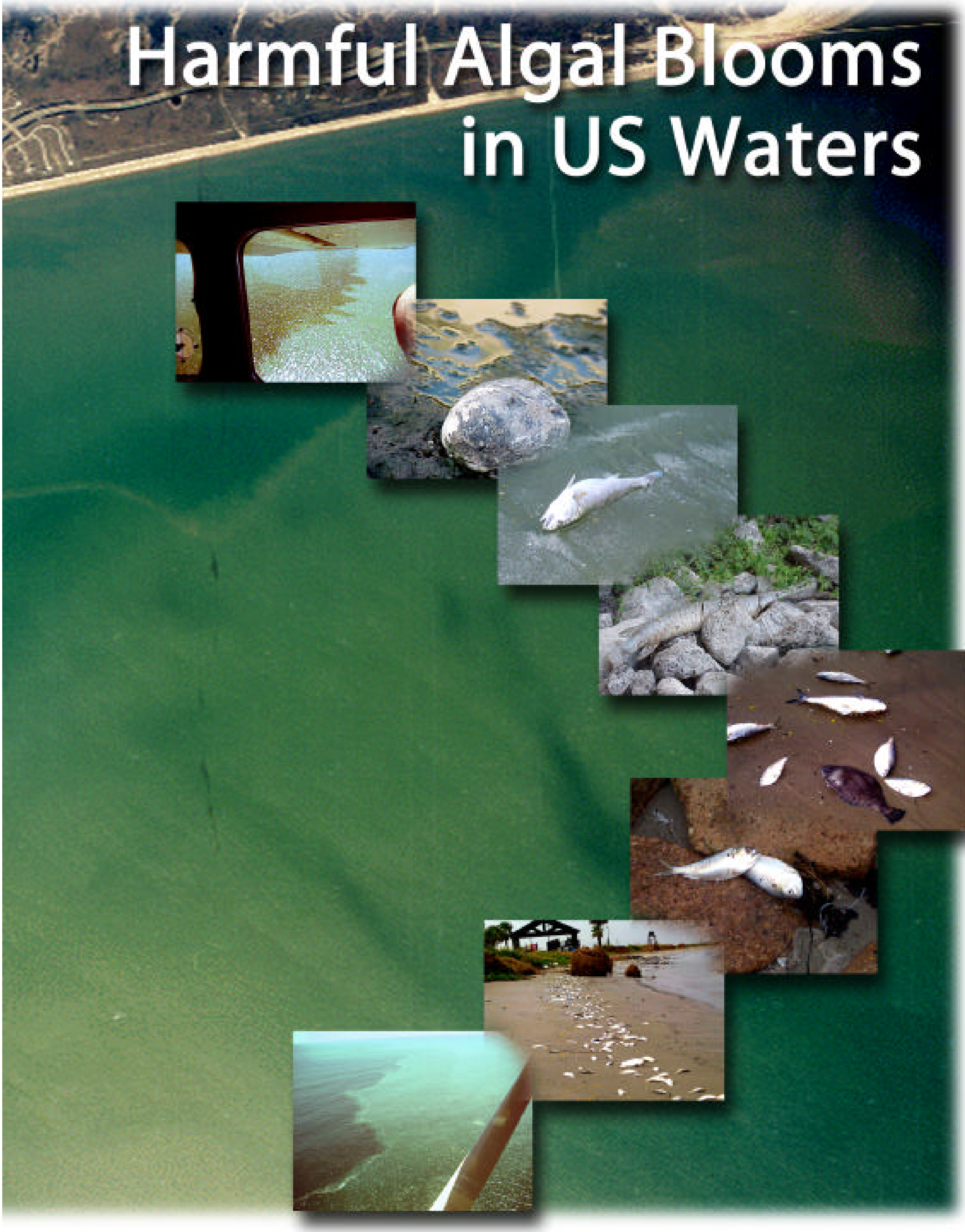
Harmful Algal Blooms in US Waters



The National Science and Technology Council

President Clinton established the National Science and Technology Council (NSTC) by Executive Order on November 23, 1993. This cabinet-level council is the principal means for the President to coordinate science, space, and technology policies across the federal government. The NSTC acts as a "virtual" agency for science and technology to coordinate the diverse parts of the federal research and development enterprise. The NSTC is chaired by the President. Membership consists of the Vice President, Assistant to the President for Science and Technology, cabinet secretaries and agency heads with significant science and technology responsibilities, and other White House officials.

An important objective of the NSTC is to establish clear national goals for federal science and technology investments in areas ranging from information technologies, environment and natural resources, and health research, to improving transportation systems and strengthening fundamental research. The NSTC prepares research and development strategies that are coordinate across federal agencies to form an investment package that is aimed at accomplishing multiple national goals.

To obtain additional information regarding the NSTC, contact the NSTC Executive Secretariat at 202-456-6100.

The Committee on Environment and Natural Resources

The Committee on Environment and Natural Resources (CENR) is one of five committees under the NSTC. It is charged with improving coordination among federal agencies involved in environmental and natural resources research and development, establishing a strong link between science and policy, and developing a federal environment and natural resources research and development strategy that responds to national and international issues.

To obtain additional information regarding the CENR, contact the CENR executive secretariat at (202) 482-5916.

NATIONAL ASSESSMENT
of harmful algal blooms in US waters

OCTOBER 2000

National Science and Technology Council
Committee on Environment and Natural Resources

Committee on Environment and Natural Resources

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Executive Summary

Harmful Algal Blooms in US waters

Harmful algal blooms (HABs) are found in the waters of almost every US coastal state. Virtually every US coastal state has experienced the environmental, human health, and economic impacts of HABs. HAB events regularly threaten living marine resources, restrict local harvests of fish and shellfish, divert public funds to monitoring programs, burden medical facilities, and depress local recreational and service industries. Some HABs produce toxins and make their presence known as massive "blooms" of cells that are so dense and extensive that they discolor large areas of water, such as Florida's toxic red tides. Still others can threaten human health and marine life even when they are not visible in the water. The algae responsible for HABs are a very diverse group of organisms. Some are single-celled microalgae or phytoplankton, while others are large, leafy seaweed-like macroalgae.

The *Harmful Algal Bloom and Hypoxia Research and Control Act* (P.L. 105-383) calls for "an assessment which examines the ecological and alternatives for reducing, mitigating, and controlling harmful algal blooms, and the social and economic costs and benefits of such alternatives." This report, *A National Assessment of Harmful Algal Blooms in US Waters*, presents a synthesis of current research and management expertise on the causes, consequences, and current status of harmful algal blooms (HABs) nationwide and presents alternatives and recommendations for addressing HABs and their impacts. This assessment was developed by the Task Force on Harmful Bloom and Hypoxia under the National Science and Technology Council (NSTC) Committee on Environment and Natural Resources (CENR). It was a multi-agency, multi-disciplinary effort that included input from States, Indian tribes, industry, nonprofit organizations, and other stakeholders.

Harmful algal blooms threaten human health and natural resources throughout US coastal waters, from Alaska to the Gulf of Maine.

Problem and Causes of HABs

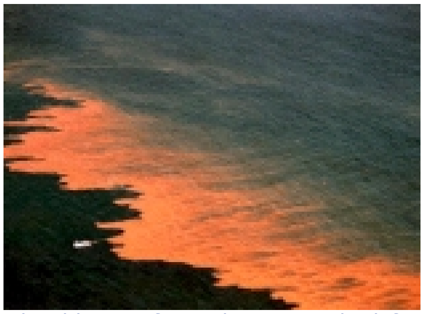
A growing body of evidence suggests that HABs are increasing worldwide. There are more HAB species, more HAB events, more algal toxins, more areas affected, more fisheries impacted, and higher economic losses today compared to twenty-five years ago. There are different opinions about the reasons for this expansion of HABs. Some "new" HAB events may simply reflect better detection methods and more observers rather than new species introductions or dispersal events—today, more researchers and managers are surveying more waterways for the presence of HAB species using more sensitive and accurate tools than ever before. Natural events may also play a role in the expansion of HABs. *Alexandrium,* a HAB species which contaminates shellfish beds in the Gulf of Maine almost annually, was introduced to those waters by a massive hurricane in 1972. Excess nutrients delivered to coastal waters may act as fertilizers and stimulate populations of micro- and macroalgae to increase to bloom proportions. The abundance of *Pfiesteria piscicida*, which has been found in tributaries with high levels of anthropogenic nutrients and organic matter, appears to be linked to nutrient loads. Blooms of *Pseudo-nitzschia* in the Gulf of Mexico and California also appear to be stimulated by nutrients. This potentially toxic diatom is a dominant species in the nutrient-rich plume of the Mississippi River. Humans may have contributed by transporting toxic species to new areas in the ballast water of ships.

Impacts of HABs

HAB impacts include human illness and death from ingesting toxins from contaminated seafood, mass mortalities of wild and farmed fish, mortalities of marine mammals, seabirds, and other protected species, and disturbances of marine food webs and ecosystems. Paralytic, neurotoxic, and amnesic shellfish poisoning (PSP, NSP, and ASP) syndromes occur when humans ingest fish and shellfish that have accumulated HAB toxins. These syndromes have severe effects, some of which are fatal. Some HABs release toxins and other compounds into the water that can kill marine fauna. Mass mortalities of wild and farmed fish, death and illness of marine mammals, sea turtles, seabirds, and other protected species, and alterations of coastal food webs through adverse effects on seagrasses, and young and adult marine organisms are common. Nontoxic HABs can cause harm by irritating or damaging fish gills, shading out other marine plants, or causing low oxygen conditions. These impacts can affect commercial, recreational, and subsistence fisheries, tourism, and coastal recreation. A recently completed study of the economic impact of HABs in the United States estimated that the average annual impact of HABs is $49 million. Individual HAB outbreaks can cause economic damage that exceed the annual average—outbreaks of *Pfiesteria piscicida* in the summer of 1997 and the consumer panic that ensued is estimated to have cost the Maryland seafood and recreational fishing industries almost $50 million in just a few months.

Management of HABs

Management options for dealing with the impacts of HABs include reducing their incidence and extent (prevention), stopping or containing blooms (control), and minimizing their impacts (mitigation). Where possible, it is preferable to prevent HABs rather than to treat their symptoms. Controlling pollution inputs is one approach that may reduce the incidence of those HAB species that are stimulated by nutrient enrichment. Potential approaches to control HABs are similar to those used to control pests on land. However, more research is needed before these means are used to control HABs in US waters. The most effective mitigation tools are monitoring programs that detect toxins in shellfish and/or monitor the environment for evidence of HAB events. These programs can provide advance warnings of outbreaks and/or indicate areas that should be closed to harvesting. Some states supplement their monitoring programs with rapid response teams that are deployed during suspected HAB events to assess the blooms' extent and impacts. Recent technological advances, such as remote-sensing and molecular techniques, have increased detection and characterization of HAB blooms, and are playing an increasing role in monitoring programs nationwide. A long-term goal of these HAB monitoring programs and tools is to develop the ability to forecast bloom development and movement.



This bloom of Noctiluca *stretched for 20 miles along the California coast (Photo: P.J.S. Franks).*

Recommendations to Address HABs

Over the past decade there has been an ongoing effort by Federal agencies working with state public health and fisheries managers, the science community, and coastal industries and constituencies to identify uncertainties and data gaps and the research needed to address the problem of HABs in US coastal waters. This has been furthered through hearings, workshops, scientific conferences, and town hall meetings. The general consensus of these discussions is that a long-term commitment and significant support are needed for research on the ecology of HABs and their causes and consequences, and for development of ways to manage the problems caused by increasing HABs nationwide.

The objective of much of the research on HABs has focused on the fundamental biological, chemical, and physical processes underlying blooms and their impacts. Such understanding is essential if we are ever to manage or mitigate blooms. The key to understanding of the influence of human activities on HABs is understanding the influence of environmental factors on harmful algal species and their competitors. This will help determine whether such activities are likely to lead to more frequent and severe HABs and if the means can be developed to mitigate HAB impacts. To fully understand the impacts of HABs, greater emphasis must be placed on estimating the economic impacts of HAB events.

The epidemiology of the human health impact of exposure to HAB toxins is in its infancy. Studies are needed on the effects of chronic exposure and how HAB toxins move through the body and how they are metabolized. These gaps in understanding prevent researchers from developing antidotes or effective treatments for HAB poisoning syndromes. Improved disease reporting and surveillance is also needed as well as education to alert public health providers to the symptoms and dangers of HAB-related illness.

As HABs continue to increase, we must focus our goals and research expertise toward developing techniques for detecting and reducing the impacts of these events. Reduction of nutrient pollution to coastal waters may reduce the incidence of those HABs that are stimulated by over-enrichment. Research into control methods may lead to ways to limit and even terminate blooms in progress. Monitoring and event response programs can be the most effective means to mitigate HAB impacts on human health. Research and development of new technologies can help make these programs more efficient, reliable, and cost-effective.

Federal Efforts to Address HABs

A recent General Accounting Office (GAO) report concluded that coordinated Federal efforts are being undertaken to learn about, manage, and protect the public from the effects of harmful algae. These include the interagency Ecology and Oceanography of Harmful Algal Blooms (ECOHAB) research program, which has initiated regional studies and targeted projects to investigate and model the growth and toxin dynamics of the major toxic species along the entire US coast. Individual agencies are also working together and with stakeholders to improve water quality, monitor shellfish toxins, and examine the linkages between runoff and water quality. These programs and others contribute to understanding and managing HABs and their impacts.

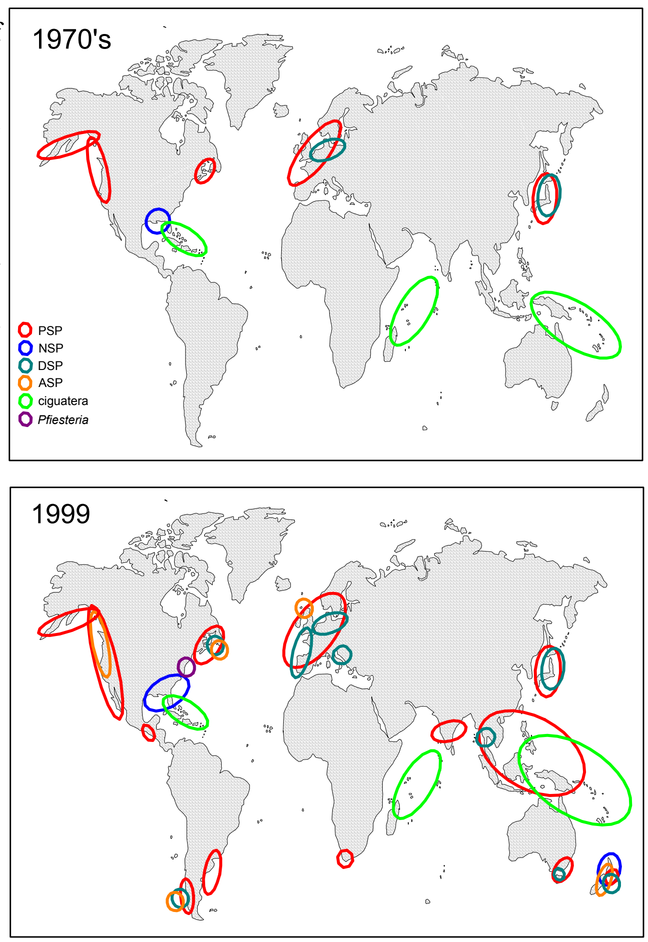
The Problem
Harmful Algal Blooms in US waters

Among the thousands of species of microscopic algae at the base of the marine food web, only a few dozen are considered "harmful."

Some of these harmful species produce toxins and make their presence known as massive "blooms" of cells that discolor the water. Other species are noticed even in dilute, inconspicuous concentrations of cells because they produce highly potent toxins that can kill marine organisms directly or can travel through the food chain and cause harm at multiple levels.

Many coastal communities have experienced the environmental, human health, and economic impacts of harmful algal blooms (HABs). HAB events regularly threaten living marine resources, restrict local harvests of fish and shellfish, divert public funds to monitoring programs, burden medical facilities, and depress local recreational and service industries. Blooms of familiar and previously unknown species are occurring in new coastal areas with increasing frequency, and HABs are now found throughout US coastal waters, from the Gulf of Maine through the Gulf of Mexico and north to Alaska.

