

Scientific Analysis of The Harmful Algal Blooms and Hypoxia Research and Control Amendments Act of 2011



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Executive Summary

Harmful algal blooms are transient increases or accumulations of algae in freshwater and marine environments that cause some degree of negative effect to aquatic systems or human health. Blooms are natural occurrences, but the frequency and magnitude of these events is increasing, likely due to human influence. Nutrients discharged from sewage and industrial outfalls and runoff from residential and agricultural land travel through river systems, eventually reaching fresh or marine water bodies. A proliferation of algal biomass occurs when the enrichment of nitrogen, phosphorous and other nutrients combines with appropriate light, temperature, and other environmental conditions.

Some algae naturally produce toxins. Toxins synthesized and released by harmful algal blooms may impact human health via the consumption of contaminated shellfish or from direct contact with algae. Algae-derived neurotoxins and other classes of harmful toxins have been recognized as a potential health problem in both coastal and inland populations for millennia.

Algal blooms may also lead to ecosystem and health damages through the reduction of dissolved oxygen in aquatic systems. When algal biomass from large blooms dies, decomposition depletes the dissolved oxygen and may cause hypoxia, or reduced oxygen availability. A significant drop in dissolved oxygen can have severe consequences for many aquatic organisms, and can result in fish death or forced migration.

The combination of toxicity and hypoxia resulting from algal blooms can have significant impacts on coastal ecosystems, leading to fish mortality and deleterious effects upon birds and protected marine mammals including death and forced migration. Outbreaks of algal blooms have become an increasing problem throughout the United States, including the Gulf of Maine and the Gulf of Mexico. Algal blooms negatively impact fisheries and coastal tourism, with estimated annual costs of \$82 million per year. Cyanobacteria in freshwater systems form high biomass blooms and may produce toxins, and have impacted human health, killed aquatic organisms and harmed fishing and other industries in the United States and worldwide.

In 1998, the Harmful Algal Blooms and Hypoxia Research and Control Act was enacted to support research on HABs and hypoxia. This report provides a scientific analysis of proposed amendments to this legislation that call for a national action plan and associated regional plans to improve prevention, control, and mitigation of algal blooms.

Scientific research and advances in technology have significantly helped in understanding the causes and consequences of harmful algal blooms, as well as in forecasting, monitoring, and responding to outbreaks. A number of research programs focus on the biology and ecology behind harmful algal blooms and hypoxia, while evolving technology aims to better detect and predict harmful algal blooms. Various methods of controlling algal blooms need further testing to evaluate the potential for incidental damage to the affected ecosystems.

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1.0 Introduction to Harmful Algal Blooms

Algae are a diverse group of simple organisms that may be either unicellular or multicellular and are typically autotrophs, meaning that they are producers for aquatic systems. Most perform photosynthesis, and are considered "simple" because they do not have the many distinct structures and organs found in land plants. Algal blooms are transient increases or accumulations of algae or phytoplankton in freshwater and marine environments, sometimes caused by an influx of nutrients. Eutrophication is the process by which nutrient loads of nitrates and phosphates wash into the water system. These high nutrient loads can often be traced back to human use of fertilizers and pesticides, as well as to waste discharges from animal agriculture (Larsson et al. 1985). Other sources can include industrial processes and municipal waste systems that may produce combined sewer overflow during rain events (Larsson et al. 1985; Glibert et al. 2005). Runoff transports these nutrients through river systems and eventually to marine or freshwater systems (Figure 1).

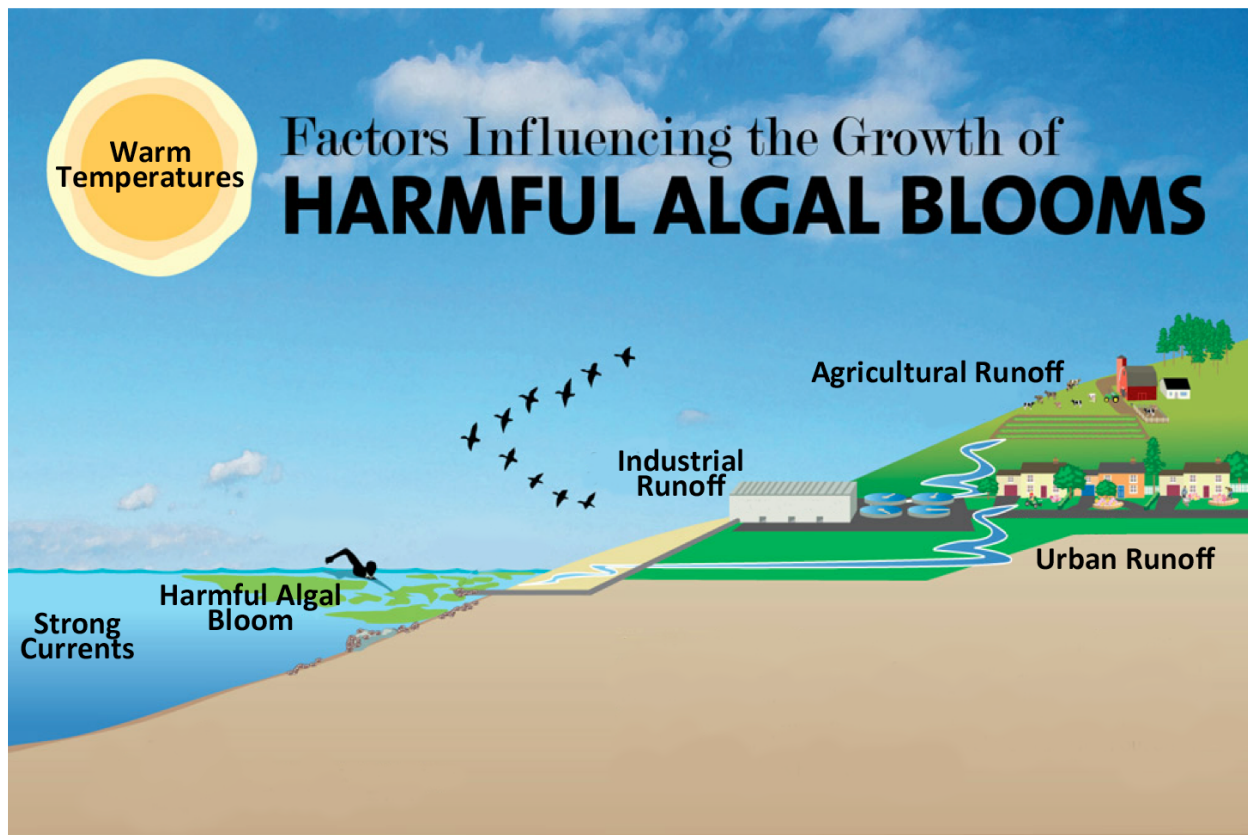


Figure 1. Factors influencing the growth of harmful algal blooms.
Image: Adapted from Michigan Sea Grant

Some algal blooms are harmless, while others can damage aquatic organisms chemically or physically (Glibert et al. 2005). Harmful Algal Blooms (hereafter HABs) are the result of a proliferation of occasionally toxic phytoplankton that may produce hypoxic conditions,

resulting in harmful impacts on aquatic ecosystems, coastal communities, and human health. Hypoxia is a condition of low dissolved oxygen in aquatic systems that may lead to the death of aquatic organisms and often occurs after a bloom of particularly high biomass.

Red tides are a particular kind of harmful bloom, which occur when a type of red-pigmented dinoflagellate accumulates and tints the water red (Anderson et al. 2002). However, algal blooms can also be green, brown, or yellow, depending on the type of algae (Glibert et al. 2005).

