentioned above are recommended. Nonetheless, one can cite several promising bloom control strategies that are under development:

- Clay treatment of blooms, making harmful algae sink and die[27].
- Aquaculture for remediation, as shellfish and seaweeds reduce nutrients in the coastal ocean[4].
- Biocontrol, using parasites, bacteria, viruses or other natural pathogens to bloom organisms[27].

Conclusion

Overall, coastal and marine ecosystems continue to deteriorate mainly because of pressures from human development. The fact that some HABs are linked to human activities makes our concerns even more urgent. Despite continuous action to deal with the problem of nutrient over-enrichment for the past few years, the desired effect is not yet being achieved. There exists a considerable time lag between the pressures imposed on the environment, the subsequent development of policies, the implementation of measures and, eventually, the visible manifestation of the impact of such response. It often takes 15 to 20 years before meaningful commitments to joint management can be secured, and an even longer time before the environment actually begins to respond[1]. There is still a long way to go, but it is now fundamentally important to reduce eutrophication impacts on natural systems.

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UNEP GRID Europe

A. Piuz, S. Kluser, P. Peduzzi

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For further information

United Nations Environment Programme
DEWA / GRID-Europe
Tel: (4122) 917.8294
Fax: (4122) 917.8029
E-mail: earlywarning@grid.unep.ch
Web: www.grid.unep.ch/ew

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