Figure 1. Global increase in reported algal toxins. Circles indicate where outbreaks have occurred or toxin has been detected at levels sufficient to impact human or environmental health. (Van Dolah, 2000).



The algae responsible for HABs are a very diverse group of organisms; some are microalgae or phytoplankton, while others are large, leafy seaweed-like macroalgae. The most well known group responsible for HABs worldwide is the dinoflagellates, which include those that form red tides as well as the toxic *Pfiesteria* species. Less common groups include diatoms *(Pseudo-nitzschia)*, the brown tide organisms *(Aureococcus* and *Aureoumbra)*, and the bacteria- like blue-green algae (cyanobacteria). Blooms of toxic algae were commonly called "red tides," since, in the case of some dinoflagellates, the tiny organisms increased in abundance until they dominated the planktonic community and tinted the water reddish with their pigments. Because other blooms may tint the water green or brown and adverse effects can occur when algal concentrations are low and the water is clear, the scientific community now uses the term "harmful algal bloom" or HAB.

In October 1998, Congress passed the *Harmful Algal Bloom and Hypoxia Research and Control Act*, which the President signed into law as P. L. 105-383 on November 13, 1998. This law calls for an interagency Task Force to complete and submit to the Congress "an assessment which examines the ecological and economic consequences of harmful algal blooms, alternatives for reducing, mitigating, and controlling harmful algal blooms, and the social and economic costs and benefits of such alternatives." This report, *A National Assessment of Harmful Algal Blooms in US Waters*, presents a synthesis of current research and management expertise on the causes, consequences, and current status of HABs nationwide. It examines alternatives for preventing, controlling, and mitigating HABs and their impacts and presents recommendations for addressing the growing problem of harmful algal blooms in US waters.

A National Assessment of Harmful Algal Blooms was developed by the Task Force on Harmful Bloom and Hypoxia under the National Science and Technology Council (NSTC) Committee on Environment and Natural Resources (CENR). The development of this assessment was a multi-agency, multi-disciplinary effort. States, Indian tribes, local governments, industry, academic institutions, non-governmental organizations, and other stakeholders were involved in the development of this assessment through the World Wide Web, town meetings, email updates, and direct editing opportunities. The assessment builds upon important federal, state, and academic HAB reports issued over the last 5-10 years which also had extensive stakeholder input.

This assessment summarizes the most up-to-date information available on the growing national problem of HABs. It should form the basis for further research, monitoring, and detailed assessments of regional HAB issues, and inform management decisions regarding HAB problems in US coastal waters.

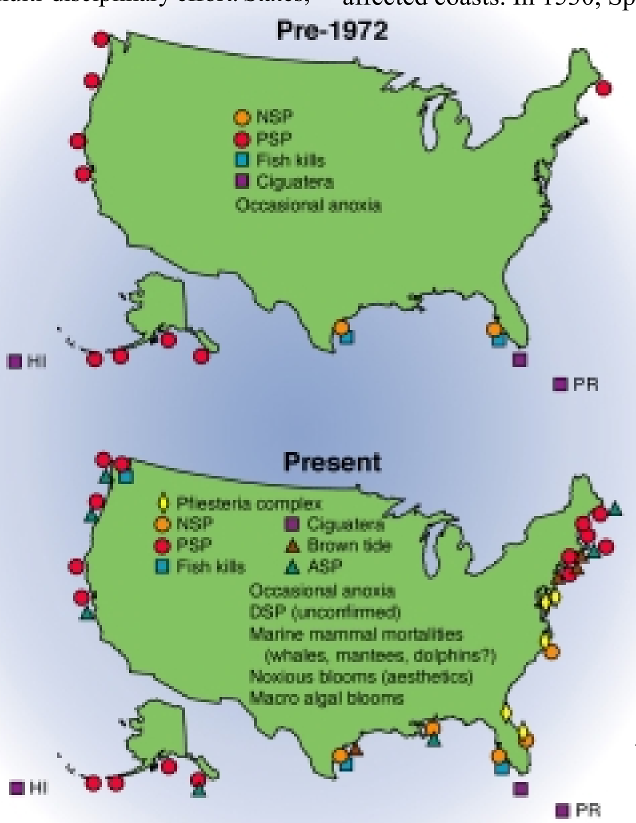


Figure 2. Since 1972, the number and distribution of harmful algal bloom species and events in U.S. waters have increased. (NOAA and WHOI).

Increasing Trends: Expansions of Harmful Algal Blooms

Harmful algal blooms are natural phenomena that have occurred throughout recorded history and such blooms were familiar events to the native peoples who lived along affected coasts. In 1530, Spanish explorers to Florida's coast noted that tribes of the Tampa Bay area knew the onsets of certain seasons by events such as red tides and fish kills. However, given the increased attention being paid to HAB phenomena, a question that scientists, managers, and the affected public ask is, "Are HABs spreading and is the problem getting worse?" A growing body of evidence suggests that HABs are increasing around the globe.[1-3] In the past, HABs impacted only a few scattered coastal areas in the US; today, virtually every US coastal state is affected. In the last three decades, there appears to have been a major worldwide expansion in the frequency, geographic extent, and magnitude of HAB events and in the number of HAB species involved [Figure 1]. A map of current US HAB events also shows more HAB species, more algal toxins, more affected areas, more impacted fisheries, and higher economic losses, compared to 25 years ago [Figure 2].

The Causes

Harmful Algal Blooms in US waters

Although few would argue that the number of toxic blooms events, toxins, and toxic species have increased over the last thirty years in the United States and around the world, there are different opinions about the reasons for this expansion.[1,2] Possible explanations include: 1) heightened scientific awareness and surveillance, 2) dispersal of HAB organisms through currents, storms, or other natural mechanisms, 3) nutrient enrichment, and 4) introduction/transport of cysts via ballast water transfers.

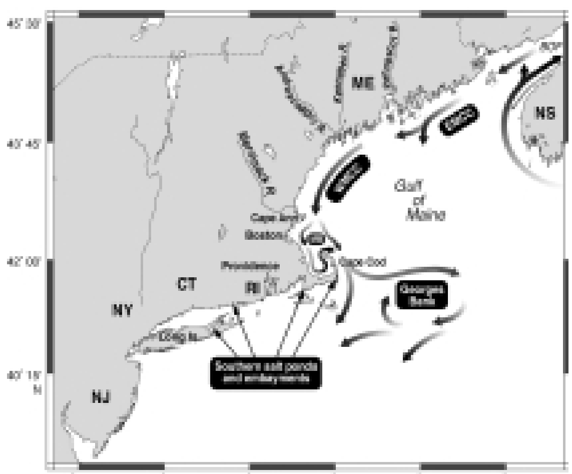
Heightened scientific awareness and surveillance

Some "new" HAB events may simply reflect better detection methods and more observers rather than new species introductions or dispersal events—today, more researchers are surveying more waterways for the presence of HAB species using more sensitive and accurate tools than ever before. Dramatically expanded aquaculture activities and reliance on fisheries resources, which have led to a concomitant increase in monitoring for product quality and safety, may now be "revealing" indigenous toxic algae. For example, the detection of amnesic shellfish poisoning (ASP) along the West Coast after 1991 may have been a result of improved detection methods that allowed the identification of domoic acid, produced by an organism that was initially thought to be a benign species. While *Pfiesteria piscicida* has only been associated with fish kills in North Carolina, Maryland, and possibly Delaware, testing of estuarine waters with sensitive molecular probes has revealed the presence of this organism in waters of numerous states along the mid-Atlantic and Gulf coasts.

Resolution of this issue is difficult because of lack of long-term data sets.[4] Among those data suitable for analysis, however, there is evidence to support an increase in HABs in US waters and worldwide.[1-3,5]

Species dispersal through unusual currents or storms

Natural events may also play a role in the expansion of HABs. Regional circulation patterns can be a very important determinant of which algae are present in an area. The distribution and occurrence of *Gymnodinium breve*, the organism responsible for neurotoxic shellfish poisoning (NSP) in the Gulf of Mexico, are largely due to the regional circulation of the eastern Gulf of Mexico. The complex winds and currents of the eastern Gulf are thought to deliver sparse, offshore populations of *G. breve* to the shelf break on Florida's western coast, allowing for growth, accumulation, and bloom formation. In 1987-1988, blooms of *G. breve* were transported to North Carolina's Outer Banks via the Gulf stream. The blooms moved onshore through a Gulf Stream eddy and persisted in NC waters for 3.5 months.[6] This mass transport, or advection, of the red tide has been documented through examination of remote sensing images collected during the period.[7]



The West and East Maine Coastal Currents (WMCC and EMCC) appear to determine the distribution and dynamics of Alexandrium *blooms in the Gulf of Maine. (WHOI).*

Alexandrium, the organism responsible for paralytic shellfish poisoning (PSP), is common along the Canadian coast. In 1972, a massive hurricane was responsible for introducing dormant cysts of this species to southern New England waters, where it has persisted to this day. *Alexandrium* species distribution and the patterns of PSP that are seen in the region are closely linked to large- and small-scale circulation of the Gulf of Maine [Figure 5]. Because of the organism's unique life cycle, which includes a resting cyst stage, resident populations of *Alexandrium* are now entrenched in Maine's river mouths and shelf sediments. These excyst or "hatch" each spring to give rise to new toxic populations that are transported to the south and west.

This kind of expansion has raised the possibility that HABs may be affected by global climate change. Some researchers suggest that recent increases in the emergence and frequency of diseases affecting marine organisms, such as coral bleaching, are linked to climate change and that HABs could respond to global change in much the same way.[8] Increases in the number of storm events or changes in circulation patterns could effect the distribution and transport of HAB species. However, in the absence of long-term data sets, it has been difficult to assess the impacts, if any, of global change on HAB events.

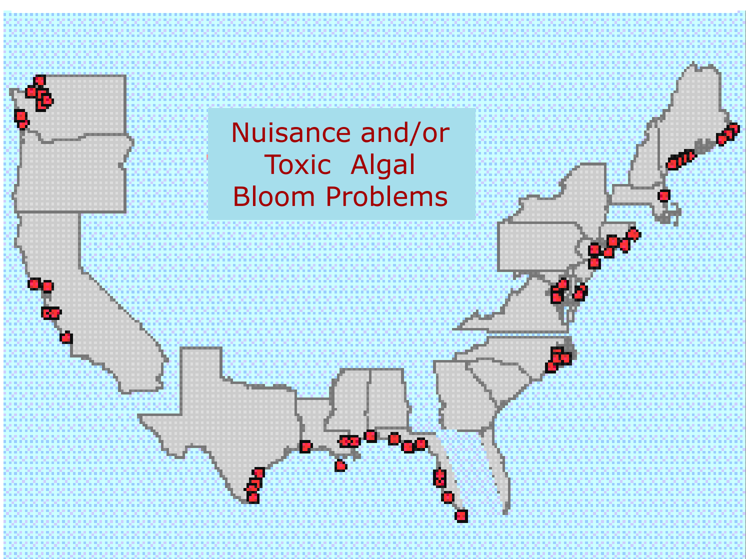
Regional circulation patterns that carry nutrient-rich deeper waters into shallow coastal zones can also result in HABs. Classic examples are the massive dinoflagellate and ciliate blooms that occur near upwelling zones off coastal Peru, but similar coastal circulation patterns have been suggested as the cause of toxic blooms of ASP-producing *Pseudo-nitzschia* off southern California. The coincidence of high levels of domoic acid in shellfish in the Northwest and seasonal upwelling also suggests that the delivery of deep nutrients to near surface waters in these regions may be potentially responsible for the annual occurrences of ASP. The response of *Pseudo-nitzschia* to this nutrient pulse has supported previous observations of an association between nutrient loading from rivers and the development of blooms of this organism.

Nutrient enrichment

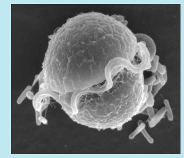
Nutrient enrichment has also been suggested as the cause for the increasing frequency of HAB events worldwide.[2-4] Manipulation of coastal watersheds for agriculture, industry, housing, and recreation has drastically increased nutrient loadings to coastal waters. Just as the application of fertilizer to lawns can enhance plant growth, marine plants (algae) may grow in response to the input of nutrients to our nation's coastal areas.

Shallow and restricted coastal waters that are poorly flushed appear to be most susceptible to nutrient-related algal problems. Nutrient enrichment of such systems often leads to excessive production of organic matter, a process known as eutrophication,[9] and increased frequencies and magnitudes of phytoplankton blooms, including HABs.[2,3,10] The National Estuarine Eutrophication Assessment, which surveyed 300 scientists and managers about 138 US estuaries, found blooms of macroalgae and other nuisance and toxic algae to be common symptoms of eutrophication.[11] Of the 44 US estuaries surveyed that exhibited highly eutrophic conditions, 20 experienced high incidence of nuisance and/or toxic algal blooms [Figure 3]. A recent National Research Council report nutrient pollution concluded that, while not all HABs are caused by nutrient loading, many are at least in part associated with the ecological changes that accompany eutrophication.[12] Two classic studies from Asia support the links between coastal development, eutrophication, and HABs. Tolo Harbor in Hong Kong experienced an increasing incidence of red tide as a result of increased urban development of the surrounding watershed, which increased nutrient inputs to the adjacent coastal waters. From 1976 to 1986, as the population of the watershed increased sixfold, nutrient loadings

Figure 3. U.S. estuaries with reported moderate to high levels of nuisance or toxic blooms, cited as symptoms of high eutrophic conditions (Bricker et al., 1999).[11]

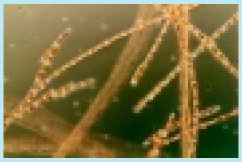


The Role of Nutrients in Outbreaks of *Pfiesteria piscicida*



Pfiesteria piscicida, the organism associated with fish kills and fish lesion events in Maryland in 1997 and North Carolina for much of the present decade, has been found in tributaries with high ambient levels of nutrient and dissolved organic matter (sugars and amino acids) relative to similar waterways.[15] Elevated populations of this HAB species have been found immediately downstream of sewage outfalls and discharges from hog farms and other animal feeding operations. Excessive nutrient loading appears to create an environment rich in the microbial prey and organic material that *Pfiesteria* and their fish prey feed upon. These observations, coupled with laboratory results, suggest a linkage between high nutrient load and abundance of this potentially toxic dinoflagellate. This conclusion was supported by the forum of scientists that was asked to advise the State of Maryland in the wake of the 1997 outbreaks on Maryland's Eastern Shore.[16] However, the presence of excess nutrients is only one of many factors that appear to be involved in *Pfiesteria* outbreaks.

Potentially toxic diatoms



Pseudo-nitzschia is a potentially toxic diatom that may also be stimulated by nutrients. Nutrient inputs to the Gulf of Mexico from the Mississippi have increased significantly since the 1950's and historical data show large increases in the abundance of this organism in the same time period. Non-toxic *Pseudo-nitzschia* species are among the dominant species of phytoplankton in the nutrient-rich plume of the Mississippi River and reach peak abundance in the spring when river flow and nutrient levels are highest.[17,18] Along California's coast, nutrients delivered to surface waters from natural coastal upwelling have stimulated *Pseudo-nitzschia* blooms.[19] In 1998, the *Pseudo-nitzschia* blooms that killed hundreds of sea lions followed upwelling and record levels of river discharge that carried high nutrient loads into Monterey Bay.

increased more than twofold, and red tide incidents increased more than eightfold (69 red tide incidents were recorded from 1980 to 1986, compared with only 4 in the preceding decade). Multiple fish kills were the red tides' major impact.[13] In the Seto Inland Sea of Japan, coastal pollution was also responsible for an increase in HAB events. From 1965, visible red tides increased steadily from 44 per year to over 300 per year a decade later, matching a concurrent pattern of increased nutrient loadings from pollution. Effluent controls to curb pollution inputs were initiated in the mid-1970's and between 1976 and 1985 red tide outbreaks decreased by 50% and remain at this level to the present day.[14]

Some scientists hypothesize that increased nutrient loads to coastal waters stimulate low-level ambient populations of microscopic and macroscopic algae to initiate a bloom. Others suggest that changing nutrient inputs may be affecting the fundamental structure of coastal ecosystems. Phytoplankton species have widely different nutrient requirements and tolerances. Species that are adapted to low-nutrient conditions may be intolerant of high nutrient conditions or unable to compete with those species that thrive when nutrient concentrations are high. Different phytoplantkon species may also require different ratios of nutrients for growth. Some experts argue that the nutrients that humans are introducing to coastal waters are delivered in proportions that differ from those found in nature, thereby favoring certain groups of algae, among them HABs.[3]

While some data are compelling, it has been difficult to determine conclusively if nutrients have played a role in the overall expansion of HABs because of the lack of historical data on nutrients and abundance of HAB organisms, especially in the U.S. *Gymnodinium* blooms, which are responsible for NSP, are initiated in nutrient-poor waters 40-80 miles offshore in the Gulf of Mexico. Therefore, the initiation of *G. breve* blooms does not appear to be nutrient-mediated. However, it is possible that the blooms that get into nearshore waters can benefit from the nutrients of the West Florida Shelf. For other HABs, there is may be no direct cause and effect relationship between nutrient pollution and the occurrence of blooms, such as those of PSP-causing *Alexandrium*, which impact more U.S. coastline than any other HAB.