Globally, algal blooms occur primarily in Europe, eastern Asia, and North America (Figure 2). Occurrences of HABs and hypoxia have increased in frequency over the past forty years in the United States, including on the southeastern and northwestern coastlines and the Gulfs of Maine and Alaska (Anderson et al. 2012). Particularly alarming, the northern Gulf of Mexico has suffered from a 7,000 square mile stretch of hypoxia, a case study that we will examine in detail. In this report, we will explore the problems posed by HABs and will consider legislative and scientific solutions to prevent them and mitigate their impact.

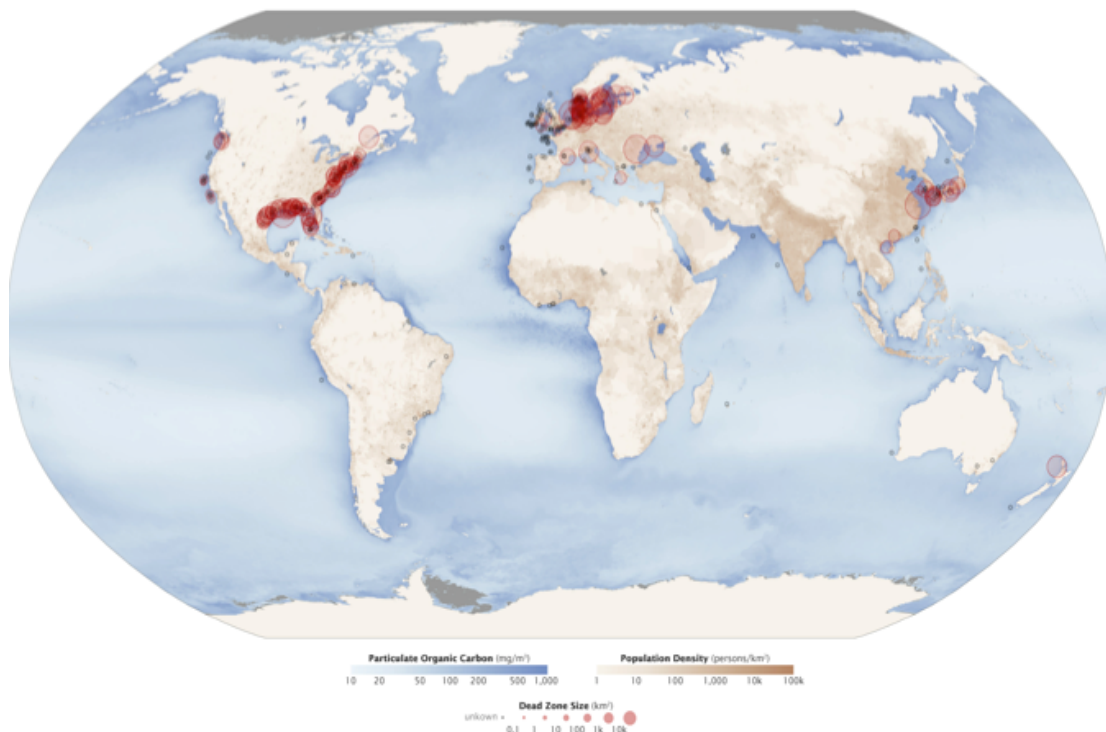


Figure 2: The global distribution of Dead Zones around the World. Image: Resilience Alliance

2.0 Problems Associated with Harmful Algal Blooms

There are two main problems related to the proliferation of HABs in aquatic systems. First, some algal blooms have a direct impact on human health because numerous species of algae naturally produce toxic compounds (Backer and McGillicuddy 2006). Humans can be exposed to the algal toxins by eating contaminated shellfish and fish or accidentally

consuming affected water during recreational activities (Graham 2007). Second, a series of events related to HABs may result in reduced levels of dissolved oxygen, or hypoxia, in a body of water, which may be detrimental to fish and other organisms. The most harmful freshwater HABs are caused by blue-green algae, also known as cyanobacteria, both due to hypoxic conditions and toxic emissions (Hudnell 2008). Certain blue-green algae form high biomass blooms and may produce toxins that have impacted human health and perpetuated adverse ecosystem and economic impacts, in the United States and worldwide (Hudnell 2008).

2.1 Algae Toxicity and Potential Health Effects

Various species of algae are harmful because they naturally produce toxins (Backer and McGillicuddy 2006). These toxins may be harmful to the fish and mollusks that consume them, but they may also have no adverse effects on these primary consumers, instead affecting their predators, the secondary consumers (Dawson and Holmes 1999). Toxins are synthesized inside the algal cells, but some toxins pass into the environment outside the algal cell as well (Pierce et al. 2003). Dinoflagellate blooms may be toxic either because they affect ion channels or because they inhibit protein function in humans (Bigelow 2009). Some algae-derived toxins bind to these ion channels, blocking ions from flowing into cells. Other toxins have the opposite effect: they bind to these channels, keeping them open and promoting higher-than-normal ion flux (Bigelow 2009). In both cases, normal cell function is disrupted, resulting in neurological damage or other health effects.

Toxins are transferred through the trophic system, leading to bioaccumulation in larger aquatic animals. Bioaccumulation happens when compounds accumulate in an organism at a rate faster than they can be broken down (Bigelow 2009). Marine invertebrates, as well as fish and shellfish, typically consume algae, including toxic algae. As fish and other organisms eat algae, they ingest toxins, which accumulate in their tissues. This buildup of toxins may affect consumers higher in the food chain such as predatory fish and whales, which consume many fish and shellfish and their associated toxin loads. When humans consume contaminated fish or shellfish from any point along this food chain, the effects can range from mild symptoms to severe illnesses and death (Table 1).

Human health syndromes caused by toxic algae

Humans can be exposed to the algal toxins by eating contaminated shellfish or fish, or accidentally consuming affected water (Graham 2007). There are several types of shellfish poisoning worldwide, but there are three types that are of major concern in the United States (Table 1).

Table 1. Summary of the health effects of various shellfish toxins.

Human Illness	Toxin	Plankton	Process
Amnesic Shellfish Poisoning	Domoic Acids	Diatom	Acts on calcium channels; Gastrointestinal Short-term memory loss
Diarrhetic Shellfish Poisoning	Okadaic Acids, Pectenotoxin, Yessotoxin, Dinophysistoxin	Dinoflagellate	Inhibit proteins; Gastrointestinal
Neurotoxic Shellfish Poisoning	Brevetoxin	Dinoflagellate	Acts on calcium channels; Gastrointestinal, tingling
Paralytic Shellfish Poisoning	Saxitoxin	Dinoflagellate	Acts on ion channels; Respiratory failure, death

Amnesic Shellfish Poisoning

Amnesic shellfish poisoning is caused by domoic acid, which is generated by certain diatoms in the genus *Pseudo-nitzschia*. Domoic acid is a heterocyclic amino acid similar in structure to kainic acid, which communicates messages between neurons in the central nervous system (Bates et al. 1989). However, domoic acid overstimulates the neurons in the brain's hippocampus until these cells start to die. Domoic acid also keeps the calcium channels open in nerve and muscle cells, where the uncontrolled increase of calcium causes the cell to degenerate (Bigelow 2009). Because the hippocampus may be severely damaged, such poisoning can result in permanent short-term memory loss, brain damage, and death. *Pseudo-nitzschia* is usually found on the northwestern and eastern North American coasts and by the Gulf of Mexico (See Case Study I; Boesch et al. 1997).

