Prevention, Control and Mitigation of Harmful Algal Blooms

A Research Plan

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Executive Summary

Harmful algal blooms (HABs) have been increasing in prevalence in the United States for the past 30 years to the point where they occur along most of our coastlines and are common in many places. The impacts of these blooms are felt in many ways: human health is placed at risk; ecosystems are altered; marine mammals are injured or killed; and the fishing, aquaculture, and recreation industries suffer substantial economic losses. The economic impacts of HABs in the U.S. for the period 1987-1992 have been estimated conservatively at $49 million annually. Other single HAB events may approach or even exceed those costs, for example the 1976 red tide event in New Jersey estimated to have caused losses of about $1 billion in 2000 dollars.

The recent National Science and Technology Council (NSTC) report, *National Assessment of Harmful Algal Blooms in U.S. Waters*, observed "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." Congress, in the FY 2001 Department of Commerce Appropriations Conference Report, directed the National Oceanic and Atmospheric Administration's National Sea Grant College Program "to develop a research plan to address the causes of harmful algal blooms and a prevention and monitoring program."

This report, *Prevention, Control and Mitigation of Harmful Algal Blooms: A Research Plan,* outlines a forward-looking research program that provides the means for academic, government, and industry scientists and engineers to combine their efforts with those of coastal communities and managers in order to lessen the impacts of HABs on our Nation's coasts. The program directly addresses prevention, control, and mitigation of HABs by integrating research findings into effective HAB management strategies, with the following goal:

To reduce the impacts of harmful algal blooms on public health, the economy, and coastal ecosystems

To achieve this goal will require an understanding of the many factors that regulate the dynamics of HABs, one of the emphases of the ongoing Ecology and Oceanography of Harmful Algal Blooms (ECOHAB) research program, and the manner in which they cause harm; however, that knowledge by itself does not provide protection. Complementary management strategies are needed that will reduce the impacts of HABs by either ***prevention*** – avoiding the occurrence of blooms or reducing their extent; ***mitigation*** – minimizing HAB impacts on human health, living resources, and coastal economies when they do occur; or by ***control*** – actions that directly reduce or contain the bloom population. If this ambitious effort is to be successful in reducing HAB impacts, there will need to be a comprehensive program with long-term fiscal support and participation not only by Sea Grant, but also by other offices within NOAA, and other Federal and state agencies. Given that we are finally reaching the stage where it may soon be possible to actually impact the course of blooms in the field, there is a compelling argument to move forward.

Detection and Characterization of Harmful Algal Blooms: Organisms

Detection of harmful algal species in discrete water samples is critical to understanding the phenomenon of harmful algal blooms and in turn is essential for the prevention, control, and mitigation of such events. Historically, detection of these organisms has relied on microscopic methods for distinguishing morphological characters, but current advances in the development of molecular probes are enabling detection of lower concentrations of cells. These have the potential to allow for discrimination of unique strains and even for assessment of the metabolic activity of target species. Remote sensing techniques, including satellite and airplane overflights, as well as *in situ* devices, hold great promise for detecting selected taxa.

Goal: Improve identification, detection, and quantification of harmful algal species / strains and their presence in coastal ecosystems in order to provide accurate and timely information on the occurrence of HAB species.

Objectives:

- Develop rapid and effective methods for the identification, detection, and enumeration of harmful algae.
- Determine the relationship between cell numbers and toxin level or concentration.
- Develop data sets over large temporal and spatial scales to support modeling and prediction of HABs.

Detection and Characterization of Harmful Algal Blooms: Toxins

The 1993 report, *Marine Biotoxins and Harmful Algae: A National Plan*, concluded that the lack of sensitive assays and specific toxin standards were the major impediment to effective management of harmful algal blooms. It must be recognized that the hazard associated with toxic blooms is the toxin. The occurrence of the organism itself is not necessarily a predictive measure of its harmful effects. Modern instrument methods offer new potential in the detection and identification of trace amounts of individual toxins. However, accurate information on the full spectrum of effects, and the amount of toxin leading to these effects is generally unavailable for many toxins. Susceptible populations, such as the very young, the very old, and the immuno-compromised, need to be identified to ensure the protection of the public health and marine resources. Finally, these problems must be investigated for the full spectrum of possible food sources, including organisms consumed by cultural and ethnic minorities.

Goal: Identify and characterize toxins and their effects on human and coastal ecosystem health.

Objectives:

- Characterize the toxins and metabolites of HAB species.
- Develop sensitive and specific detection methods and toxin standards.
- Determine the effects of HAB toxins on marine resources and public health.

Prevention and Mitigation of Harmful Algal Bloom Impacts

HABs can have a strong influence on utilization of our natural resources, for example by causing human illness and death from consumption of shellfish that have become toxic from ingestion of toxic algae. To protect human health, state agencies are required to regulate harvesting of shellfish, but decisions are often made in the absence of information about how shellfish accumulate and depurate toxins or data about a particular toxic event. Similarly, HABs cause mortality of fish, birds, marine mammals, and turtles, but little is known about the mechanisms by which toxins cause mortality, how this impacts fisheries or endangered species, and how the impacts can be minimized. Human activities can facilitate the occurrence and spread of HABs, for example through increased nutrient inputs as a result of changes in land-use patterns or changes in hydrology. HAB species can be transported to new areas in ballast water or in live shellfish, where they may thrive and threaten human and ecosystem health.