Transport of HABs via ballast water

Still other researchers hypothesize that humans may have contributed to the global HAB expansion by transporting toxic species in ship ballast water.[20] Ballast water is used to stabilize cargo ships. When ships take on ballast water, they also take on the millions of microscopic organisms that are present in that water. Ballast water transfer has been responsible for the transfer of non-indigenous and invasive species among marine ecosystems.[21] While the planktonic stages of phytoplankton show limited survival in ballast water tanks, the cysts of these organisms may remain viable under such conditions. Some researchers suggest that ballast water transfer may have been responsible for the recent appearance of PSP-producing HABs in Australian waters in the 1980's.[5,22]

The environmental conditions that trigger, maintain, and terminate algal blooms are not well understood, and the diversity of HABs makes it likely that these factors will differ among species and therefore difficult to generalize about the causes of these trends. Blooms of some HAB species such as *Alexandrium* appear to occur independent of human activities, in relatively pristine or isolated offshore waters. Other HABs, such as *Pfiesteria*, appear to be strongly influenced by human activities such as nutrient over-enrichment of coastal waters. The role of nutrients in the initiation of *Pseudo-nitzschia* blooms, or in the maintenance of *Gymnodinium* blooms, is still unclear.

Harmful Algal Blooms in US waters: The Impacts

HAB impacts include human illness and death from ingesting contaminated shellfish or fish; mass mortalities of wild and farmed fish; death and illness of marine mammals, sea turtles, seabirds, and other protected species; and alterations of coastal food webs through adverse effects on seagrasses, and young and adult marine organisms. Impacts from some HABs occur when marine fauna are killed by algal species that release toxins and other compounds into the water. Nontoxic HABs can cause harm by irritating or damaging fish gills, shading out other marine plants, or causing low oxygen conditions. These impacts can affect commercial, recreational, and subsistence fisheries, tourism, and coastal recreation.

Public Health Impacts

Human illnesses caused by marine toxins in seafood have been recognized for over 200 years. When Captain George Vancouver landed in British Columbia in 1793, he observed that among the local Indian tribes it was taboo to eat shellfish during phosphorescent algal blooms. In one of the earliest recorded cases of human fatalities from HABs, two members of members of Vancouver's crew died from paralytic shellfish poisoning (PSP) after eating toxin-contaminated shellfish. In 1799 PSP claimed the lives of more than 100 Aleuts in the region that is now Alaska.

A single clam can accumulate enough HAB toxin to kill a human or a large marine mammal.

Shellfish poisoning syndromes have been given names that reflect some of their dominant and dangerous symptoms: paralytic, neurotoxic, and amnesic shellfish poisoning (PSP, NSP, and ASP). These syndromes have severe effects, some of which are fatal. These syndromes are caused by biotoxins synthesized by marine dinoflagellates, or in the case of ASP, by marine diatoms. When toxic algae are filtered from the water as food by shellfish such as clams, mussels, oysters, and scallops, their toxins accumulate in the shellfish tissues.[23,24] Typically, the shellfish are only marginally affected. However, a single clam can accumulate sufficient toxin to kill a human or large marine mammal. Humans can also become ill from ingesting fish that have accumulated HAB toxins. Ciguatera Fish Poisoning (CFP), common in subtropical regions, accounts for more than half the food poisonings associated with fish in the United States and is the most common food-borne illness caused by a chemical toxin.[25]

HAB toxins pose serious threats to human health because they cannot be destroyed by cooking or storage (e.g., freezing, drying, or salting), and there are few effective antidotes. Historically, marine seafood poisonings were limited to geographic areas where specific algae and host organisms (clams, mussels, reef fishes) thrived, i.e., temperate to tropical coastlines and coral reefs. However, given the global distribution of marine seafood products, the growth of aquaculture, tourism, and the increased frequency of HABs, much of the world's population could potentially be at risk for these diseases.

Epidemiological data on marine seafood toxin syndromes primarily consist of case reports presented in the scientific literature or popular press, or present as part of local history. Seafood poisonings are less likely to be recognized by physicians outside of areas where poisonings have historically occurred, and poisonings are often not reported to physicians in areas where the disease is endemic and symptoms are therefore commonplace, e.g., CFP in Hawaii. Thus, documented cases of illness from marine seafood toxins may represent only a fraction of true exposures.

Humans can also become ill from direct environmental exposure to HAB toxins and these exposures may be equally important in terms of public health impact. For example, in Florida and Texas elderly people, asthmatics, and otherwise healthy adults have experienced eye and nose irritation and respiratory distress during red tide events. The extent of health effects from environmental exposure to these toxins when they become aerosolized during HAB events are currently undocumented, although respiratory irritation is so common that it is used as a sentinel of red tide.

As we identify new toxic species and toxins, the nature and extent of the problem is shown to be larger than previously thought. Unknown and newly identified microorganisms, such as *P. piscicida,* may produce toxins harmful to people and marine life. The increasing frequency, intensity, and distribution of HAB events increases the likelihood that people will become ill from exposure to these toxins, and their presence has implications not only for public health, but also for nutrition, medical care, resource development, and tourism. There is an urgent need for multifaceted public health action, particularly in the areas of disease surveillance, health care provider education, epidemiologic studies, and emerging issues. This is especially critical given the large-scale under-reporting, the apparent increase in the incidence and geographic distribution of HABs, and the evidence that public health impacts of HABs are not limited to food poisonings.

HAB-related Illness in the US

Paralytic Shellfish Poisoning (PSP). PSP is a worldwide problem that affects more US coastline than any other HAB.[26] PSP is caused by several closely related species of dinoflagellates in the genus *Alexandrium*. These organisms produce saxotoins and gonyautoxin, which are accumulated by filter-feeding shellfish and other grazers, and can affect higher levels of the food web, including lobsters, fish, and marine mammals,[27,28] as well as humans. Ingestion of contaminated shellfish can lead to illness, incapacitation, and even death. There is no antidote and health risks are controlled primarily through monitoring shellfish and rapidly closing affected regions to harvest once toxins have been detected.

Amnesic Shellfish Poisoning (ASP), also known as Domoic Acid Poisoning (DAP). ASP, so named because one of its severe symptoms of the permanent loss of short-term memory, has been fatal to humans, marine mammals, and birds. Domoic acid, the ASP toxin, is produced by diatoms in the genus *Pseudonitzschia*. ASP was discovered in 1987 when more than one hundred people became ill and three died from eating contaminated mussels harvested on Prince Edward Island. ASP became a concern along the West Coast of North America in September, 1991 when more than one hundred brown pelicans and cormorants were found dead or suffering from unusual neurological symptoms in Monterey Bay, CA.[29-31] Domoic acid has been detected in shellfish almost annually for the last decade and presents potential health risks to commercial, recreational, and subsistence harvesters all along the West Coast.

Neurotoxic Shellfish Poisoning (NSP). NSP is caused by the dinoflagellate *Gymnodinium breve*, which forms red tides in waters of the eastern Gulf of Mexico. *G. breve* produces neurotoxins and hemolytic substances called brevetoxins that can harm human and marine mammal populations. When humans eat shellfish that have fed on *G. breve*, they may suffer severe gastrointestinal and neurological symptoms. While there is no antidote for NSP, full recovery usually occurs within several days. The substances produced by *G. breve* can also cause human respiratory irritation.

Ciguatera Fish Poisoning (CFP). CFP is a malady associated with dinoflagellate toxins that accumulate in the flesh of tropical fish. CFP toxins (ciguatoxins) are produced primarily by epiphytic dinoflagellates (*Gamberdiscus toxicus, Amphidinium carterae, Coolia monotis*, and several species in the genera *Prorocentrum, Ostreopsis*, and *Thecadinum*) that grow on the surface of red and brown macroalgae in virtually all subtropical and tropical waters. Ciguatoxins accumulate in fish tissues, persist over extended periods and often become concentrated in the flesh of top predators. When these contaminated fish are eaten by humans, these toxins can cause long-term nonlethal but debilitating illness.[32,33] CFP is the most frequently reported nonbacterial illness associated with eating fish in the United States and its territories, with Southern Florida, the Caribbean, and Hawaiian islands accounting for the majority of documented CFP incidents. CFP was once restricted to tropical coastal areas but reports of CFP intoxications from temperate "inland" locations have been increasing as a result of the widespread commercial distribution of subtropical and tropical fish.

Pfiesteria-related illness. Laboratory workers working with cultures of *P. piscicida* have reported respiratory irritation and problems with concentration and memory and a recent report suggests that people experienced learning and memory difficulties following exposure to waterways containing *P. piscicida*.[34] However, the toxins produced by this organism have not been identified and characterized. Therefore, there is no biological marker of exposure, and it is currently not possible to verify environmental exposures to either the organism or its toxins. CDC, in collaboration with other federal, state, and local government agencies and academic institutions, is conducting multistate surveillance, epidemiologic studies, and laboratory research for possible *Pfiesteria*-related human illness.[35,36]

Impacts on Marine Life

HABs impacts on marine life range from subtle to the dramatic, from almost invisible effects on microscopic plankton organisms to the deaths of the world's largest animals, whales. Although deaths of endangered marine animals often focus public attention on these harmful algal species, many of the consequences of HABs are seen at every trophic level and stage of development.

This California sea lion was treated for DAP during a 1998 Pseudo-nitzschia *bloom off Monterey–over sea lions 400 died. (Marine Mammal Center, Sausalito, CA).*

Fish mortalities are the most frequent animal impact of HAB events. In the winters of 1997 and 1998, millions of fish washed up onto the Texas shore, with more than 21 million reported in 1997 alone. The red tide dinoflagellate *G. breve* was found to be the cause. The accumulation of dead fish along beaches of the Gulf is not unusual and coastal communities and counties on Florida's western coast have had to maintain active beach-cleaning activities to dispose of rotting fish for the last forty years. In North Carolina waters alone, fish kills of millions of fish have been associated with *P. piscicida* in the last decade. This dinoflagellate is also implicated as the likely agent for smaller fish kills in Maryland's Eastern Shore tributaries in 1997.

Catastrophic losses of cultured and wild fish not only occur from many toxic algal species but also from others that do not cause illness in humans. Nontoxic HABs can kill fish and shellfish through physical damage, disruption of coastal ecosystems, or creation of low oxygen conditions. Blooms of the flagellate *Heterosigma akashiwo* and the diatoms, *Chaetoceros convolutus* and *C. cavicornis,* do not produce toxins but have caused massive kills of pen-reared fish in the Pacific Northwest. Chains of these diatoms, which are armed with long setae and short spines, become lodged in fish gills and cause irritation, mucus production, and eventually suffocation. These species which do not appear to harm wild fish that can avoid blooms and swim to safety, can cause near instantaneous mass mortalities of the densely aggregated populations associated with fish pen mariculture operations. The problems caused by these species are so damaging that the mere knowledge that they have been detected locally can foreclose any possibility of fish pen mariculture as a viable industry in an area.

Fish farms in the Pacific Northwest lose many fish to nontoxic blooms of Chaetoceros *and* Heterosigma. *(Photo: WHOI)*

Algal toxins also affect many bird and mammal species. There have been a number of documented occurrences of HAB-related mortalities in marine and freshwater aquatic species. Brevetoxin has been documented as the cause of mortality in manatees and, most recently, bottlenose dolphins, and is suspected as the cause of mortality in lesser scaup and other bird species on the Gulf Coast for a number of years.[37,38] In 1996, a Florida red tide (*G. breve*) was responsible for the deaths of 149 of these endangered animals. Many of the deaths appeared to result from the inhalation of brevetoxin released into the air just above the highly concentrated bloom.[39] A red tide bloom that persisted off the Florida coast from August 1999 to January 2000 killed over 100 bottlenose dolphins. Saxitoxin, produced by *Alexandrium* species, has been strongly suspected as the cause of mortality in sea birds (common terns, shags, great cormorants, northern fulmars, herring gulls, common murres, Pacific loons, and sooty shearwaters).[40-42] Domoic acid has caused mortality in brown pelicans and Brandt's cormorants as well as sea lions on the central California coast, and is recently suspected to be affecting southern sea otters. In 1998, over 400 California sea lions died and many others were sickened during a bloom of *Pseudo-nitzschia australis* along the California coast. The animals died as a result of ingesting anchovies contaminated with domoic acid, demonstrating that this toxin can be transferred through the food web and affect marine mammals.[43] Cyanobacterial toxins have been suspected as the cause of mortalities of free-ranging ducks, geese, eared grebes, gulls, songbirds, and have been fatal when ingested by domestic animals such as cattle and dogs.[40,44]

Affected wildlife may serve as suitable models for the study of physiologic and pathologic changes produced by algal toxins and may also provide insights into toxic effects on humans and domestic mammals. Because of their position in the food web, sickness and death in these higher-level aquatic animals may serve as early indicators of toxin-producing algal blooms. Little is known about the toxicity of algal toxins in fish and wildlife, including the induced physiologic changes, toxin exposure levels, and subacute or chronic effects. In addition, field signs of illness or tissue lesions caused by

HABs are not well known or described for wildlife species. There are generally poor baselines for comparison or laboratory studies that have established concentrations of toxins required to produce sickness or death in wildlife species. Thus, even when levels of particular toxins can be measured in animals from mass mortality events, it may be difficult to assess their significance. Little work has been done to document the effects of acute or chronic exposure of algal toxins on wildlife specie. Exposure to sublethal levels of toxin may reduce productivity, decrease resistance to other diseases, and alter an animal's behavior thereby predisposing it to predation. Toxic algal blooms might also disrupt food chains in marine ecosystems, thereby indirectly affecting animal health by reducing food supplies.

Large, prolonged blooms of nontoxic brown tide species and macroalgae can reduce light penetration to the bottom, decreasing densities of valuable submerged aquatic vegetation (SAV) in coastal areas.[45,46] Loss of SAV can have dramatic impacts on coastal ecosystems as these grass beds serve as nurseries for the food and the young of commercially important fish and shellfish populations. These impacts can result in long-term damage to local shellfish and aquaculture fish stocks, sometimes leading to the collapse of fisheries.

Macroalgae (seaweeds) cause problems throughout the coastal waters of the United States and its territories. Over the past several decades, blooms of macroalgae have been increasing along many of the world's developed coastlines in response to coastal eutrophication. Macroalgal blooms occur in nutrient-enriched estuaries and nearshore areas that are shallow enough for light to penetrate to the sea floor. Macroalgal blooms have a broad range of ecological effects, and often last longer than "typical" phytoplankton HABs. They can have significant negative effects, pervasively and fundamentally altering coastal ecosystems.[47,48] Once they are established, macroalgal blooms may remain in an environment for years unless the nutrient supply decreases. Macroalgal blooms can be particularly harmful to coral reefs, which are fragile, highly diverse ecosystems that are adapted to stable oligotrophic (low nutrient) conditions. Under high nutrient conditions, opportunistic macroalgal species out-compete, overgrow, and replace coral reefs. Studies of coral reefs from around the Caribbean[49-55] and around the world[56-59] have confirmed the link between nutrient enrichment and increased dominance of reefs by macroalgae. Seagrass ecosystems can also be shaded out and destroyed by macroalgal blooms.