In 1987, amnesic shellfish poisoning triggered over a hundred cases of human infection and several deaths due to the consumption of affected mussels from the Atlantic Ocean near Canada (Bates et al. 1989; Anderson et al. 2012). The news about massive HAB outbreaks motivated people to become aware of shellfish poisoning and avoid seafood during HAB events (Anderson et al. 2000; Anderson 2007).

Diarrhetic Shellfish Poisoning

Diarrhetic shellfish poisoning is primarily caused by okadaic acids, which are produced by the dinoflagellate *Prorocentrum lima* and species of the genus *Dinophysis* (Stewart 2005). This acid inhibits intestinal cellular de-phosphorylation, causing cells to become very permeable to water and resulting in profuse diarrhea with a risk of dehydration. However, life-threatening symptoms generally do not result. Diarrhetic shellfish poisoning and its symptoms usually set in within about half an hour of ingesting infected shellfish, and last

for about one day (Dawson and Holmes 1999). Cases have been reported worldwide, beginning in the 1960s (WHOI 2012).

Neurotoxic Shellfish Poisoning

The dinoflagellate *Gymnodinium breve* produces brevetoxins that cause neurotoxic shellfish poisoning (Watkins et al. 2008). Symptoms in humans include vomiting and nausea and a variety of neurological symptoms such as slurred speech (Watkins et al. 2008). Continuous exposure to airborne brevetoxins aerosolized by waves can lead to severe respiratory symptoms (Backer and McGillicuddy 2006). These dinoflagellates predominantly occur on the coastline of the Gulf of Mexico (See Case Study I). No fatalities have occurred as a result of neurotoxic shellfish poisoning, but there have been several cases of hospitalization (Watkins et al. 2008).

Paralytic Shellfish Poisoning

The algal blooms that trigger paralytic shellfish poisoning are created by several species of dinoflagellates that belong to the genus *Alexandrium* and release saxitoxins (Zingone and Enevoldsen 2000). The positive charge on part of the saxitoxin molecule allows it bind to and block the sodium channel, inhibiting the passage of sodium ions and causing muscles to relax. This may lead to respiratory failure or death (Bigelow 2009). These dinoflagellates occur in northern California, the Pacific Northwest, Alaska, and New England.

2.2 Hypoxia

When large pools of algal biomass created in these blooms die and decompose, the decomposition process depletes the dissolved oxygen in the water and causes hypoxia (Figure 3). The lack of oxygen leads to the death of many organisms in the area, causing these water areas to be labeled “dead zones” (Anderson et al. 2002). Hypoxia may also lead to the mortality of marine mammals, birds, and reptiles (Graham 2007). HABs are usually short-lived, from days to months; however, their effects on water quality and habitat-degradation can become ongoing problems, impacting the ecosystem for several years or longer (Paerl et al. 2001).

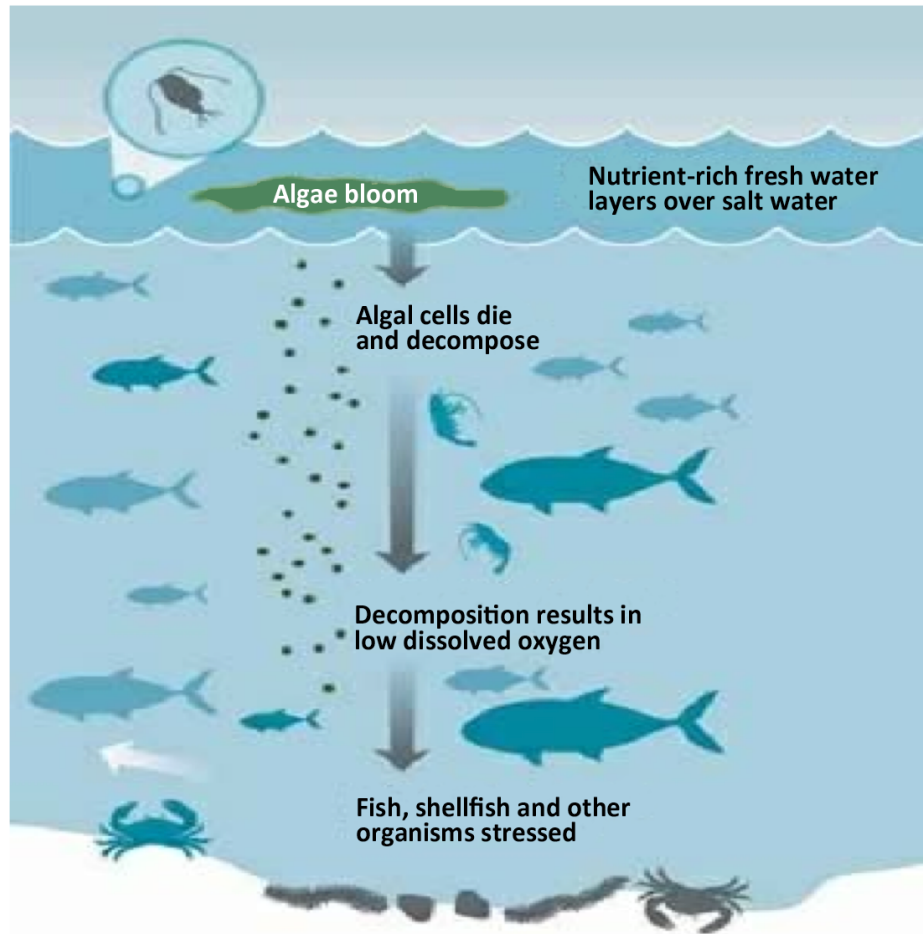


Figure 3. The processes and spatial structure of stresses to marine ecosystems caused by harmful algal blooms. Image: Adapted from Mother Nature Network

Formation of Hypoxic Zones

There are several steps involved in the formation of a hypoxic zone. Blooms often begin with the addition of excess nutrients to an aquatic system (Anderson et al. 2002). These often come from agriculture and urban runoff within the watershed, though they may occur naturally as well (Glibert et al. 2010). As a result, algae are fertilized and flourish, producing a period of algal bloom. These algae then die, sink down the water column, and are decomposed by bacteria. These bacteria respire as they decompose the phytoplankton, consuming dissolved oxygen in the process. Hypoxia, a condition of water with low dissolved oxygen, occurs as a result.

Stratification may intensify this effect; in summer months, fresh water that is less dense flows into the water body from rivers, and continually covers the dense salty water. This creates a barrier between the water masses that prevents oxygenated surface water from mixing with the deeper, oxygen-depleted waters (Zingone and Enevoldsen 2000).

Ecosystem Effects from Hypoxia

Hypoxia affects ecosystems in several ways. When facing hypoxic conditions, mobile invertebrates and fish may migrate away from hypoxic zones to areas with sufficient levels

of oxygen. Plants and slow-moving animals, however, face death from exposure to hypoxic conditions. The large spatial extent of some algal blooms may even affect the ability of fish and other fast-moving animals to avoid contact with the hypoxic zone (Paerl et al. 2001).

2.3 Additional Adverse Effects

Even though many algae do not produce toxins, both toxic and non-toxic algal blooms can be detrimental to aquatic organisms because algal biomass can block sunlight and clog the gills of aquatic organisms (Glibert et al. 2005). Other ecosystem effects include a change in phytoplankton species composition in coastal ecosystems that sustain consistently higher nutrient loads, often resulting in the presence of more harmful species of phytoplankton (Anderson et al. 2002). Harmful algal blooms can produce noxious odors and aerosols in the vicinity of water bodies where they occur, as well as unpleasant slimes and airborne components that may cause eye, nose, and throat irritation (Paerl et al. 2001). Many of these effects can have serious economic implications on coastal communities that depend on marine resources for their livelihood and subsistence.