The over-accumulation of plant life, primarily macroalgae and phytoplankton, can lead to high rates of plant decomposition. Bacterial decay of this excess plant matter can strip much of the oxygen from local waters, causing conditions of low or no oxygen (hypoxia and anoxia). These HAB events need not produce toxins to cause detrimental impacts. Some of those HABs that result in visible water discoloration, e.g., the mahogany tides of the Chesapeake, the red sea slicks off southern California, often produce hypoxia during the night. This reduction of oxygen can be severe enough that the area may not be suitable for normal fish, shellfish, and other animals that require oxygen.

Economic Impacts

HABs result in wide-ranging impacts, many of which involve some degree of economic loss. Overall, the economic impacts from HABs are diverse and large. Perhaps more important, these impacts are recurrent, and show signs of increasing as the number of toxic and harmful algal species grows and our reliance on the coastal zone for aquaculture, commerce, and recreation expands. Most coastal states have neither conducted economic analyses of HAB impacts nor collected data that can be used to generate reliable quantitative estimates of economic impacts. In many cases, the complex physical and ecological characteristics of the coastal environment make it difficult to determine whether an algal bloom is the immediate and relevant cause of a fish kill, low oxygen event, or seagrass die-off. Moreover, local experts often differ substantially in their opinions about the magnitude of economic impacts from HABs. There may also be indirect or hidden costs such as constrained development and lost opportunities for marine recreation.

Summaries of two of the few recent studies that have been conducted on the economic impacts of HABs are included below. The first, from the Woods Hole Oceanographic Institution, looks at the impacts from HABs nationwide. The second study focused on the economic impacts of the 1997 outbreaks of *Pfiesteria* on Maryland's Eastern Shore.

A Recent Study of the Economic Impacts of HABs in the United States

Researchers at the Woods Hole Oceanographic Institution (WHOI) conducted a study of the estimated average annual economic impacts resulting from HABs in the United States.[60] This study represents the first attempt to develop a coherent estimate of the economic impacts of HABs in the nation. The analysis is based primarily on a survey of experts and literature, covering the period from 1987 to 1992. The most reliable data was available for this period, from which the most consistent estimates could be made.

Economic impacts were classified as those affecting: (1) public health, (2) commercial fishery, (3) recreation and tourism, and (4) monitoring and management costs. The annual economic impacts from HABs for each of these categories are provided in Table 1. The average total annual impact was approximately $49 million, ranging from $34 to $82 million over the six-year interval.

Individual blooms have been known to cause economic impacts equal to or greater than the annual averages for this study interval. For example, in 1976, a red tide in New Jersey caused more than $1 billion in losses to commercial shellfish harvesting and processing sectors. The 1997 outbreaks of *Pfiesteria piscicida* in the Chesapeake Bay were estimated to have cost the Maryland seafood and recreational fishing industries more than $40 million. Each of these events exceeded the annual average of HAB impacts for the entire nation during the study period.

(1) Public Health. Human sickness and death from eating tainted seafood resulted in lost wages and workdays. Costs of medical treatment and investigation were also an important part of the economic impact. Estimates of total public health impacts from HABs from 1987 to 1992 ranged from $18-$25 million, averaging $22 million per year over the six year interval.

Cases of sickness and death from shellfish toxins are probably the most clearly documented impact of HABs, in part because they are recorded by public health agencies in individual states as well as at the federal level. Average annual public health impacts due to shellfish poisoning from HABs from 1987 to 1992 were estimated at $1 million (caused by PSP, NSP, and ASP).

Ciguatera fish poisoning (CFP) predominantly affects residents of and visitors to tropical and subtropical areas, such as Florida, Hawaii, Puerto Rico, and Guam. Over the study interval, the economic impact of ciguatera poisoning alone varied from $18 million to over $24 million per year, averaging $21 million. These estimates were probably low, because any CFP that may have occurred from exports of tropical fish may not have been diagnosed or reported.

(2) Commercial Fisheries. Commercial fishery impacts from HABs include wild harvest and aquaculture losses of fish and shellfish resources due to NSP, PSP, ASP, ciguatera, and brown tides. Annual impacts varied from $14-$26 million with average

Table 1: Estimated Annual Economic Impacts from Harmful Algal Blooms*[60]

	Low	High	Average	% of Total
Public Health	$ 18,493,825	$ 24,912,544	$ 22,202,597	45%
Commercial Fishery	$ 13,400,691	$ 25,265,896	$ 18,407,948	37%
Recreation/Tourism	$ -	$ 29,304,357	$ 6,630,415	13%
Monitoring/Management	$ 2,029,955	$ 2,124,307	$ 2,088,885	4%
TOTAL	$ 33,924,471	$ 81,607,104	$ 49,329,845	100%
15 Year Capitalized Impacts (discounted at 7%)	$308,981,162	$743,270,485	$449,291,987	

*** Estimates are for 1987-1992, reported in 1999 dollars***

annual impacts of $19 million. Some currently untapped fishery resources may have had economic value that could have been realized in the absence of HAB threats. Because such values are difficult to estimate they were not included. A prominent example was the shellfish resource of coastal Alaska, which is permanently closed due to persistent PSP toxicity, and the difficulty of monitoring such a vast coastline. The potential gross revenues of this presently untapped resource have been estimated at $6 million per year.

(3) Tourism and Recreation. Estimates of economic impacts on recreation and tourism during the 1987-1992 period ranged from zero to $29 million with an annual average of $7 million. In Florida, recurrent red tides have been estimated to cause over $20 million in tourism-related losses every year. Unfortunately, these impacts, as well as similar losses in Texas and other areas, were not well documented and thus impact estimates were not included. Although many experts argue that the impacts of HABs on recreation and tourism are important and potentially large, there is little available data describing the size of the impacts.

(4) Monitoring and Management. Annual average costs for monitoring and management of HABs were estimated to total $2 million, distributed among twelve states: Alaska, California, Connecticut, Florida, Maine, Massachusetts, New Hampshire, North Carolina, New Jersey, New York, Oregon, and Washington. These costs included the routine operation of shellfish toxin monitoring programs, plankton monitoring, and other management activities. It is important to note that expenditures made to improve monitoring and management are likely to result in decreases in the other categories.

Economic Impact of *Pfiesteria* on the Seafood and Recreational Fishing Industries [61]

During the summer of 1997, several fish kills associated with blooms of *Pfiesteria piscicida* occurred on Maryland's Eastern Shore. Approximately 30,000 fish died and many others showed lesions which were thought to be related to *P. piscicida.* These blooms were confined to small areas; only a few commercially and recreationally important fish species were affected, and only a few commercial fishermen complained of health effects. Despite this limited impact, and the fact that there was no evidence that *P. piscicida* toxins would affect consumers of seafood, the economic impact of *P. piscicida* was extraordinary.

The Maryland Sea Grant Extension Program, in conjunction with the Maryland Department of Agriculture's Office of Seafood Marketing, attempted to measure declines in Maryland seafood sales that may have resulted from the public's concern about the safety of Chesapeake Bay seafood during these outbreaks. A survey was mailed to retail and wholesale seafood businesses in the state.

Seafood sales in 1997, prior to the *P. piscicida* outbreak, were running ahead of the 1996 baseline by about 7.4% and would have totaled $253 million. Actual 1997 seafood sales were $210 million, a loss in revenues of $43 million. Firms that specialized in Chesapeake Bay products had a greater reduction in sales (12.8%) than those that sold products from other areas (9.4%), but both types of firms were greatly affected.

The recreational fishing industry also felt the far-reaching impacts of *P. piscicida*. The loss of roughly 28,000 party/charter boat trips, presumably due to concerns regarding *P. piscicida*, translated into lost revenues for party/charter boat captains of approximately $2.2 million. Total expenditures of party/charter boat fishermen were reduced a total of $4.3 million. The lost benefit to the fishermen on the party/charter boats due to the loss of a fishing opportunity was approximately $1.9 million.

Overall, the aggregate impact of the *P. piscicida* outbreak for just a four-month period in 1997 approached $50 million in Maryland.

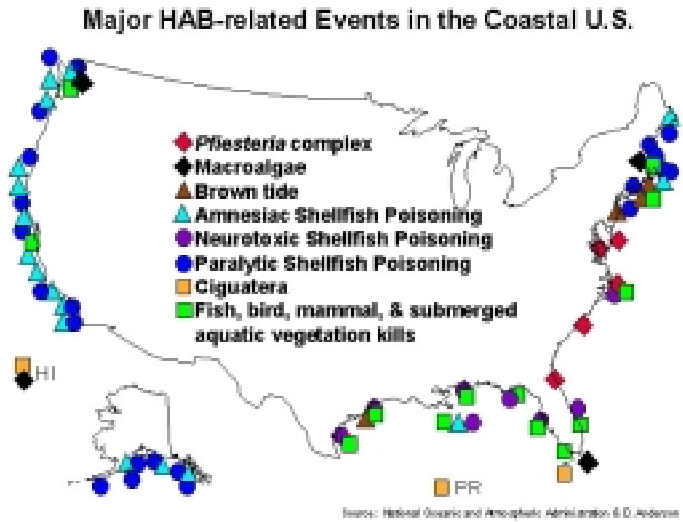
The ***"Halo Effect".*** The consumer panic caused by the *P. piscicida* outbreaks is a good example of what has become known as the halo effect. In general terms, the halo effect refers to a situation in which seafood consumers switch to substitute foods because of concerns about the possible contamination of seafood due to one or more HAB events. A halo effect typically affects producers of seafood or providers of recreation and tourist services. Because consumers can switch to other foods or to other recreational activities, the halo effect may not be serious for consumers, but it can be detrimental for producers. Tourists may choose an alternative vacation destination because of the risk of a HAB event. Because the public may be unsure of the public health risks of a HAB event, a halo effect may occur for seafood that is not even contaminated. As in the Maryland *Pfiesteria* case, the economic impacts associated with a halo effect can be substantial. The halo effect can be reduced through monitoring, management, and risk communication.

A supermarket sign displayed to ease consumer fears about Pfiesteria.
Photo: J.A. Purcell, the Washington Post.

Regional Effects

Harmful Algal Blooms in US waters

HAB events were previously confined to a few coastal areas in the U.S.; today, they are common throughout U.S. coastal waters, from the Gulf of Maine, through the Gulf of Mexico to Alaska, Hawaii and the tropical islands and territories.



Northeast: Gulf of Maine

Paralytic Shellfish Poisoning. PSP has recurred every year over large areas of the northeastern United States for more than two decades. Prior to 1972, shellfish toxicity was known only in eastern Maine. That year, a massive bloom introduced *Alexandrium tamarense* to more southern waters, and now the entire New England coastline experiences PSP outbreaks almost annually, with extensive shellfish bed closures and economic losses. In 1989, the rich beds of Georges Bank were contaminated, closing the surf clam fishery to this day.

Although blooms have not occurred in all regions, the detection of *A. tamarense* cells and cysts in Connecticut and Long Island small embayments, and as far south as New Jersey, suggests a gradual southward dispersion of these toxic *Alexandrium* species.[62-64]

Southern New England and the Mid-Atlantic

Brown Tide Blooms. Brown tides, which occur in shallow, poorly-mixed waters during the late spring and summer, can persist up to four months. The first U.S. outbreaks of brown tides occurred concurrently in New York and Rhode Island in 1985; blooms have occurred in New York many times since. Brown tide algae have been detected in aquatic systems ranging from Massachusetts to Virginia, although many of these areas have no previous history of visible or destructive blooms.[65] Blooms of the brown tide species *Aureococcus anophagefferens* have been confirmed in Narragansett Bay, Rhode Island, Barnegat Bay, New Jersey, Maryland's inland bays, and the Peconic-Gardiners Bay estuary and south shores of Long Island, New York.[66]

The initial notable impacts of brown tides were on the eelgrass and bay scallops in Long Island bays[54-56] and mussels in Narragansett Bay. Brown tides reduce the penetration of sunlight and thus destroy eelgrass beds, important habitats for scallops and other marine organisms.[45,67] These brown tide blooms are so dense and the cells so small that shellfish either stop filter feeding or retain very little food and starve to death. During brown tide events, the hatching success of important estuarine fish species, such as red and black drum and spotted seatrout is reduced and the larvae die from lack of food. Brown tides also cause mortality, recruitment failure, and growth inhibition of numerous commercially important bivalves, including blue mussels in Rhode Island[68] and bay scallops in New York.[69, 70]

Pfiesteria piscicida *and* Pfiesteria-*like organisms.* In 1991, *Pfiesteria piscicida*, an ichthyotoxic dinoflagellate, was found at a fish kill in the Pamlico River, a large estuary in North Carolina.[71,72] Since then, fish kills associated with this organism have become an almost yearly event in North Carolina, with an estimated 1 billion fish dead over the last decade. In 1997, toxic *P. piscicida* was associated with fish kills in three tributaries on Maryland's Eastern Shore. *P. piscicida* is one of several newly-discovered species of dinoflagellates that have multiple life stages, making them difficult to detect and study. Laboratory studies suggest that *P. piscicida* is stimulated to transform from benthic cysts, amoebae, or nontoxic flagellated stages to icthyotoxic zoospores by some unknown substances freshly secreted by finfish and shellfish.[72] A second icthyotoxic species has been discovered in the same genus *(Pfiesteria shumwayae* sp. nov.*)* but it does not appear to be as toxic as *P. piscicida.*[73]

Pfiesteria-like organisms (PLOs) have also been detected in estuarine waters. PLOs are dinoflagellates that are morphologically similar to *Pfiesteria* species and can easily be confused with them under a light microscope. Since they can co-occur with *Pfiesteria* species in the same habitat and may have similar niches, they may be present during fish kills and fish lesion events. Whether they produce neurotoxic or bioactive compounds that can be icthyotoxic has not been demonstrated.

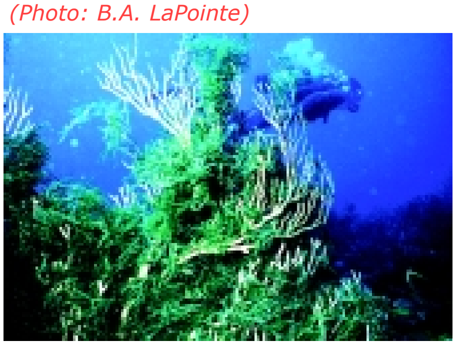
Southeast and the Gulf of Mexico

Neurotoxic Shellfish Poisoning. The toxic dinoflagellate *Gymnodinium breve* forms red tides in waters from the Gulf of Mexico to the South Atlantic Bight (off the Southeastern United States). *Gymnodinium breve* blooms are usually seasonal, starting in late summer or early fall and many occur over three to four months. Extensive blooms can cover areas as large as 30,000 km^2 and persist for up to eighteen months. Bloom events significantly impact fishing and tourist industries and alter population levels or recruitment potential of affected marine animals.[7,74] Toxic blooms of *G. breve* are generally identified by visual confirmation (water discoloration and fish kills), illnesses in people who have consumed contaminated shellfish, and human respiratory ailments.[47,75,76] Other detection strategies include time-intensive chemical assays for the presence of brevetoxins within shellfish tissue samples as well as mouse bioassays.[77-79]

G. breve is primarily a problem along Florida's shoreline coasts but occasionally blooms can be transported to the Texas coast. In 1987, a red tide bloom was transported from Florida waters to the coast of North Carolina, where it persisted for 3.5 months. During this time there were 48 cases of NSP and 1,480 km^2 of shellfish harvesting waters closed.[6]

Macroalgae. Seagrass ecosystems in Florida waters have been disrupted and destroyed by macroalgal blooms.[80] Dramatic evidence of this impact is visible in South Florida where macroalgae blooms have contributed to the marked decline in extent and vigor of coral reef and seagrass ecosystems that provide a vital nursery habitat for pink shrimp, spiny lobster, and many species of finfish.

Figure 14. Enrichment of nutrient-poor tropical waters stimulates macroalgae that can overgrow coral reefs. (Photo: B.A. LaPointe)



Brown Tide Blooms. A second brown tide population, *Aureoumbra lagunensis,* first created an extensive bloom in Laguna Madre, Texas in 1990, persisted for many years, and has bloomed several times since. These blooms have had substantial ecological impacts including decreased light penetration levels, loss of seagrass beds, and reduced zooplankton grazing rates.[46, 81] Recent investigations have focused on whether hypersaline conditions in the Laguna Madre are selecting for *A. lagunensis* which may have an adaptive tolerance to such extreme conditions.[82] It is possible that significant ecosystem changes will result from the long-term dominance of the Laguna Madre system by these brown tide blooms.

Subtropical Regions: Florida, the Caribbean, and the Pacific Islands

Ciguatera Fish Poisoning. CFP is the most frequently reported nonbacterial illness associated with eating fish in the United States and its territories, with Southern Florida, the Caribbean, and Hawaiian islands accounting for the majority of documented CFP incidents. An estimated 50% of the adults in the U.S. Virgin Islands have likely been poisoned at least once. Presently, no coordinated, systematic monitoring program exist for CFP in the United States and its territories.

West Coast: California

Paralytic Shellfish Poisoning. Since PSP was made a reportable disease in California 1927, there have been over 500 reported incidents, with more than 30 deaths. From the 1960's through the 1980's, there were toxic events most years along the California coast.[83] Today, most toxic events occur in the summer and fall, and the state imposes an annual mussel quarantine of sport-harvested mussels from May 1 to October 31 along the entire California coastline.[84]

Amnesic Shellfish Poisoning. ASP, also known as Domoic Acid Poisoning (DAP), became a concern along the California coast in September 1991 when more than one hundred cormorants and brown pelicans were found dead or suffering from unusual neurological symptoms in Monterey Bay, CA.[29-31] This event was attributed to poisoning by domoic acid, a toxin produced blooms of the diatom *Pseudo-nitzschia australis*. In 1998, over 400 California sea lions died as a result of ingesting fish contaminated with domoic acid during a bloom in the same area.[85-87] In both cases, the blooms of *Pseudo-nitzschia* appeared to originate offshore and then get transported to the coast.

Northwest: Oregon, Washington, and Alaska

Paralytic Shellfish Poisoning. Native American tribes and early European explorers on the West Coast reported illness and mortalities from eating shellfish over 200 years ago.[88, 89] In 1942, PSP resulted in the deaths of three people as well as mass mortalities of seabirds in this region.[90] Since then, the Washington coast from the Strait of Juan de Fuca to the mouth of the Columbia River has been closed to bivalve harvesting each year from April through October. In Alaska, PSP is so widespread that all beaches and waters are closed to recreational shellfish harvesting; commercial harvesting is strictly limited. In 1917, five million pounds of shellfish were harvested from Alaskan waters, but today the state's commercial bivalve industry is virtually nonexistent. The destruction of the clam industry, estimated at 25-50 million pounds per year, is in large part a result of product contamination by PSP.[91] Other commercially valuable species, such as Dungeness crabs, are also affected by PSP.

Amnesic Shellfish Poisoning. When ASP was first found in razor clams on the Oregon and Washington coasts in October 1991, both commercial and recreational harvests were halted. This event caused a combined $15-$20 million in damages to the Oregon and Washington coastal economies. Since then, the fall and spring recreational harvesting seasons in these states have been delayed, shortened, or not opened at all due to domoic acid contamination almost annually.[92] Coastal tribes that have traditionally depended upon these shellfish for food and income are particularly hard hit by these closures. Contaminated razorclam beds, which often must be closed with less than 24 hours notice to visitors, can remain closed for over a year due to residual toxins. In 1998, when record levels of domoic acid were detected in Oregon and Washington razor clams, the coastal tourism industry experienced an estimated $15 million loss. Repeated closures have, in fact, reduced tourist visits to the WA coast.

HAB-related Fish Kills. Blooms of the diatom *Chaetoceros convolutus* do not produce a toxin but have caused massive fish kills. Chains of these spiny cells become lodged in fish gills and cause irritation, mucous production, and eventually suffocation. *C. convolutus* and *C. concavicornis* have been repeatedly implicated in the death of pen-reared salmon, especially in the Pacific Northwest.

Blooms of the golden-brown alga, *Heterosigma akashiwo*, have been associated with kills of farmed fish in U.S. and Canadian waters of the Pacific Northwest. In 1986, *H. akashiwo* was responsible for the loss of $2.5 million worth of farmed salmon (about 1/3 of the stock) in British Columbia's Sechelt Inlet. In 1989, Washington State and Canada each lost $4 million worth of penned salmon from such blooms. Since then, commercial salmon aquaculturists in both countries have experienced substantial economic losses from these blooms. *H. akashiwo* has also recently been linked to mortalities of salmon in the wild.[92]

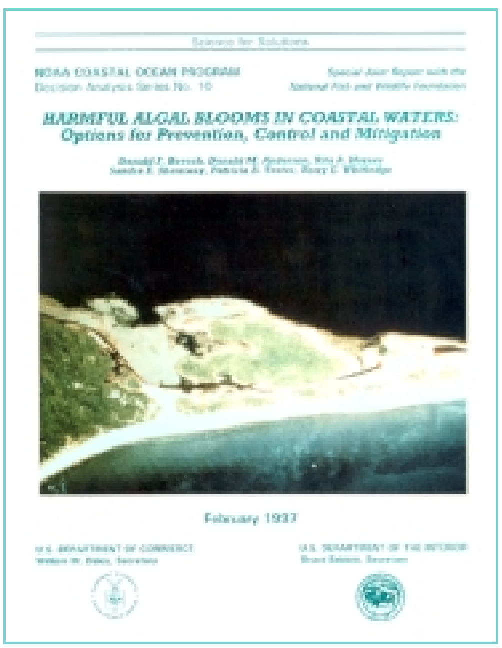
Nationwide

Harmful cyanobacterial blooms. Cyanobacterial blooms are common in freshwater systems throughout the world and can be fatal to humans. Excessive growths of *Anabaena, Aphanizomenon*, and *Microcystis* species lead to blooms that can cause severe neuro-, cyto-, and hepatotoxicity in humans, domestic animals, birds, and fish. Such blooms are often associated with excessive nutrient loading in low-salinity systems and have occurred in the Chesapeake Bay, Albemarle-Pamlico Sound, Florida Bay, and the Great Lakes. In 1991, an algal bloom, dominated by the species *Synechococcus elongatus*, appeared in mid-north central Florida Bay. It spread to central and western areas, and persists to this day. This bloom and the resultant turbid waters and reduced light penetration have been linked to large-scale mortalities of seagrass and sponge beds and even the degradation of coral reefs in the Florida Keys. Large blooms of *Microcystis* occurred in Lake Erie during the summers in the mid- and late 1990's, despite recent improvements in the lake's water quality. These blooms may be related to the infestation of zebra mussels, which selectively graze on other planktonic species. Harmful cyanobacterial blooms often terminate rapidly ("crash") in response to sudden physical changes (e.g., rapid drop in temperature, reduced light associated with poor weather). When crashes occur, oxygen consumption from the decaying biomass can lead to anoxia. This chain of events has been responsible for major estuarine fish and shellfish kills and loss of benthic habitat.[93 94]

Cyanobacterial blooms, often caused by nutrient over-enrichment, are a problem for many states (NOS Image Library).

Management Options

Management options for specific HABs vary, depending on the species, the region, and the impacts. In general, however, management options for dealing with the impact of HABs include reducing their incidence and extent (**prevention**), stopping or containing blooms (**control**), and minimizing human health risks and reducing the losses of resources or economic values (**mitigation**). [26,95] In 1996, the National Oceanic and Atmospheric Administration (NOAA) and the Department of the Interior (DOI) requested an assessment on the status of HABs in the U.S. and options for their prevention, control, and mitigation (PCM). Representatives from NOAA, DOI, the National Fish and Wildlife Foundation, and academic scientists worked in partnership to produce the report *Harmful Algal Blooms in Coastal Waters: Options for Prevention, Control and Mitigation*.[26] Regional meetings were convened in Texas, Washington, and Florida to bring together scientific experts, managers, and user constituencies to provide input to the assessment report.



The report offered numerous specific recommendations and generally concluded that the following were needed: 1) improved precautions for the protection of human health, 2) more concerted efforts to manage activities which may cause HABs, and 3) renewed consideration of strategies to control blooms once they occur. The assessment focused attention on the control of HABs and the evaluation of control techniques in the context of risk assessments (i.e., similar to those applied in the agricultural industry).

The report also noted that research being initiated by federal agencies on the Ecology and Oceanography of Harmful Algal Blooms (ECOHAB) program would contribute basic information on the causes and behavior of HABs and ultimately lead to the development of prevention, control, and mitigation strategies. To complement this program, federal and state agencies with responsibilities for resource management, environmental protection, and public health should support research addressing prevention, control, and mitigation (PCM).

Prevention

Prevention refers to environmental management options for reducing the incidence and extent of harmful algal blooms before they begin. It is preferable to prevent HABs in the first place rather than to treat their symptoms; therefore, where possible and practical, prevention is the preferred management option. Since increased pollution and nutrient loading may cause an increased incidence of outbreaks of some HAB species (e.g., *Pfiesteria*, *Pseudo-nitzschia,* cyanobacteria), these events may be prevented by reducing pollution inputs to coastal waters, particularly those industrial, agricultural, and domestic effluents high in plant nutrients. This is especially important in shallow, restricted, poorly flushed coastal waters that appear to be most susceptible to nutrient-related algal problems. For such waterbodies, preventive reduction of nutrient inputs would be the preferred management strategy.

Other strategies that may prevent HAB events include: regulating the siting of aquaculture facilities to avoid areas where HAB species are present (e.g. *Heterosigma*, *Chaetoceros*), modifying water circulation for those HABs where restricted water exchange is a factor in bloom development (cyanobacteria), and restricting species introductions, e.g. through regulations on ballast water discharges or shellfish and finfish transfers for aquaculture.

Control

Human efforts to control insects, diseases, and weed species are common on land. There are many reasons for the lack of similar efforts to control marine pests, but in general, they reflect concerns about costs, effectiveness, and environmental impacts.[95] There are numerous success stories in agriculture where biological control or integrated pest management have eliminated problem weeds or insect pests, often over millions of acres and without significant adverse impacts on the environment.[96] Another factor is that no federal agency has been given the mandate for marine pest management in the way the U.S. Department of Agriculture has been assigned this responsibility for the terrestrial pests that threaten agriculture. Approaches to direct bloom control include chemicals, flocculants, and biological control agents.

Attempts to use chemicals to directly control HAB cells in blooms encounter many logistical problems and environmental objections. The dispersion of copper sulfate over 16 square miles using crop dusting planes in a 1957 Florida red tide control effort highlights several of these problems, the most significant being that the chemicals are likely to be nonspecific and thus kill co-occurring algae and other organisms indiscriminately.[97] Efforts to find a magic chemical bullet that would somehow kill only a specific, targeted HAB species may be futile, as

In South Korea, clay has been used in attempts to control HABs and protect fish ponds. (Photo: WHOI)

it is difficult to develop a chemical that would only be lethal to a single phytoplankton species. Even if such a chemical were found, objections on environmental grounds are likely to be significant. Each candidate chemical will require extensive testing for lethality, specificity, and general safety, and each must surmount regulatory hurdles such as those imposed on industrial discharges to coastal waters. Although direct chemical control of red tides may not be a strategy of choice given other more benign alternatives, the use of this approach in terrestrial systems (e.g., application of herbicides and pesticides) suggests that it should not be completely ruled out.

A flocculant is a material that, when added to water, scavenges particles as it falls to the sediments below. One natural mineral flocculant that shows considerable potential for HAB control in coastal waters is clay. When added to seawater, clay particles absorb inorganic and organic materials, including algae and other particles to form a floc that falls to the sediments. In field trials, Asian scientists have used clay to treat natural red tide blooms on several occasions, including major blooms in Korea covering 100 square miles. Studies are needed that examine the effectiveness of this strategy on U.S. HAB species and the environmental effects of the treatment, especially the potential release of toxin during flocculation and the impact of sedimented cells and clay on bottom-dwelling organisms. Some of these studies are presently underway, but it will be several years before scientific results are sufficient to justify pilot studies and field tests.

Biological control of HABs is another option. There are a variety of organisms that could conceivably be used to control HABs. However, in reality, this approach has many logistical problems and is far from the application stage. Introductions of non-indigenous species or strains pose unknown risks and may be irreversible. Biological control is used extensively in agriculture, but there is still considerable opposition to the concept of releasing one organism to control another. Concern is likely to be greater regarding the marine environment, as there is little precedence for such activities. Despite examples where such an approach has had negative long-term consequences on land, there are cases where the approach has been both effective and environmentally benign (e.g., sterile male releases for control of the Mediterranean fruit fly). The concept deserves some consideration in marine systems, focusing on control agents such as zooplankton, bacteria, parasites, and viruses, and several studies are in progress. Viruses, for example, have the potential to be highly specific and effective control agents. They are abundant in coastal seawater and are recognized as being significant in the dynamics of phytoplankton blooms. They replicate rapidly, releasing hundreds of viral particles when a host cell is disrupted. Another important feature is that viruses tend to be host-specific. This means that a single algal species could be targeted, leaving closely related, co-occurring organisms unaffected. In reality, however, viruses are sometimes so host-specific that they are unable to infect different genetic strains of the same host species.

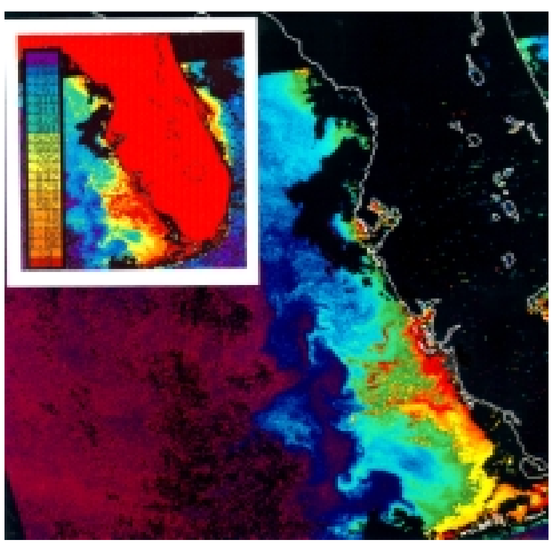
With respect to future research, studies are needed to determine if viruses, bacteria, or parasites exist that can be effective pathogens to targeted HAB species. Once pathogenic isolates are established, they must be tested for specificity and efforts made to understand the dynamics of infection and replication. The environmental implications of the release of non-indigenous organisms will need to be fully understood before this strategy could be tested in the field.

Mitigation

Mitigation involves steps taken to minimize human health risks, ecosystem damage, or fisheries losses from HABs that are otherwise not prevented or controlled. Many different types of actions can be taken to mitigate the impacts of HABs, including forecasting the development and movement of HABs, and responding rapidly to HAB events.

Monitoring HAB Cells and Toxins. To prevent human illness from shellfish poisoning syndromes, the most effective mitigation tools are monitoring programs that detect toxins in different fisheries species to provide either advance warning of outbreaks or to delineate areas that require harvest restrictions. This is predominantly a state activity, coordinated with the Food and Drug Administration (FDA) through the Interstate Shellfish Sanitation Conference (ISSC). States differ in their monitoring strategies. Some, such as Maine, Massachusetts, Florida, Oregon, and Washington, monitor their shellfish seasonally at sites along the coast and then close specific areas to harvesting when toxins approach dangerous levels.[98] Other states (e.g., Alaska) maintain permanent shellfish closures due to persistent toxicity or the logistical difficulties of monitoring remote stretches of coastline.

Another aspect mitigating HAB impacts is monitoring the environment for blooms and forecasting their development and movement. Many coastal states have developed monitoring programs for plankton and fish in coastal estuaries and bays that provide early warning of blooms. The state of Florida has been monitoring *G. breve* blooms in some form since the 1950's and effective monitoring programs have prevented most human exposure to contaminated shellfish, except when blooms have occurred in previously unaffected areas.[99] The Gulf of Maine states have been monitoring *Alexandrium* since the 1970's. Recent outbreaks of *Pfiesteria* have encouraged mid-Atlantic states to develop or expand monitoring for this organism. On the West Coast, increasingly frequent *Pseudo-nitzschia* blooms have led those coastal states to expand their monitoring programs and improve detection of *Pseudo-nitzschia* toxins and cells.