2.4 Economic Impacts

HABs damage commercial fisheries and aquaculture through the loss of fish and shellfish. In freshwater environments, HABs can degrade the quality of drinking water, thereby increasing the cost of water treatments (Paerl et al. 2001; Graham 2007). The contamination of the water can also affect the health of livestock. In addition, the presence of toxins in lakes, rivers, and oceans can limit recreational activities, which decreases revenue from recreation and tourism (Graham 2007). The annual economic cost of HABs from 1987 through 2000 was estimated to be at least \$82 million a year (Hoagland and Scatasta 2006), which may be broken down as follows:

- Loss of revenues in commercial fisheries and aquaculture: \$38 million
- Costs to public health: \$37 million
- Impacts on recreation and tourism: \$4 million
- Expenses for coastal monitoring and management: \$3 million

The timing, extent, and duration of algal blooms vary from year to year, and a single bloom can cause damages that surpass the annual estimate of economic costs (Anderson 2007). For example, there was an enormous bloom of *Ceratium tripos*, a dinoflagellate, in 1976 that led to the loss of lobsters, scallops, surf clams, finfish and ocean quahogs in New York Bight (Figley et al. 1979). The estimated economic cost for this particular event when adjusted to U.S. dollars for the year 2000 was \$1.33 billion (Figley et al. 1979; Anderson et al. 2000). In addition, some factors are not taken into account when determining the economic costs, including unreported illnesses, property value decline, lost seafood sales due to unfounded consumer fears and lost revenue from some untapped fisheries (Anderson et al. 2000).

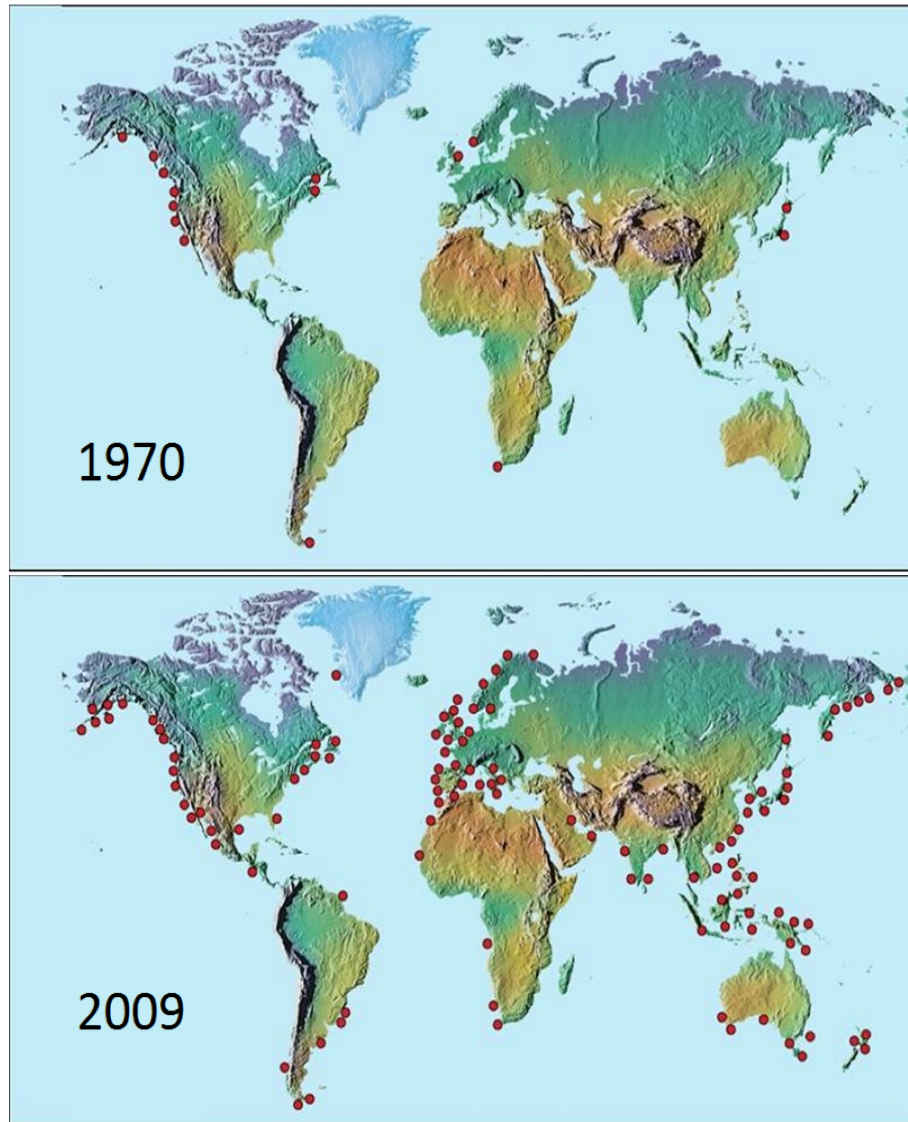


Figure 4. Algal bloom outbreaks reported over a 39-year span.

Image: U.S. National Office for Harmful Algal Blooms, Woods Hole Oceanographic Institution

2.5 Scientific Challenges

HABs have complex cycles and succession patterns, making their outbreaks difficult to predict and manage (Anderson 2007). In addition, the effects of anthropogenic influences, as compared to natural influences, on HABs are poorly understood. There are many complex factors affecting HAB expansion and growth, making it harder to identify specific factors affecting the problem. Some toxins remain unidentified, and the marine populations that are susceptible to these toxins are unknown. These uncertainties pose many challenges to the mitigation of the effects of HABs, and make it difficult to react appropriately.

3.0 Legislation Related to Harmful Algal Blooms

In response to increased HAB events in the United States, Congress passed the Harmful Algal Bloom and Hypoxia Research and Control Act of 1998. The Act established the Inter-Agency Task Force on Harmful Algal Blooms and Hypoxia to oversee assessments of the economic and ecological impacts of HABs and hypoxia, and to develop strategies for reducing, mitigating, and controlling outbreaks. In addition, the Act required the Task Force to complete an assessment of the Northern Gulf of Mexico Hypoxic Zone (See Case Study I).

The initial research revealed some of the complexity of the problem and the scope of research needed to effectively prevent, control, and mitigate HABs and hypoxia. The 2004 amendments reflected that understanding by intensifying the focus on scientific research and making the Task Force an ongoing entity. These amendments established requirements for prediction and response reports, regional and local scientific assessments for marine and freshwater HABs and hypoxic events, and the further development of a national research plan.

The Harmful Algal Bloom and Hypoxia Research and Control Amendments Act of 2011 builds on what has been learned over the last fifteen years and mandates the creation of a national action plan, as well as regional action plans to effectively prevent, control, and mitigate HABs and hypoxic outbreaks (S. 1701). The proposed amendments reauthorize the 1998 Act until the year 2015 and establish the National Harmful Algal Bloom and Hypoxia Program. The Program will develop a national action strategy, produce regional research and action plans, and continue coordinating the research, planning, and implementation work of the relevant agencies.

The National Oceanic and Atmospheric Administration (NOAA) is authorized to coordinate implementation of the Program and supports the Task Force in promoting national strategy development and regional research and planning. The legislation aims to use these tools to control the human and environmental costs of HABs and hypoxia, with an emphasis on protecting coastal economies, improving human health, and supporting fisheries. Work on the Northern Gulf of Mexico hypoxic zone was a priority from the onset of the initial act, and regional scientific assessments and an action plan approach are proposed in the current legislation (S. 1701; see Case Study I).

Case Study I: The “Dead Zone” in the Gulf of Mexico

The “dead zone” in the northern Gulf of Mexico is a high-profile example of algal blooms having far-reaching ecological consequences (Figure 5). It has been a priority region since the adoption of 1998 Act. This large hypoxic zone is likely linked to eutrophication from agricultural runoff in the Mississippi watershed (Anderson et al. 2012). The Mississippi River/Gulf Nutrient Task Force, established in the 1998 legislation, fostered initiatives in many states to protect wetlands, manage agricultural run-off, and reduce excessive nutrient loading in watersheds draining to the Gulf of Mexico. The report by the national HAB Task Force examined the ecological and economic impacts, the distribution dynamics, the causes, sources, and loads of nutrients transported by the Mississippi River to the Gulf, the effects of reducing nutrient loads, methods for nutrient load reduction, and finally the social and economic costs and benefits of such methods (Committee on Environment and Natural Resources 2010). The Task Force developed a plan to reduce, mitigate, and control hypoxia in the Northern Gulf of Mexico based on the assessment. \$52 million was appropriated over three years for research, education, and monitoring activities related to the prevention, reduction, and control of HABs and hypoxia.

The proposed amendments continue to prioritize the regional scientific assessments and action-plan focused approach for this hypoxic zone (S. 1701). The Act dedicates financial resources and sets regional goals for this high-risk area. Two years after the enactment of S. 1701, the committee will submit an assessment on the Northern Gulf of Mexico explaining how wind and current patterns, nutrient influx, topography, water column stratification, and seasonal flows affect the size of the hypoxic zone (S. 1701). The Ecology and Oceanography of Harmful Algal Blooms (ECOHAB), a multi-agency partnership, has begun a project called “The Mechanism of Harmful Algal Bloom Initiation in the Western Gulf of Mexico,” which focuses on the algal species *Karenia brevis*, another species of concern (Stumpf 2008). This project identifies the influence of upwelling and downwelling (caused by wind direction and speed), current flow, and non-point source pollution in producing algal blooms in the Gulf.

Several organisms of management concern are involved in this dead zone, including those that cause neurotoxic shellfish poisoning and amnesic shellfish poisoning. Because of the high profile and large spatial extent of the Gulf of Mexico dead zone, site-specific tests were developed in 2011 (NOAA 2011), and a project called the Harmful Algal Bloom Operational Forecast System (HAB-OFS) monitors sea surface temperature, dissolved oxygen, and other oceanographic data (Anderson 2009). This system uses remote sensing in the form of satellite data and wind monitoring on buoys to post bi-weekly bulletins with HAB event warnings. These remote sensing systems are a significant improvement over other methods of identification of algal blooms, which rely mostly upon manual seawater sampling from boats and often involve visual identification of the phytoplankton (Kulis, personal communication 2012; Laurent 2009).

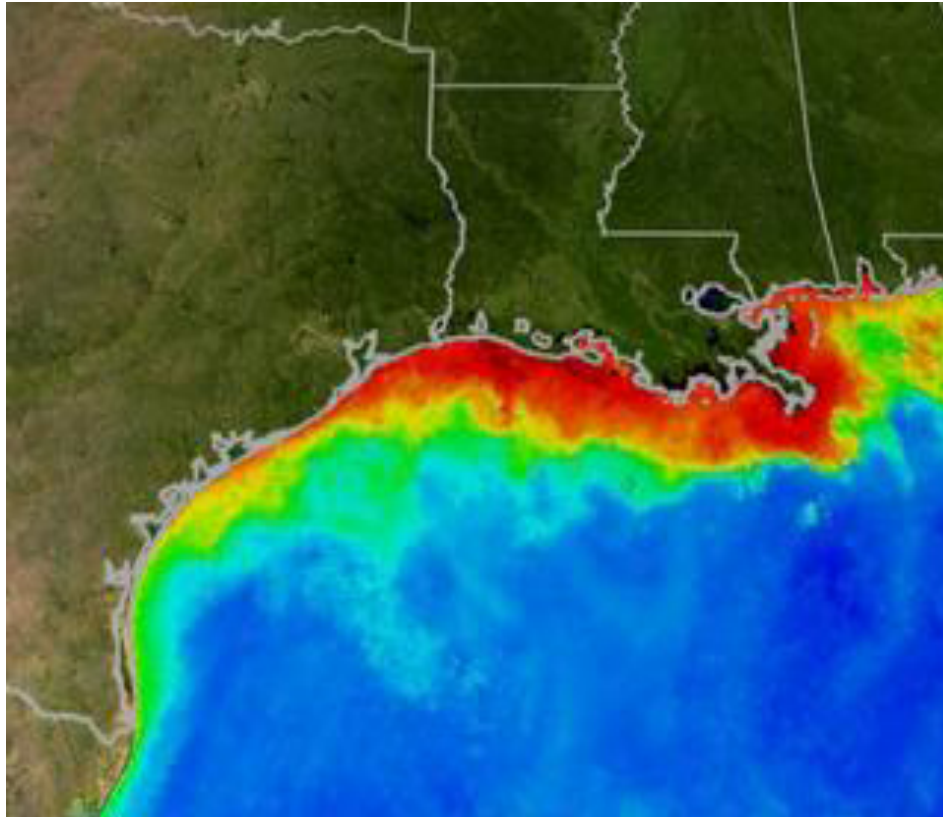


Figure 5. Hypoxic zone in the Gulf of Mexico

Image: NASA/Goddard Space Flight Center Scientific Visualization Studio

4.0 Solutions to Harmful Algal Blooms

Algal blooms occur naturally and can be caused by something as innocuous as the right combination of tides and sunlight, which makes predicting a bloom event difficult (Anderson 2007). The triggers for HAB events are region-specific due to differences in species involved, coastlines, runoff, oceanography, nutrient regime, other organisms present in the water, and other factors (Anderson 1997). However, algal blooms are also propagated by human activities, including the release of ballast water and increased nutrient loading due to agricultural, industrial and urban runoff (Glibert et al. 2005). The 2011 bill proposes to continue funding for research on HABs and for ongoing programs such as the Ecology and Oceanography of Harmful Algal Blooms (ECOHAB) Research Plan, as well as the Monitoring and Event Response for Harmful Algal Blooms (MERHAB), under the auspices of the Center for Sponsored Coastal Ocean Research (CSCOR) within NOAA. These programs will contribute to both national and regional strategies to prevent, control, and mitigate the effects of toxic algal blooms and hypoxic events.

If the proposed amendments are passed into law, the government will appropriate \$30 million per year towards these goals from 2011 to 2015, (S. 1701). Whereas the 1998 bill and 2004 amendments primarily focused on research and assessment of the problem, the 2011 amendments emphasize the need for action plans as well as further scientific

research. The bill delegates responsibility to state and local governments to implement monitoring and response techniques in regions affected by HAB outbreaks. Similar to the national plan, regional plans will research HAB impacts and further develop technologies and research to address regional outbreaks. Scientific models will be created that can simulate different conditions that may lead to a better understanding of HABs and potential solutions to the problems they cause. These solutions can be categorized into three main sections: biological and ecological research, monitoring and prediction of algal blooms, and finally prevention, control, and mitigation actions.