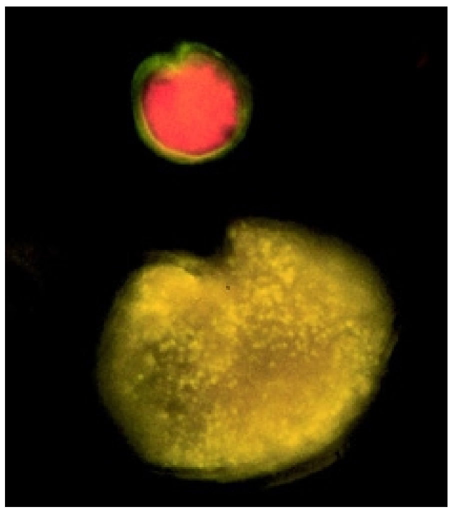


The concentrated regions of chlorophyll visible in this satellite photo are large blooms of G. breve *off the coast of Florida. (Photo: P. Tester).*

Monitoring programs are expensive, but they do provide an important measure of safety to consumers and to the fisheries industries. However, one important result of the HAB expansion over the last several decades is that the monitoring programs of many states are under severe financial pressures, due to flat or declining budgets and the need to monitor for more toxins in more organisms over larger areas. Programs that formerly monitored only a single toxin in one or two shellfish species now must assay for several toxins in multiple shellfish species, as well as crabs, snails, and other wildlife. One improvement in this area has been the development of networks of observers under the SEAPORT (Signal Environmental And Plankton Observations in Real Time) program. Volunteers are trained to use field microscopes to do real-time observations of plankton in coastal waters. These observations, when combined with other environmental signals, help states focus their toxicity monitoring efforts. SEAPORT programs are now active in California and most New England states. In addition to helping states expand their monitoring coverage, these programs have proven to be effective for establishing long-term baseline databases on coastal plankton populations and for engaging the public in marine resource management.

Technological Advances in HAB Detection and Monitoring. Recent technological advances, such as remote-sensing methods, have increased detection and characterization of HAB blooms, and are playing an increasing role in monitoring programs nationwide.[100-107] Computer-based instrumentation has enabled the use of bio-optical techniques for identifying and characterizing HAB blooms.[108] Various algal blooms can be detected and monitored using satellite remote sensing data. Integration of satellite imagery with field data from state monitoring programs is providing an improved method for warning of blooms, tracking them, and characterizing their source. Satellite imagery can serve several purposes; while the goal is direct detection, imagery can provide a means of identifying blooms that should be sampled allowing investigators to focus their efforts. Imagery can also provide an estimate of the extent of a bloom, particularly in areas of low chlorophyll.

The SeaWiFS (Sea Wide Field-of-view Sensor), the current operational ocean color sensor, became operational in September 1997, and other sensors are expected to appear over the next year (including MODIS, the Moderate Resolution Imaging Spectrometer, which is in orbit but not yet fully operational). These color satellite sensors have the capability of determining chlorophyll and some optical properties of materials in the water. HABs are caused by several organisms, each with different characteristics and life histories—these factors influence the potential effectiveness of remote sensing for monitoring. For remote sensing to be effective, the HAB organism must be either detectable directly through its effect on the water color, indirectly by correlation with other algal blooms, or through association with a water mass that can be monitoring by several means, such as sea surface temperature (SST). Of the HAB species of critical concern in the US, *G. breve*, which causes NSP in the Gulf of Mexico, is the most amenable to remote sensing. New investigations on *Pseudo-nitzschia* in the Northwest will provide information on the effectiveness of remote sensing to detect these blooms.



A fluorescently-labeled Alexandrium *cell (red) from a bloom near Casco Bay, ME in 1998. (Photo: K. Gribble WHOI)*

Rapid progress has also been made in the development and use of molecular techniques to detect the presence of harmful algal bloom cells.[109-111] Many harmful algal bloom species are virtually impossible to distinguish from similar nontoxic species based solely on morphology (shape and size). Therefore, identifying when species of public health concern are present is difficult, particularly when they are present at low pre-bloom levels. To overcome this problem, sensitive molecular techniques, called assays, are being designed that can identify HAB species based on their unique DNA or surface composition, not their morphology. The goal is to develop accurate molecular assays that are sensitive, rapid, and cost effective. Using unique cellular characteristics of each HAB species, field detection of individual species is now possible for several HABs, including species of *Pseudo-nitzschia, Heterosigma, and Alexandrium*.

Many of the current molecular assays being developed focus on a unique DNA or RNA sequence from the harmful algal species of interest. First, the species of interest is isolated and grown in a pure culture. DNA is then extracted from these cells and cloned. These DNA clones can be of either known genes or of random non-coding DNA segments. These clones are subsequently sequenced and compared to other species to identify sections of DNA that are unique to the harmful species of interest. Unique sections of DNA, if expressed, will produce unique sequences of RNA, which can also be used in molecular assays. Once the species-specific DNA sequences have been identified, various molecular assays can be developed. Two of the most common assay methods under development are polymerase chain reaction (PCR) and *in situ* hybridization techniques. PCR allows minuscule amounts of a species-specific DNA found in a cell extract to be amplified over one million times. This amplified DNA can be stained with a fluorescent dye that specifically binds DNA and glows when viewed under a fluorescent microscope. Modified versions of this technique, known as competitive PCR and quantitative PCR, have also been developed that allow the numbers of HAB cells present in the sample to be estimated (quantified) in addition to confirming the presence or absence of a particular HAB. These techniques have proven useful in identifying toxic dinoflagellates including *Alexandrium*, *Gonyaulax,* and *Pfiesteria* species.[112-122]

In situ hybridization involves fluorescently labeling a short piece of DNA that binds a specific RNA molecule that is present in the HAB of interest. The cells are then viewed under a fluorescent microscope and the number of brightly glowing cells indicates how many harmful algal cells are present. In a modified version of this technique, sandwich hybridization, RNA extracted from the cell is trapped on a special membrane and fluorescently labeling it with a complementary piece of DNA. Both systems have proven particularly successful at identifying species that release domoic acid, the toxin responsible for recent sea lion deaths in California.[43] Other molecular techniques being developed to identify and understand the biology of HABs include antibody detection and electrochemical detection of HAB DNA or RNA. These 'molecular techniques' are likely to be the primary detection methods for many HABs in the future.

Response to HAB Events. Harmful algal blooms can endanger human health and cause major impacts to aquatic living resources. When reports of potential HAB activity, such as marine mammal strandings, erratic fish behavior or fish kills, are made to state authorities, it is critical that trained and equipped personnel respond and assess the situation quickly. HABs have the potential to develop rapidly and, as in the case of *Pfiesteria* outbreaks, the observable event may be short-lived. Rapid response is essential to ensuring that the appropriate sampling is conducted to determine if a HAB event is in progress.

Many states supplement their HAB monitoring programs with rapid response teams that are deployed to assess suspected HAB events. To determine if aquatic disease or mortality events are caused by HABs, and whether there are human health risks, an event must be thoroughly investigated following scientific protocols and procedures. Such a response can help answer critical questions about the event: is it related to other events, e.g., chemical spills, that are dangerous or threatening? Should beaches or shellfish beds be closed to protect public health? Can aquatic resources be saved?

Communication among researchers, managers, and the public is also critical to HAB event management response. Citizens in coastal communities often play a pivotal role in noticing and reporting HAB events. Many coastal states have established and maintain efficient and accessible systems for allowing citizens to report aquatic disease and mortality events to agencies responsible for HAB rapid response. Risk communication, both long-term and during a bloom event, is another important mitigation activity. Many regions have programs to inform the public, the media, and the medical community about the risks (and misconceptions) of HABs and their toxins. Doctors and hospitals should be well informed and prepared to recognize and treat individuals suffering HAB toxicity. Public education and communication should be increased in areas that are subject to HAB events so that those visiting or living on the shore or consuming seafood are informed about the risks and can be cautious, but not unduly alarmed. Accurate and timely information about HAB risks, can also help to limit the

Federal/State Workshops to Standardize *Pfiesteria* Monitoring Protocols

In 1998, NOAA, EPA, and involved states and researchers agreed there was a need to standardize monitoring protocols among the many agencies that collect information on water quality, fish health, plankton, and environmental conditions associated with suspected *Pfiesteria* events. NOAA held two workshops to gain consensus among State and Federal agency representatives and scientific experts: the Workshop to Standardize *Pfiesteria* Monitoring Protocols, 14-15 December 1998, and the Workshop to Standardize Fish Health Monitoring Protocols, held 22-23 June 1999. They had three goals: (1) to reach agreement on protocols for rapid-response assessments of toxic *Pfiesteria* outbreaks, (2) to recommend a suite of standard parameters that should be measured (e.g., water quality, fish health, and phytoplankton) when responding to potential HAB events, and (3) to discuss the integration of state and federal agency data sets into regional and national assessments.

Coastal states from New Jersey through Texas sent experts on water quality, fish health, and phytoplankton. Representatives from several Federal agencies also attended: the Environmental Protection Agency (EPA), the Centers for Disease Control and Prevention (CDC), the Food and Drug Administration (FDA), the U.S. Department of Agriculture (USDA), and the U.S. Geological Survey (USGS). Both workshops were conducted by the Center for Coastal Monitoring and Assessment (CCMA) of National Ocean Service's (NOS) National Centers for Coastal Ocean Science (NCCOS) in Silver Spring, MD. The more than 60 managers and scientists who participated in the two workshops reached consensus on the need for consistency in the parameters measured, the methods of analysis for samples collected, quality control and quality assurance, and the need to share monitoring data with other state and federal agencies. The group proposed a three-tiered monitoring program: (1) rapid response to fish kill events, assisted by appropriate experts, (2) comprehensive surveys and assessments in areas that have experienced or are at risk for toxic *Pfiesteria* outbreaks (as well as other harmful algal blooms), and (3) routine monitoring at sites that might support toxic strains of toxic *Pfiesteria* species. Attendees called for concurrent collection of phytoplankton, fish health, and water quality samples for each tier of their program. The draft report, "Standardized Protocols for Monitoring Suspected *Pfiesteria* Events," presents the deliberations and recommendations of participants from both workshops. These recommendations provide a valuable foundation to state and federal agencies that are refining and improving rapid response and assessment at sites of suspected toxic *Pfiesteria* outbreaks, as well as to those states that are developing such monitoring programs for the first time.

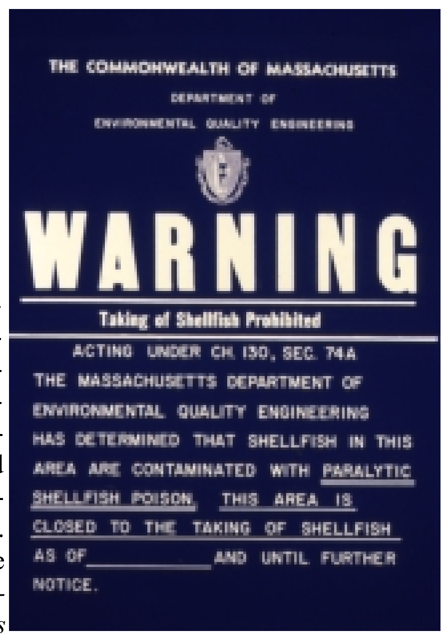
Federal Event Response Plan for Harmful Algal Blooms

In 1997, when outbreaks of *Pfiesteria piscicida* in the mid-Atlantic threatened public health and local economies, a strong Federal-State response effort was initiated to ensure public and environmental safety. Public health and seafood safety teams were mobilized to ensure public safety, document potential illnesses associated with the events, and assay seafood for toxicity. A number of Federal agencies participated in these response activities, which included medical diagnoses, epidemiology, fish toxicity, and assessments of water quality, fish lesions and mortality, watershed land use, and nutrient and pollution loads.

While this response was rapid and effective, these events clearly demonstrated the need for a formal mechanism to coordinate and efficiently focus Federal and State response capabilities. The Federal Event Response Plan for Harmful Algal Blooms identifies Federal capabilities and resources that could be mobilized to supplement existing State rapid response programs and to assist those States who have not yet implemented a rapid response plan for suspected outbreaks of toxic *Pfiesteria* species. The HAB Response Plan describes the basic mechanisms by which the participating Federal agencies can: (1) work with States to identify and communicate State response needs; (2) mobilize resources and conduct activities to augment State and local response efforts; and (3) communicate and coordinate Federal response efforts to avoid duplication. This Plan was developed by the National Oceanic and Atmospheric Administration (NOAA) National Ocean Service with the Environmental Protection Agency (EPA) and the cooperation and support of participating Federal agencies and offices (Centers for Disease Control Prevention, Food and Drug Administration), the States, and the academic community.

impacts of the "halo effect" on resources and regions that are not directly affected by HAB events.

HAB Modelling, Forecasting, and Prediction. The ultimate goal of many HAB monitoring programs is to eventually be able to forecast bloom development and movement. HAB events result from a combination of physical, chemical, and biological mechanisms and interactions that are, for the most part, poorly understood. A workshop cosponsored by NOAA and NSF in 1994 focused on developing a research agenda to increase our understanding of the fundamental processes underlying the impacts and population dynamics of HABs. Participants identified the physical, biological, and chemical oceanographic questions critical to scientifically based management of fisheries resources, public health, and ecosystem health in regions threatened by toxic and harmful algae. The findings of this workshop were published in *Ecology and Oceanography of Harmful Algal Blooms (ECOHAB): A National Research Agenda*,[123] which became the multi-agency research program of the same name. The overall goal of the ECOHAB program is to develop forecasting capabilities for HABs in all US coastal waters (e.g., HAB predictions like weather forecasts).



To accomplish this, ECOHAB research rigorously investigates and models the growth and toxin dynamics of the eight major toxic species along the entire US coast. Five-year ECOHAB research projects have been implemented on four of these harmful species: *Alexandrium* in the Gulf of Maine, *Gymnodinium* in the Gulf of Mexico, the brown tide organism *Aureococcus* in eastern Long Island, and *Pfiesteria* in the mid-Atlantic states. Research has just begun on *Pseudo-nitzschia* in southern California waters. The rest of the U.S. coastline and other HAB species need investigation: *Pseudo-nitzschia* blooms in the waters of the Pacific Northwest, brown tide and *Gymnodinium* populations in Texas, macroalgal blooms on Florida's and Hawaii's coral reefs, ciguatera dinoflagellates in the subtropical and tropical US, developing populations of *Dinophysis* in the Northeast and on the West Coast, and several species, including *Chaetoceros* and *Heterosigma*, that jeopardize fish pen mariculture in the Northwest. Future efforts must also focus on development of management strategies to prevent, control, and mitigate the blooms and their impacts, ensuring reduction of HAB-generated problems to coastal resources, local economies, and public health as well as guaranteeing that the intervention techniques do not cause negative impacts themselves. Expansion of research into these critical unfunded areas is needed.

Harmful Algal Recommendations Blooms in US waters

Over the past decade there has been an ongoing effort by Federal agencies working with state public health and fisheries managers, the science community, coastal industries and constituencies, to identify uncertainties and data gaps and the research needed to address the problem of HABs in US coastal waters. These are detailed other important HAB reports such as *Marine Biotoxins and Harmful Algae: A National Plan*;[124] and *National Harmful Algal Bloom Research and Monitoring Strategy: An Initial Focus on* Pfiesteria*, Fish Lesions, Fish Kills and Public Health*.[125] The general consensus of these reports and more recent discussions and forums is that a long-term commitment and significant support are needed particularly in the areas of research on the ecology of HABs and the causes and consequences of these blooms, and developing ways to manage the problem of increasing HABs nationwide.

The PROBLEM of HABs: furthering our understanding

The objective of past and ongoing research on HABs in the United States has generally been to seek an understanding of the fundamental biological, chemical, and physical processes underlying blooms and their impacts. Such understanding is essential if we are ever to manage or mitigate blooms

Studies at the organismal level. To understand the population dynamics of HABs and their toxic and/or harmful effects, studies at the level of a single HAB cell are essential. The goals of such studies are to determine the biological factors that influence HAB bloom dynamics, general ecology, and negative impacts.

Studies at the community and ecosystem level. Studies that focus on the interactions between HABs and other members of coastal ecosystems are essential if we are to understand the ecology of harmful algal blooms. The goals of such studies are: 1) to determine the impacts of interactions among organisms in the coastal food web on the dynamics of HABs and 2) to determine the impacts of HABs on food web structure and processes.