4.1 Biological and Ecological Research

Research comprises the majority of the bill's financial investment. It reauthorizes financing for the Ecology and Oceanography of Harmful Algal Blooms Program (ECOHAB), which focuses on developing extensive research on HABs in order to better understand the causes and effects of harmful algal blooms (NOAA 2011). Specifically, the purpose of ECOHAB is to gain deeper knowledge of the biosynthesis, transfer, and metabolism of toxins and how they affect upper trophic levels (NOAA 2011). The continuation of existing research programs will improve the understanding of the biology behind HABs and enable the development of new technologies. This in turn will enable these agencies and private organizations to more effectively solve the problems associated with these blooms.

ECOHAB provides the funding for researchers, NOAA, the Center for Sponsored Coastal Ocean Research (CSCOR), and a collection of public and private universities and research centers (NOAA 2011). A full listing of current projects being funded is available on their website, and many of the research papers referenced in this report were partially funded by ECOHAB (<http://www.ecohabpnw.org/>).

4.2 Predicting and Monitoring Algal Blooms

In order to enact a national HAB strategy, new technologies will be required to enhance bloom detection and forecasting in order to better predict HAB outbreaks. As illustrated in Case Study 1, the Harmful Algal Bloom Operational Forecast System (HAB-OFS) uses satellite imaging, scientific models, field observations, public health reports, and buoy data to provide advance warnings of HABs (NOAA 2011). Quantitatively monitoring HABs before, during, and after outbreaks provides information used to produce models for prediction (Stumpf 2008). Early detection due to adequate monitoring may allow resource managers to mitigate and control adverse effects during the course of an algal bloom (NOAA 2011).

The proposed amendments would reauthorize funding for the Monitoring and Event Response for Harmful Algal Blooms Program (MERHAB), which uses new technologies to improve existing water and shellfish monitoring programs (NOAA 2011). This program is a product of partnerships between federal agencies, which outreach to state, tribal, and local programs as well as academic institutions to form identification, detection, and prediction strategies. Professional training in identification and response is an example of public

outreach to equip local resource managers with techniques for responding to HAB outbreaks (NOAA 2011). While monitoring and response programs are ongoing, these programs would benefit from a greater understanding of HAB toxins and more effective monitoring techniques (NOAA 2011).

Programs for Prediction and Monitoring

There are several federal and many regional programs that are involved in the prediction and monitoring of HABs. These agencies make use of data from satellites, ocean buoys, and field observations in order to predict HABs. These data are then used in models to produce forecasts, which in the case of seasonal blooms can be determined years in advance (Recknagel et al. 1995). Systems for predicting these outbreaks are impeded by several factors, including the lack of adequate information about the organisms involved and difficulties in detecting the development of a bloom, including the fact that some blooms are not able to be identified visually because of the size of the organisms, and the fact that the identification of a single algal cell of a species of concern is not necessarily indicative of an impending outbreak because an algal bloom is often harmful only if the organisms are present in sufficient quantities (Anderson et al. 2012).

Sea Monitoring

Existing systems for predicting and monitoring rely mostly upon manual seawater sampling from boats and often involve visual identification of the phytoplankton (Kulis, personal communication; Laurent 2009). Surface Plasmon Instrumentation for the Rapid Identification of Toxins (SPIRIT) is a piece of equipment capable of identifying toxins in affected areas (Laurent 2009).

These monitoring programs can be extremely expensive, and while the technology exists to remotely monitor nutrient loads, chlorophyll-*a* concentration, toxins, and even genetic analysis, in practice this is done only as a part of specific research projects (Kulis, personal communication 2012). Automated systems are potentially less expensive. An instrument called the Environmental Sample Processor (ESP) is being used in some research projects (Kulis, personal communication 2012). This instrument is on a mooring/marker system and measures concentration of multiple organisms, their toxins, water temperature and conductivity, and light in the water column. This is one of the few examples of a remote monitoring system that is able to monitor toxin and algal concentration levels, but the cost of each unit (\$200,000) is prohibitive for large-scale implementation at this time (NOAA 2011).

The future of buoy, ship, and specialized aquatic drone use in monitoring marine ecosystems depends upon funding levels, but there are many methods under discussion. A Tethered Spectral Radiometer Buoy can be used to describe spatial and temporal variability in algal concentrations (Cullen 1997). Measurements of chlorophyll-*a* are also used in these techniques, and many hand-held devices are capable of detecting specific toxins through chromatographic and mass spectrometry techniques (Anderson 2009). Surface plasmon resonance techniques, which involve the mechanized identification of specific genetic strands, allow for the rapid identification of algal species (Laurent 2009).

Satellite Imaging of HABs

Satellites can detect accumulations of cyanobacteria such as *Nodularia spumigena*, *Trichodesmium*, and coccolithophores in near surface waters by their high reflectivity (Kahru et al. 2005). Other blooms can be detected because of lower reflectivity in the UV spectrum due to the high concentration of particular amino acids (Stumpf and Tomlinson 2005). The presence of phycocyanin, which is produced by cyanobacteria, provides evidence of high-concentration blooms (Vincent et al. 2004). Satellite images have been used to monitor blooms in Peru (Kahru et al. 2005). This project used specific colors from satellite images to forecast algal blooms, an essential step in avoiding shellfish poisoning from affected fisheries along the Peruvian coast.

Satellite imaging can provide information about the spatial extent of an algal bloom as well as its severity through the detection of chlorophyll-*a*, which is often associated with HABs. In the case of *Karenia brevis* forecasting along the coast of Florida, satellite data is often focused on anomalies in chlorophyll-*a* concentration, allowing researchers to track changes in location and the initiation of potential blooms (Stumpf 2008). This method is not species-specific, but requires the species in question to produce sufficient biomass to produce detectable changes in chlorophyll-*a* concentration. This also requires the bloom to be on the surface of the sea, which complicates forecasts for blooms that initiate in the subsurface (Walsh et al. 2001). The researchers involved in this project used satellite data in conjunction with field observations (including rigorous assessments by lifeguards) to produce accurate forecasting of *K. brevis*, a species of concern due to its oral and inhaled toxicity.

Satellite data is often used in conjunction with other data to produce models. The HAB-OFS system in the Gulf uses remote sensing satellite data and wind monitoring on buoys, which are adequate to produce accurate forecasts up to two weeks in advance of a bloom (NOAA 2011).

HAB Modeling

Models can be used to predict forecasts of the initiation and duration of HABs. An HAB must be modeled as a “special” event in plankton succession, and therefore models must be able to predict which environmental factors led to the proliferation of these organisms and why that particular organism has proliferated in a particular way. The answer to this question depends upon the algal species of concern as well as the dynamics of the larger ecosystem. Models that are developed for marine environments do not apply to freshwater systems, and vice versa (Recknagel et al. 1997).

Acquiring sufficient data is important in both developing predictive models as well as making accurate predictions. Some models are able to use only a few inputs such as nutrient loads and turbulence, while others incorporate salinity and wind measurements, the locations of cyst beds prior to bloom seasons, preemptive sampling, the presence and efficacy of zooplankton “grazers” to control algal populations, the “excitability” of the system, light availability, the details of the physical environment “as an agent controlling

population,” satellite data on sea-surface pigment concentration, upwelling and downwelling in particular areas, and the proportion of “limiting” nutrients to other nutrients (Franks 1997; Paerl 1997; Sacau-Cuadrado et al. 2003; Stumpf 2008).

Difficulties in modeling include differing life cycles of algal species, variation in zooplankton associated with these algae, lack of knowledge about the initial environmental conditions, and unknown initial algal population sizes. Changes in species composition in coastal ecosystems with consistently higher nutrient loads will also affect these models (Anderson et al. 2002).

4.3 Prevention, Control, and Mitigation

National solutions to decrease HABs emphasize prevention, control, and mitigation. Prevention efforts include regulating freshwater flow, modification of water circulation, restricting introductions, and nutrient management (Anderson 2001). Control techniques attempt to create chemical interventions that would manage harmful algal blooms without damaging non-target organisms. These techniques would also have to be evaluated for the environmental impacts of chemical agents used to remove HAB cells (Anderson 2001). Mitigation would be used not only to restore affected areas but also to forecast and monitor at-risk HAB zones before damage to human health and ecosystems occur (Anderson 2001). One suggested method of mitigating the human health problem, in particular, is the temporary filtration of water to shellfish hatcheries prior to or during a bloom (Anderson 2001). Finally, education programs will provide the public with insight about the problem and how to prevent HAB outbreaks (Anderson 2001).

Prevention

It is difficult to implement policies to prevent HABs when so little is known about the specific conditions that will cause them. Nutrient runoff from chemical fertilizers used in agriculture is an obvious factor, as are the growing amounts of sewage discharge (Anderson 2009). Less obvious factors are nutrient introduction from aquaculture (Sakamoto 1986) and even increased fossil fuel combustion and the raising of cattle, each of which releases nitrogen and phosphorus pollution into the atmosphere, which is then deposited into coastal waters (Anderson et al. 2002). The proposed amendments do not attempt to directly address the issue of increased nutrient loads in coastal waters due to agricultural and urban runoff.

Mitigation and Control

Prediction of HAB events is important mainly because it allows for more aggressive mitigation and control measures. These control measures include mechanical, biological, chemical, genetic and environmental controls, and may be controversial in their implementation (Anderson 2009). One method in particular being used to control algal bloom outbreaks presently involves the application of dissolved clay or specific glycolipids, sometimes in combination with specific chemicals, on the surface of the water (Pierce et al.

2003; Sengco and Anderson 2004; Lee et al. 2007).

Before the widespread use of clay flocculation as a control method (see below), algal bloom control often incorporated ozonation, ultrasonics, and various chemical treatments (Sengco and Anderson 2004). Chemicals used include copper sulfate, sterol surfactants, sodium hypochlorite, magnesium hydroxide, and others, but they have not been used widely because of concerns about ecosystem effects and the price of these treatments. These methods can have acute ecological side effects such as damage to non-target organisms, which has prompted the search for less invasive methods (Rey 2011). The Center for Sponsored Coastal Ocean Research (CSCOR) guideline calls for control methods that are environmentally friendly, not detrimental to other aquatic organisms, and have no long-lasting effects. Meeting these criteria may require “softer” methods than the aggressive application of such chemicals.

Clay Flocculation



Figure 6. Clay flocculation process. Image: J. Culter, Mote Marine Laboratory

Clay flocculation is a method of controlling algal blooms that involves the application of dissolved minerals (clays) in combination with chemicals to the surface of water affected by HABs (Figure 6). The clay binds to the algal cells, causing them to sink to the sea floor (Figure 7). It has the potential of being a very efficient, rapid, and cost effective control method that has low environmental impacts, and there is field documentation showing the removal of algae from the water column within hours (Anderson 1997; Sengco and Anderson 2004). This reduces toxicity and limits the scale of the hypoxic conditions. It also mitigates the acute effects of algal bloom outbreaks and measurably increases the survivorship of fish (Shirota 1989). These methods have been used extensively in Korea, where algal blooms have high economic costs (Anderson 2009).

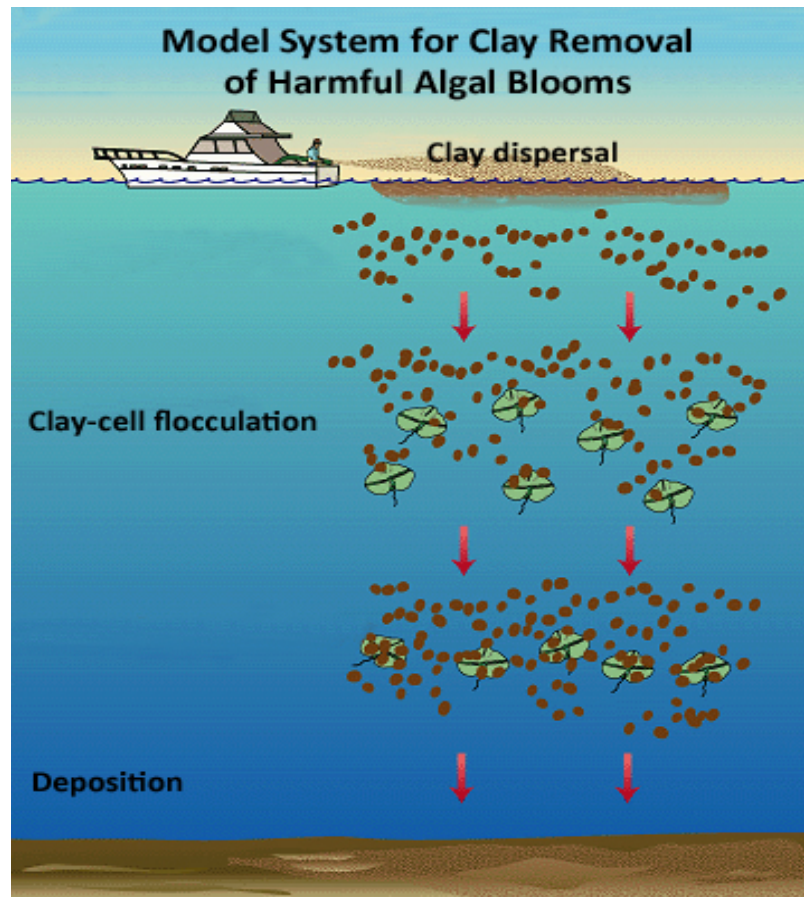


Figure 7. Depiction of clay flocculation, a method in which clay particles bind to algae and sink to the bottom.
Image: Adapted from Smithsonian Environmental Research Center

Clay treatment increases water transparency, reduces toxicity, and limits the extent of hypoxic conditions to the sea floor, mitigating the acute effects of algal bloom outbreaks. Additionally, clays have the potential of removing not only HAB cells but also brevetoxins associated with these blooms, although the effectiveness of this method is dependent upon the addition of a flocculant and displays lower efficiency (Pierce et al. 2003). The addition of sophorolipids, which are produced by fungi, increases the effectiveness of clay treatments by inhibiting motility and damaging the cell membranes of algae. They display minimal ecological effects because of high specificity to target algal species, lack of toxicity and high biodegradability (Sun et al. 2004). The process of applying the clays, however, is controversial due to potentially adverse effects to sea floor benthic communities (Table 2).

Table 2. Advantages and disadvantages of clay flocculation.
Adapted from Pierce et al. 2003 and Lewis et al. 2003

Advantages	Disadvantages
>80% success rate within 3-5 hours	Initially increases turbidity (blocks sunlight)
Successful for various species	No clay >35% effective on brown tide
Effect on organisms not higher than that due to toxic algae	Negative effects of clay not yet measured under field conditions
Survival of organisms increased with addition of chemical flocculant	Phosphates commonly adsorb to clay (phosphorus linked to blue-green algae blooms)

The potential effects of the application of clay flocculates on benthic sea floor life are not fully understood, and further research is being conducted (Rey 2011). Preliminary studies have concluded that there is no additional fish mortality above that occurring during a red tide, and that clams, a representative benthic species, displayed no mortality under laboratory clay treatments, although they displayed slower growth rates under certain circumstances (Sengco and Anderson 2004). It is not known whether simply removing toxic algal cells from the water column will significantly reduce fish kill or whether the removal of extracellular brevetoxins is essential to mitigating the effects of HABs (Pierce et al. 2003).