Studies of HAB toxins. HAB toxins represent a significant and expanding threat to human health, fisheries, and coastal ecosystems. However, information is lacking about toxins, their public health risks, and their impacts on fisheries. The key to this knowledge is an understanding of HAB toxin pharmacology and toxicology. This includes studies to: 1) determine the structure and chemical properties of HAB toxins, 2) develop means to extract, purify and synthesize them, and 3) develop rapid and cost-effective methods for detecting and quantifying HAB toxins in water and tissues.

The CAUSES of HABs: identifying the triggers

The number of toxic HAB events, toxins, and toxic species have increased over the last thirty years in the United States and around the world. The key to understanding of the influence of human activities on HABs is understanding the influence of environmental factors on harmful algal species and their competitors. This will help determine whether such activities are likely to lead to more frequent and severe HABs and if the means can be developed to mitigate HAB impacts. The goals of studies focused on environmental factors are: 1) to determine the environmental factors that govern the initiation, growth, maintenance, termination, and impacts of HABs, and 2) to identify ecosystems that are susceptible to HABs and understand why the types of blooms occur in the systems they do. Such studies will require both large-scale field studies and smaller-scale experimentation in the laboratory. Shipboard observations, field programs, satellite remote sensing, and moored instrument arrays are all potential strategies for identifying the mechanisms underlying HAB outbreaks. Research efforts focusing on environmental factors influencing bloom dynamics would complement studies at the organismal level and are necessary to foster a greater understanding of HAB dynamics.

The potential influence of human nutrient inputs on HABs is generally unknown and will require a focused commitment of resource and effort including time-series analysis of existing databases for phytoplankton communities These should be tied to data about contaminants and other environmental variables and require long-term monitoring programs of at least ten-years duration in coastal areas where anthropogenic changes are of concern. Laboratory studies on the stimulatory effects of chemicals contained in effluents or terrestrial runoff are also needed.

The IMPACTS of HABs: assessing the damage and counting the costs

Public Health. The epidemiology of the human health impact of exposure to HAB toxins is still in its infancy.

First, there is a need for basic analytic studies. While the acute effects of HAB toxins have been studied in the laboratory, little is known about chronic and/or repeated exposure in humans, which may be a more common experience. There is also a lack of understanding about how HAB toxins move through the body and how they are metabolized. These gaps in understanding prevent researchers from developing antidotes or effective treatments for HAB poisoning syndromes. There is a definite need for improved disease reporting and surveillance. The current passive systems (e.g., reportable disease status, calls to poison information centers) are inadequate to allow more than an estimation of the magnitude of the problem. Active surveillance in appropriate counties or states would allow the public health community to determine appropriate public health response activities. Health care professionals are not likely to recognize these illnesses in their patients. Health care providers should be made aware of the symptoms of these illnesses so they can be included in diagnostic procedures.

Newly identified diatoms and dinoflagellates from US estuaries are currently being characterized. These populations (e.g., *Chattonella verruculosa, Pfiesteria piscicida*) may pose unexpected health risks and epidemiologic studies will be needed to determine whether there are associations between exposure to these organisms or their toxins and subsequent adverse human health effects.

Early warnings of HABs and the presence of toxins in coastal waters and shellfish are required to adequately protect public health. Risk of human illness and fatalities from seafood poisonings have been significantly reduced through seafood sampling programs. However, current sampling programs are not sufficient for early bloom detection or characterization, and in many areas do not adequately protect subsistence fishers or harvesters.

Impacts on Marine Life. Marine biotoxins can move throughout marine food webs and cause impacts for organisms at various levels in the food web. Little is known about the impacts of HABs on shellfish, fish, and other marine species. Studies are needed to: 1) identify the mechanisms of biotoxin uptake and metabolism in shellfish, fish, and other marine animals, 2) determine the long-term effects of biotoxins on growth of fish including commercially valuable species, as well as marine mammals, birds, and other protected species, 3) develop rapid field assays for fish and shellfish and analytical methods for detecting biotoxins in animal tissues, and 4) develop improved diagnostic techniques to identify symptoms of biotoxin poisoning in marine fish and wildlife.

The difficulties encountered in generating a national estimate of HAB economic impacts underscores the need to formalize the reporting practice and format for HAB events. At present, information about HAB events is fragmentary and inconsistent. Local and state governments and federal agencies should place much higher emphasis on the quantification of economic impacts. Discussions of economic impacts should include the causes of the impacts and the degree of their uncertainty. The following specific actions are recommended:

- Hold a national workshop to agree on procedures and methods for the economic analysis of HAB impacts.
- Include the causes of economic impacts and the degree of their uncertainty in discussions of economic impacts and report economic factors affecting the impact estimates.
- Undertake another national compilation of the economic impacts of HABs for the years following 1992.

MANAGING HABs: reducing occurrence and impacts

Reducing HAB impacts is a major emphasis for national HAB efforts. As HABs continue to increase, we must refocus our goals and research expertise toward developing techniques for detecting and ameliorating the impacts of these natural disasters.

Reduction of nutrient pollution to coastal waters may reduce the incidence of those HABs that are stimulated by over-enrichment. Implementing best management practices (BMPs) on agriculture lands can help reduce overall nutrient loads. New mechanisms to encourage the implementation of BMPs are needed with monitoring to assess the effectiveness of the BMPs after they are implemented. This kind of monitoring will not only aid in evaluation but can also contribute to continuing development and improvement. The Environmental Protection Agency and the American Society of Civil Engineers are developing a National Stormwater BMP Database (http://www. bmpdatabase.org). The long-term goal of this project is to promote technical design improvements for BMPs. The cost of implementing BMPs is also an important planning consideration and economic data is needed to help determine the most cost-effective means.

Monitoring and event response programs are among the most effective means to mitigate HAB impacts on human health. Research on how to make monitoring programs more efficient while providing better coverage in time and space is sorely needed. Research should be encouraged on technologies such as: 1) remote sensing (to detect and track blooms), 2) molecular probes (to identify and quantify cells and toxins in a rapid or even automated fashion), 3) improved toxin assay methods (to provide fast, accurate, and inexpensive methods for use by agencies, industry, and consumers), and 4) moored or automated sampling arrays that can detect cells or toxins and telemeter the information to shore. These are but a few examples of areas where funding will provide practical benefits to consumers and to the fisheries industry.

Although the significance and recurrence of HAB phenomena would seem to justify bloom control as a high-priority research topic, virtually no focused research has been undertaken on this topic in the United States.[26, 96] In fact, there are currently no national research initiatives to promote efforts in prevention, control, and mitigation (PCM) of HABs and their impacts. Targeted funding is needed for a program focused on prevention, control, and mitigation and should be separate from, and complement, funding for ECOHAB or other ecology programs.

The following steps should be taken to ensure progress on HAB PCM:

- Convene a workshop to define the specific science agenda for the prevention, control, and mitigation of HABs.
- Develop partnerships with the private sector, perhaps through cooperative research with industry, since it is private industry that will be focused on practical aspects of HAB research and development.
- Involve others outside the HAB community in the effort, e.g., the Agricultural Research Service (ARS) or engineering companies. The ARS in particular may have much to offer given its long involvement in pest control.
- Provide sustained funding specifically for PCM programs. These funds for PCM should not come at the expense of fundamental studies on the biology, ecology, and toxicology of HAB species, but should be supplemental.
- Take steps to ensure the program includes efforts to transition research and application activities from federal-sponsored research development to implementation where States and industries take on the burden and responsibilities to reduce HAB impacts.

Federal Efforts

Clean Water Action Plan (CWAP)

The President's CWAP, announced on February 19, 1998, created a partnership between Federal, State, and local officials to increase the protection of public health and restore our nation's precious waterways. The CWAP emphasizes collaborative strategies to coordinate existing programs and develop new means to protect watersheds and benefit the communities they sustain. For the past two years, nine agencies have been working with states and local groups to carry out over one hundred key actions called for in the CWAP to improve watersheds. A complete listing of these key actions and an electronic copy of the CWAP can be found at http://www.cleanwater.gov/.

The CWAP focuses attention on the need to continue support for coordinated efforts to understand harmful algal species and to prevent, control, and mitigate the impact of HAB outbreaks. The CWAP also highlights the need for a coordinated Federal response system to assist state and local governments during major HAB outbreaks. An interagency Federal Event Response Plan [p.24], put in place in August 1998, continues to guide Federal, state and local authorities in dealing with the consequences from HAB outbreaks.

The second major concern affecting coastal waters is polluted runoff and nutrient enrichment. The CWAP recognizes the potential benefits of non-point source and other pollution controls to reduce eutrophication and limit HAB outbreaks in coastal waters. CWAP partners are working on a number of fronts to reduce excess nutrients entering our nation's watersheds. State non-point source controls are being strengthened on farm and urban lands to reduce excess nutrients entering our watersheds. The regulation of concentrated animal feeding operations is being updated to reflect modern practices and problems. Programs to control stormwater and combined sewer overflows are being improved. Efforts to improve the control of airborne nutrients and better monitor the impacts of air deposition are also being undertaken. In addition to coordinating federal efforts to reduce polluted runoff, the CWAP also supports efforts at the local level such as "Smart Growth" that can help plan for less runoff of nutrients in the future, even as populations grow. The combination of federal and local nutrient reduction efforts supported by the CWAP have the potential to prevent or limit the environmental problems associated with eutrophication and HAB outbreaks.

National Oceanic and Atmospheric Administration (NOAA)

National Centers for Coastal Ocean Science (NCCOS). NCCOS has established expertise and programs that focus on harmful algal blooms. NCCOS's HAB activities include research, monitoring and assessment, and event response components. NCCOS's research components include the Marine Biotoxins Program at Charleston and the Harmful Algal Bloom Program at Beaufort. The Marine Biotoxins Program was established in 1992 to address research impediments identified in the National Plan for Marie Biotoxins and Harmful Algae. The Program is national in perspective and multi-disciplinary in approach. The Marine Biotoxins Program has developed rapid, specific detection methods for all classes of algal toxins that impact human and environmental health and state of the art analytical methods for elucidation of toxin chemistry. The Program serves as a national analytical response facility, and has employed this suite of suite of detection methods to provide identification of toxins involved in novel human toxic outbreaks and marine mortality events throughout the past decade. The Marine Biotoxins Program also encompasses research on genetic and biological control measures to terminate harmful algal blooms. The Harmful Algal Bloom Program at Beaufort has focused on mechanisms that control development and distribution of HABs since the 1987 red tide occurrence in North Carolina. Current research focuses on the application of remote sensing for monitoring and predicting blooms, and the transfer of toxins through the food web. NCCOS also coordinates the interagency Ecology and Oceanography of Harmful Algal Blooms (ECOHAB) research program, overseeing an intensive modeling effort to examine linkages between the ecology, physiology, toxicity, and behavior of the HAB species, their planktonic and pelagic neighbors, their chemical environment, and physical movements of particles and water. The models developed through this activity will be transferrable between different physical environments and bloom species. These research and modeling foci will draw upon NCCOS' recognized expertise in marine biotoxins and fish lesion characterization, HAB ecology, photobiology, physical transport mechanisms, and remote sensing as well as involve other Federal agencies, States, and academia in new partnerships to address some of these issues.

NCCOS developed the *Federal Event Response Plan for Harmful Algal Blooms* with the Environmental Protection Agency and other Federal agencies. NCCOS is responsible for coordinating with EPA all Federal HAB event response efforts initiated under the plan. NCCOS has also identified existing internal scientific and technical capabilities that can be mobilized to support State efforts to respond to HABs and other unusual biological events. NCCOS recently initiated an intensive monitoring program that focuses on the environmental conditions believed to be conducive to occurrences of HABs. Small teams of Federal, State, and academic experts coordinate the planning, implementation, and analytical phases of the monitoring studies. Where appropriate, these studies incorporate emerging monitoring methods and technologies, such as remote sensing and identification methods for individual species, to encourage their development and to provide opportunities for field testing. Monitoring studies have been developed that focus *Pfiesteria* and *Pfiesteria*-like organisms in Maryland, and Florida, and on *Pseudo-nitzschia* in Washington State. Retrospective analyses of existing databases will also be carried out to identify the magnitude and duration of the US HAB problems through time and possible linkages with anthropogenic activities in coastal waters. Results from these analyses will be used to develop and further refine research hypotheses.

National Environmental Satellite, Data, and Information Service, National Oceanographic Data Center (NODC). The NODC is developing a system which will provide access to physical, chemical, and biological information acquired from various sources, to assist in harmful algal bloom (HAB) management and research. Initially, a prototype system will be developed for the Gulf of Maine and the Gulf of Mexico in coordination with the Ecology and Oceanography of Harmful Algal Bloom (ECOHAB) program. This system will be expanded to include data from other US coastal areas where HABs occur. Sources of data include routine monitoring efforts, event driven monitoring, topical research initiatives (ECOHAB), and the NODC archives.

National Marine Fisheries Service, Northwest Fisheries Science Center (NWFSC). The NWFSC Biotoxin Program focuses on and integrates methodology, food web interactions, species susceptibility, and coastal ecosystem health. Recent highlights include the development of new receptor binding and DNA probes for toxin and toxic algae detection, studies of toxin transfer through the food web, and culture studies to determine effects of nutrients on toxin production.

The NWFSC's Biotoxin Program has formed several productive research and monitoring partnerships with Federal, state, and private institutions. The NWFSC Biotoxin program and the Olympic Coast National Marine Sanctuary (OCNMS) have an ongoing partnership to study offshore and inshore HAB events within the Sanctuary. The NWFSC Biotoxin program has also established a partnership with the Quileute tribe whose lands abut the Sanctuary. This project includes research, monitoring, and assessing the severity and spatial distribution of domoic acid in both shellfish and local waters where the tribal fisheries occur. This pilot project is a model for creating partnerships between Indian Tribes, other coastal communities, Federal agencies, and scientific research institutions. Plans are underway to expand this project to include other tribes along the northern coast of Washington State.

Office of Ocean and Atmospheric Research, Sea Grant. With its role in marine research, education, advisory services and public outreach, Sea Grant's expertise and its network of local experts play major roles during HAB events. Sea Grant has long supported individual investigators studying local HAB problems (e.g., research first identifying *Pfiesteria* in North Carolina) and this support has built the foundation for several of the large regional HAB field projects. A series of articles published by Maryland Sea Grant (e.g., *In Harm's Way? The Threat of Toxic Algae*; *Harmful Algal Blooms on the Move*; and *The Trouble with Toxics in the Bay*) explained to readers the latest information on algal blooms, particularly those in the Chesapeake Bay region and the role of the complex of *Pfiesteria*-like organisms in fish mortalities in the Pocomoke River. Sea Grant programs in Maine, Massachusetts, New York, Florida, Texas, Washington, North Carolina, and Alaska have released similar materials on HABs from those areas of the country. In 1999, the National Sea Grant Program contributed funds to ECOHAB to support research on prevention, control, and mitigation of HAB impacts on commercially important fisheries, mariculture, public health, and focused economic assessments of HABs in the U.S.

Environmental Protection Agency (EPA)

EPA's Office of Water and Office of Research and Development are working to support State rapid response and monitoring activities, HAB research, and public outreach. The Office of Water (OW) is supporting efforts in State governments to establish and maintain rapid response and monitoring programs for toxic *Pfiesteria* outbreaks. Additionally, OW has supported a pilot monitoring project in the Neuse River estuary which has provided information on the role of nutrient pollution in toxic *Pfiesteria* outbreaks. Many other monitoring efforts supported by EPA, largely conducted by States to determine water quality overall, can serve to provide information on HABs. EPA's water quality database,

Coordinated Efforts to Learn About and Manage the Effects of Harmful Algae.