One of the most significant challenges to this research is the lack of data on longer-term effects, as the pertinent studies have all commenced within the last 10 years. While the use of clay flocculates continues in both Asia and the United States, the effects of the clay particles on the marine ecosystem will be determined through continued monitoring.

Sediment Resuspension

The goal of a new mitigation project called sediment resuspension is to suppress the cysts of *Alexandrium funyense*, a toxic dinoflagellate that occurs in the Gulf of Maine (Anderson 1997). Sediment resuspension involves turning over the top 10 to 20 cm of the sediment on the ocean floor, comparable to how farmers till surface soil on agricultural lands (Anderson and Ralston 2011; Figure 8). This redistributes and buries most cysts under the sediments in an anoxic layer that discourages germination and growth (Anderson and Ralston 2011). Therefore, sediment resuspension has the potential to greatly reduce the density of cysts in

the surface sediment before the occurrences of algal blooms, which can possibly decrease algal bloom duration and intensity and reduce the quantity of toxins produced (Anderson and Ralston 2011).



Figure 8. Process of sediment resuspension. Image: UC Davis

This method only applies to the types of algae that produce cysts and spores (Anderson and Ralston 2011). It is important to determine what proportion of *Alexandrium* cysts, as well as other cyst forming dinoflagellates, are buried through sediment resuspension (Anderson and Ralston 2011). In addition, scientists are quantifying the rate at which the cysts are sinking, what nutrients are released during the process, and how this affects the benthic community (Anderson and Ralston 2011).

Biological Control

The possibility of incorporating ecosystem-level control mechanisms such as biological control is under discussion, although the subject remains controversial (Anderson 2009) and logistical problems such as lack of effective mass rearing and storage facilities have emerged (Shirota 1989; Sengco and Anderson 2004).

5.0 Measuring Success

The broad categories for evaluation of the success of HAB management activities are 1) the extent of biological and ecological research of HABs and hypoxia, 2) prediction technology, 3) the monitoring of and response to harmful algal blooms, and 4) the prevention, control and mitigation of HABs and hypoxia. Within each category, we are looking for an increased

understanding of the problem, advances in technology, and efficient means of sharing information within regions and across the country.

Biological and Ecological Research

To date, the outcomes of NOAA's research on the biological and ecological impacts of HABs and hypoxia have established general causes and consequences, including identifying the toxins responsible for various types of shellfish poisoning and their impacts on fish and invertebrates (Committee on Environment and Natural Resources 2010). One of the key outcomes from the proposed amendments is a sufficient understanding of the variety of toxins caused by different algae that cause HABs in different regions of the country. The research authorized in these amendments will establish a comprehensive catalogue profiling the different toxins by region and evaluating the human health and ecological impacts of those algal toxins. The next steps include organizing regional research teams, forming a team to compile the regional research into one catalogue, and establishing a national network in order for the public to easily access this catalogue.

Predicting Outbreaks

The Harmful Algal Bloom Report required by the 1998 Act indicated the need for a HAB prediction system to assist control and mitigation efforts. Advance warning of even a few days can give response teams a significant advantage in controlling HABs and mitigating the negative impacts to communities and aquatic ecosystems. Currently, the HAB-OFS is undergoing field-testing in the Northern Gulf of Mexico (Tomlinson 2009). HAB-OFS measures salinity, temperature and chlorophyll-a levels using buoy monitors, but these data are limited by the fact that the buoys are stationary (Tomlinson 2009). Because HABs have fairly defined boundaries, unless the buoy is located within the area of the developing HAB, it will not detect the indicators needed for effect prediction (Tomlinson 2009). There are several possibilities for improving prediction models. These may include using a wider range of indicators that lead to HAB development, weighing certain indicators that have a greater impact in causing HAB outbreaks, and developing prediction models that are specific to different algal species of concern.

Detection methods have progressed from visual identification of HABs to chemical identification of HABs through advances in monitoring technology. Research to develop monitoring and response strategies has led to regional monitoring programs as well as the development of increasingly sophisticated monitoring devices (NOAA 2011).

Accurately understanding the patterns of HAB development will require thirty consecutive years of monitoring (Anderson et al. 2012). With that in mind, it is important to progress from the development and testing of monitoring technologies to the implementation of these technologies, resulting in consistent monitoring of water bodies. The desired outcomes are improved accuracy, faster reporting time, lower cost and ease of use of the monitoring technology.

Prevention, Control and Mitigation

Previous efforts in prevention, control, and mitigation of outbreaks primarily focused on developing control methods, but progress has more recently addressed better understanding of potential prevention and mitigation techniques. Desired future outcomes include implementing prevention strategies, efficient control of HAB outbreaks, and effective mitigation of negative impacts to human health, local economies and ecosystems. Next steps in each include:

Prevention

The Mississippi River/Gulf of Mexico Watershed Nutrient Taskforce was required to complete an assessment specific to the Northern Gulf of Mexico hypoxic zone in the 1998 Act, as well as an action plan in the 2004 legislation (EPA 2001). By bringing together state agencies, local interest groups and watershed managers to do this difficult work together, the politics of the problem and potential solutions have to be negotiated at the same time as prevention methods are explored through research. The Mississippi River/Gulf Nutrient Task Force fostered initiatives in many states to protect wetlands and manage agricultural run-off, and continues to work on reducing excessive nutrient loading. The desired outcomes of the 2011 Amendments is to replicate this regional approach to other areas of the country.

The USDA established the Agricultural Drainage Management Systems Taskforce in 2003 to develop methods to reduce nitrogen and phosphorus runoff, to reduce cost, and to improve the efficiency of fertilizer use by farmers (Committee on Environment and Natural Resources 2010). Such measures decrease nutrient run-off, resulting in fewer instances of eutrophication. This will ultimately be effective in preventing HAB outbreaks from occurring.

Mitigation

The average annual economic impact of HABs and hypoxia on the restaurant, tourism, and seafood industries is conservatively estimated as \$82 million in losses (Hoagland and Scatasta 2006). In order to decrease economic costs from HAB damages, regions can work towards implementing programs that decrease the severity of these damages across many different industries. Furthermore, mitigation efforts toward potential health and ecological risks associated with HAB outbreaks must be considered as well. For example, a program providing local training for health professionals on the human health effects of region-specific HAB toxins could mitigate human illness as well as prevent human mortality after an outbreak.

Necessary steps include further development of the Environmental Sample Processor (ESP) technology. After this technology is implemented locally, professional training sessions teaching people how to use this technology to respond to HABs will also be effective in decreasing the negative impacts of the problem.

Conclusion

Harmful algal blooms present numerous complex problems, not all of which are easily addressed by the policies the United States is currently considering. The 2011 Harmful Algal Bloom and Hypoxia Research and Control Amendments goals are constrained mostly by lack of funding and time, as well as difficult decisions about when to move forward with newly designed strategies based on the available research, versus waiting for more information from research that is in progress. The Senate's proposed budget of \$30 million annually through 2015 is likely not sufficient to cover the costs of the programming specified in the legislation, especially considering the intensive focus on scientific research at the regional level. Additionally, the stated goals require a significant amount of research progress in order to form a comprehensive structure for rehabilitation programs. Overall, scientists and policy makers must attempt to strike a balance between responding to the real impacts on human health, local economies, and ecosystems, putting in the effort and time required to complete research, and establishing the networks that are needed to determine the most effective and efficient path forward.

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