The following is excerpted from a General Accounting Office report.[126]

The 1992 NOAA-sponsored workshop brought scientists and regulatory officials together to address the problems of harmful algae. This workshop resulted in the 1993 publication of a national plan—Marine Biotoxins and Harmful Algae: A National Plan—for conducting basic research and developing management and mitigation strategies to protect the public and the environment from problems associated with harmful algae. In the plan, representatives from federal and state government, academia, and industry stated that the US research, monitoring, and regulatory infrastructure is not adequate to meet the expanding threats from harmful algae and established the goal of effectively managing fisheries, public health, and ecosystem problems. According to the plan, the following eight specific research objectives must be addressed to comprehensively evaluate, model, and manage harmful algae and its impacts:

- Isolating algae toxins and characterizing their chemical and pharmacological actions,
- Developing tests to identify individual toxins based on their unique chemistry,
- Developing the capability to predict the occurrence and assess the impacts of harmful algae,
- Determining the source and consequences of algae toxins in the marine food web,
- Developing management and mitigation strategies to minimize the impacts of harmful algae,
- Identifying and improving access to databases on toxic algae occurrences and impacts,
- Developing programs to communicate educational and public health information, and
- Providing rapid response programs for harmful algae outbreaks.

The national plan set in place an interagency process for addressing these objectives. A December 1995 report—The Ecology and Oceanography of Harmful Algal Blooms: A National Research Agenda —serves as a blueprint for carrying out the federal research program on the ecology and oceanography of harmful algae. This report resulted in the establishment of the ECOHAB program, the first federally coordinated effort dedicated to conducting the basic research necessary to understand the nature of harmful algae, the reasons they occur, and the steps that can be taken to control them. Under the auspices of the ECOHAB program, five federal agencies—NOAA, the Environmental Protection Agency (EPA), the National Science Foundation (NSF), the Office of Naval Research (ONR), and the National Aeronautics and Space Administration (NASA)—have funded research projects that are carried out in-house or by universities and other organizations. Other agencies, including the Centers for Disease Control and Prevention (CDC), the National Institute of Environmental Health Sciences (NIEHS), and the Food and Drug Administration (FDA), are involved in conducting research and disseminating information to the public on harmful algae. Research supported by CDC and NIEHS primarily focuses on the human health effects that result from exposure to water or aerosols containing harmful algae, while FDA's research focuses on the human health effects from exposure to toxins from consuming seafood. Collectively, these agencies spent more than $40 million in 1997 and 1998 on these efforts.

Before the ECOHAB program, research on the effects of harmful algae was typically isolated and uncoordinated. Often, the research was carried out by individual scientists and was not sustained over time. Before the program, there was essentially no overall federal coordination of the work to ensure that important national priorities were being addressed. A second report was issued in February 1997. Developed on the basis of the objectives in the national plan—Harmful Algal Blooms in Coastal Waters: Options for Prevention, Control and Mitigation—describes the processes and mechanisms that need to be employed to control harmful algae and their impacts. According to NOAA officials, this report is the basis for new initiatives for intervention strategies to deal with harmful algae to minimize human health, ecological, and economic impacts. The National Harmful Algal Bloom Research and Monitoring Strategy, published in November 1997, presents a national strategy for federally-supported research and monitoring for problems associated with harmful algae, particularly *Pfiesteria* and *Pfiesteria*-like organisms. The report is intended to serve as an action plan for *Pfiesteria* research and monitoring within the framework of the broader objectives identified in the National Plan.

STORET, may also house valuable information that can be correlated to outbreaks of HABs.

Beyond monitoring, many EPA and EPA-supported programs can play a primary role in reduction of excess nutrients. Programs addressing non-point source pollution, including agricultural and urban runoff, stormwater and combined sewer overflows, concentrated animal feeding operations, and air deposition, are critical to addressing all the problems generated by excess nutrients. In addition, voluntary partnerships, such as support of local Smart Growth efforts, can reduce the areas of water with excess nutrients. These programs all have excellent potential for HAB prevention, as well as the benefit of producing other environmental improvements in the affected waters.

OW is also working with the academic community, States, and our Federal partners to produce public fact sheets on HABs. The EPA Regions and OW have conducted national conferences on *Pfiesteria* that have served as forums for information exchange among State and Federal resource managers and the academic community. Other methods of information exchange include a web-site and monthly conference calls with States, other Federal agencies, and academics, the later coordinated by the EPA Chesapeake Bay Program.

The Office of Research and Development (ORD) is supporting research to identify the effects of *Pfiesteria* and other HABs on the fresh water and marine environment through a multi-investigator research program supported and conducted at the Gulf Ecology Division (GED) in Gulf Breeze, Florida. GED research concentrates on HABs in the Gulf of Mexico, primarily *Gymnodinium breve*. This research includes:

- Determining the critical environmental and genetic factors regulating population growth, life cycle transitions, and toxin production of HAB species;
- Determining the effects of HAB toxins on water quality, higher trophic level species, and ecosystem condition;
- Developing and implementing a real-time coastal ecosystem monitoring system with early warning capabilities for HABs;
- Investigating and evaluating potential strategies to control, mitigate, and prevent HABs in coastal ecosystems; and
- Developing and implementing a national coastal mortality monitoring network to investigate and report coastal mortalities and their most likely cause(s), including the occurrence of harmful algal blooms.

Pfiesteria piscicida has not been reported in the Gulf of Mexico to date. However, GED is developing methodologies, based on electron microscopy, to identify *Pfiesteria*-like species and other potential HABs in the marine and estuarine environment.

An Interagency Agreement has been approved between EPA/GED and NOAA/Charleston Laboratory to coordinate research on causes and impacts of marine HABs. Additionally, a Memorandum of Understanding has been approved between EPA/GED and the US Geological Survey/Columbia Laboratory that includes coordinating research on HABs, particularly freshwater cyanobacteria

The EPA Advanced Measurement Initiative, Application of the SeaWiFS for Coastal Monitoring of Harmful Algal Blooms, seeks to identify unique spectral absorption, scattering, and reflectance properties of the red tide organism *Gymnodinium breve*, which can be applied to the SeaWiFS ocean color satellite sensor, thus allowing for the remote sensing of this organism from space.

Specific EPA-sponsored research projects include ECOHAB: Control of Harmful Algal Blooms Using Clay; ECOHAB: Florida, a multi-agency/investigator project that addresses HAB in Florida; and the Environmental Consequences of the Use of Veterinary Pharmaceuticals in Concentrated Animal Feedlot Operations which will investigate the relationship between these operations and HABs. Finally, the US Office of Coastal Global Ocean Observation Systems and LABNET have approved a pilot project on HAB monitoring in the Gulf of Mexico. This project will be coordinated through a partnership with EPA/GED, NOAA/NODC, and NASA.

Centers for Disease Control and Prevention (CDC)

CDC is in a unique position to lead the public health response to the issue of marine seafood poisonings related to HABs. CDC has the crucial epidemiologic expertise required to address marine toxin syndromes in a timely manner. CDC's mandate is to respond to the needs of the state public health agencies and thus has a history of successful collaborations with these agencies. CDC has the ability to initiate and oversee the multi-state activities necessary to critically examine the public health problems from HABs as demonstrated by our long history of surveillance activities and specifically in 1997, by our multifaceted and timely response to the public health issues associated with blooms *Pfiesteria piscicida*.

Food and Drug Administration (FDA)

FDA's ongoing marine biotoxin research program continues to progress in characterizing the various seafood toxins, developing methods for detecting them, and culturing the organisms that produce them. The FDA also routinely supplies reference standards of saxitoxin and domoic acid to other laboratories for regulatory and research purposes.

A major function of the FDA's research program is to provide technical support to state and other regulatory agencies when there are management questions or HAB outbreaks. For example, FDA provided technical support in working out a management strategy regarding giant clams (geoducks) in Washington State, and in dealing with an outbreak of PSP due to shellfish from Burley Lagoon, in southern Puget Sound in October of 1998. The latter case involved three mild illnesses from eating mussels that had been harvested and sold in a local market.

Over the past two years the FDA's research labs have investigated five outbreaks of ciguatera, all in the continental United States. One of these, in Chicago, involved 21 victims who had eaten amberjack from South Florida.

The FDA, the states, and the shellfish industry continue to work together, through the structure of the Interstate Shellfish Sanitation Conference (ISSC), to ensure the safety of bivalve molluscs. Components of the FDA contributing to this effort include research laboratories, regional shellfish specialists that maintain close ties with each producing state, the Shellfish Program Implementation Branch which provides overall coordination and technical standardization, and the Office of Seafood, which provides policy guidance. The ISSC and its regional components (such as New England and Pacific Rim) also hold annual meetings.

With assistance from FDA, Signal Environmental And Plankton Observations in Real Time (SEAPORT) networks of volunteer observers are well established in California, Maine, and Massachusetts and are being developed in Connecticut, Rhode Island, and New Hampshire. The FDA encourages their development in other coastal states that have HAB problems, particularly Alaska, Washington, and Oregon. The FDA assists the states with technical support and in conducting training and refresher workshops for the volunteer observers. In addition to providing advance warning of toxicity outbreaks, these networks are accumulating an important and unprecedented body of baseline data on plankton populations along our coasts.

The FDA is a participant in the Gulf of Mexico program and, from the FDA research laboratory in Dauphin Island, Alabama, continues to provide direct lab support of marine biotoxin management programs in the Gulf coast states.

US Geological Survey (USGS)

USGS is conducting research and monitoring the delivery of nutrients to coastal waters in an effort to provide information on linkages between eutrophication and algal blooms. USGS research includes the evaluation of strategies to reduce nutrient runoff, including the use of wetlands and riparian areas, particularly in the Mississippi River basin. In the Chesapeake Bay watershed, USGS is looking at modeling nutrient delivery and examining the effectiveness of buffer strips to reduce runoff. Other sources of nutrient enrichment, such as groundwater, are being examined as well. USGS conducted preliminary health assessments of fish potentially affected by *Pfiesteria* and found an invasive fungus to be associated with the lesions detected on fish in the Chesapeake Bay. Therefore, further research is underway to determine the relation between the invasive fungus, *Pfiesteria*, and other environmental factors that may weaken the immune systems of the fish.

In the Gulf of Maine, a collaborative ECOHAB project is examining the source population dynamics of "red tide" dinoflagellates. Researchers on this project have determined how physical transport mechanisms have affected the distribution and fate of toxic *Alexandrium* cells and how physical dynamics and the nutrient environment affect their growth. A physical/biological model is being created for the Gulf of Maine to potentially be used for evaluating resource management strategies. In the Laguna Madre, Texas, USGS continues to research the linkage between changes in the seagrass community and brown tide. Seagrass habitat is critical to a number of wildlife species and the long lasting brown tide has caused significant changes in the structure and composition of this habitat.

USGS scientists are working to improve the assessment of toxic algae by developing immuno- and bioassays for the detection of cyanobacterial toxins. The most potent cyanobacterial toxins produced by HABs can cause paralysis and even death making them a serious public health issue. The technologies developed will allow for the exact identification of toxins present in water samples and specifically the isolation of the lethal anatoxin-a neurotoxin. Additionally, researchers are working to determine which water quality parameters appear to favor cyanobacterial production.

US Department of Agriculture (USDA)

USDA agencies work with landowners and land users to reduce runoff from farms, ranches, and private lands to improve water quality in adjacent streams and water bodies. USDA's actions are based on sound scientific research that takes into account the linkages between land use and the conditions of natural resources in watersheds. Through management programs that focus on improving and protecting water quality, the USDA encourages farmers, ranchers, and other private landowners to include conservation practices in their operations.

Researchers in USDA's Agricultural Research Service (ARS) are investigating the environmental effects of farming. Scientists from various disciplines are engaged in evaluating agricultural activities. Research includes pathogens such as *Crytosporidium* and *Pfiesteria,* livestock feed efficiencies, animal waste management, ammonia source and delivery, sustainable agricultural, composting wastes, and erosion control. ARS scientists are continually evaluating new agricultural technologies to help land managers enhance and protect their natural resources.

The Natural Resources Conservation Service (NRCS) provides technical and financial assistance to private landowners and land users to reduce polluted runoff and enhance natural resources. NRCS utilizes authorities to help local groups tackle community resource concerns. Tools include natural resource inventories, soil surveys, conservation practice specifications, funding, and a comprehensive knowledge of resources conservation.

The agency, as an active participant in the President's Clean Water Action Plan, has agreed to increase technical and financial assistance to reduce polluted runoff and enhance natural resources. NRCS utilizes authorities provided through the 1996 and other farm bills, offering a wide range of conservation options that can be tailored to fit special situations. Some important programs offered by NRCS and Farm Services Agency (FSA) include the Environmental Quality Incentives Program (EQIP) which targets assistance to high priority areas, the Wetland Reserve Program (WRP) which offers 30-year easements or restoration cost-share agreements, the Conservation Reserve Program (CRP), which allows landowners to take environmentally sensitive areas out of production, and the Wildlife Habitat Incentives Program (WHIP), which allows landowners to improve habitat for wildlife.

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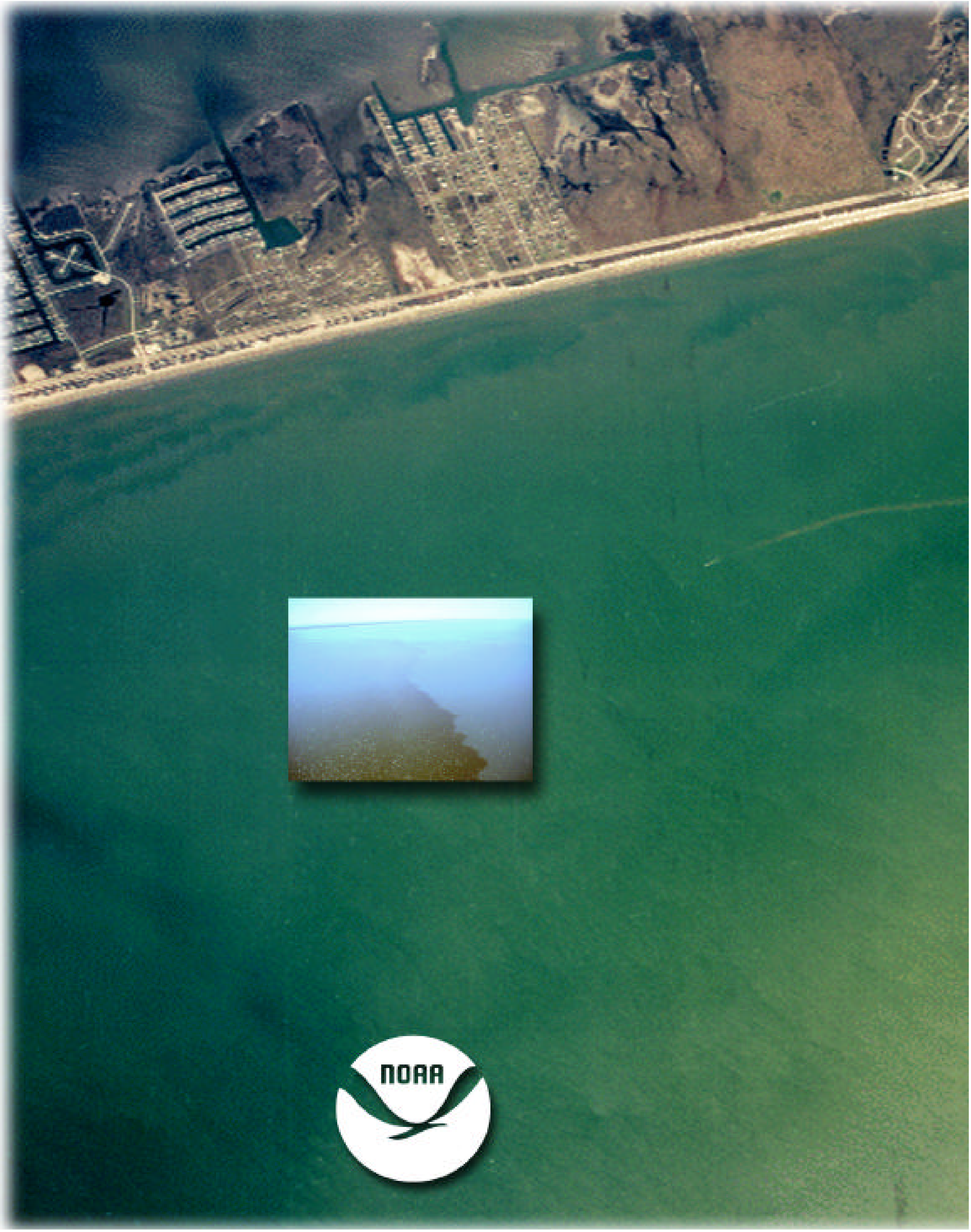
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