Goals: Ensure the public can use and enjoy coastal waters safely, free from exposure to HABs, thereby protecting public health and economic vitality; Ensure a safe and sustainable seafood supply by developing fisheries and aquaculture management strategies to minimize the impacts of HABs; Provide information and tools so that coastal managers and policy makers can consider HABs in their decision-making processes at local and regional levels; Prevent the spread or enhancement of HABs from human activities.

Objectives:

- Evaluate the role of habitat alteration (e.g. increased nutrient loading resulting from changes in land-use practices, altered hydrology, or reduced shellfish populations) in increasing occurrence of HABs, and develop techniques and policies to reverse the trend.
- Develop methods to reduce the likelihood of HABs being initiated due to transport of cells or resting stages in ballast water or live organisms (primarily shellfish) and by sediment dredging.
- Identify the mechanisms by which HABs harm higher trophic levels, and develop techniques to protect shellfish and fish aquaculture.
- Develop methods and policies to protect human health, and ensure the information reaches the public and resource managers in the most useful form.
- Facilitate the development of procedures for rapid regional response to HAB events.

Control of Harmful Algal Blooms

Human efforts to control insects, diseases, and fungi are a common agricultural practice on land, and control of freshwater HABs has been a significant component of public utility management of drinking, agricultural, and recreational water supplies. However, attempts to control HABs in the marine environment have been minimal in the United States, presumably because of over-riding concerns about cost, effectiveness, and environmental impacts, and there has been little research to develop more effective methods. However, bloom control efforts need not be massive and worrisome; not all blooms are large in scale – many are small and localized. Approaches to direct bloom intervention fall into three categories: *mechanical, physical/chemical,* and *biological control*.

Goal: Develop environmentally acceptable strategies for direct intervention in ongoing HAB events for the purpose of eliminating toxic or harmful cells or inhibiting their growth.

Objectives:

- Develop effective mechanical bloom control strategies.
- Identify effective chemical control methods that have minimal impact on non-target organisms, and evaluate the effects of any toxins released from dying HAB cells.
- Assess the effectiveness of clays in flocculating and removing HAB cells from the water column for various blooms species and hydrographic regimes, and evaluate the environmental impacts.
- Determine whether biological control of HABs is feasible, and evaluate the specificity and environmental impact of any proposed agents.

Socioeconomic Impacts of Harmful Algal Blooms

Policy and decision makers must take the social and economic costs of HAB events into consideration. For example, closure of a body of water or beach due to HAB-related fish kills and toxic aerosols can have substantial effects on tourism and fishing. Negative public reaction to HAB events can be severe and prolonged, creating heavy pressures on management agencies and increasing economic losses. In order for managers to make better decisions on how to manage blooms, additional research is needed to understand the nature and extent of public and industry reactions to HABs, the interactions among various market sectors, and to develop methods of reporting that provide some consistency from different locales.

Goals: Improve understanding of public and commercial reactions to HABs in order to manage bloom events for maximum safety and minimum disruption; Improve the ability of policy makers and managers to manage HABs by taking the true costs into account.

Objectives:

- Assess the nature of public and commercial sector reactions to HAB events and use that understanding to guide the responses of public officials.
- Analyze the true costs associated with HAB events in order to provide a better basis for decision-making.

Monitoring And Prediction of Harmful Algal Blooms

The widespread expansion of HABs throughout U.S. coastal waters has led to increasing stress on government agencies responsible for protecting public health and providing timely, accurate information to citizens, policymakers and businesses dependent on the health of these waters. State and local agencies that did not need to monitor or once monitored their waters for one or two potentially dangerous species have been forced to expand monitoring efforts with significantly raised costs. The inability to accurately predict the onset of many blooms before they occur can be detrimental to businesses in these regions, among them commercial harvesters, aquaculturists, recreational fishermen, seafood handlers and those in the tourism industry. Clearly, there is a strong need for a monitoring and detection system that will enable local, state, and federal agencies to work together in developing early warning systems and providing accurate forecasts on bloom occurrence, development, and transport – such capabilities will make it possible to develop realistic mitigation strategies that minimize the risks to human health and reduce the economic impacts.

Goals: Develop a regionally based, nationally cohesive HAB monitoring program; Provide forecasts to predict bloom events with a 1-5 day lead time to public health and resource managers; Develop national and regional contingency plans with funding so that the response to HAB events can be rapid and effective.

Objectives:

- Establish a regionally based, nationally cohesive monitoring program.
- Develop forecasting methods for blooms.
- Prepare contingency and rapid response plans and develop a regional communications network.
- Develop, test, and implement new monitoring tools, including the identification of sentinel species.
- Apply data assimilation and modeling to HAB monitoring and forecasting.

Outreach and Education Related to Harmful Algal Blooms

Outreach and public education are an integral part of the Prevention, Control, and Mitigation of HABs Research Program, particularly important since the primary audience is not the research community. As was made clear once again during the recent *Pfiesteria* outbreaks in the mid-Atlantic, public perceptions of risk and the actions they take in response can have major economic impacts, over and above the direct impacts of HABs. It is critical that research results be delivered accurately and in a timely manner so as to increase public confidence and the utility of the results to resource managers. Education represents a long-term delivery tool to increase public understanding of extreme environmental events such as HABs and their health effects on humans and aquatic ecosystems. The creation of new monitoring capabilities with information being available on a real-time basis presents a challenge to be sure the public is not overwhelmed, but instead is provided with tools that will help to interpret the information. In addition, there is a great deal of existing information that needs to be transferred to the public and management communities.

Goal: Ensure that the results of the HAB prevention, control, and mitigation research program are delivered in a timely manner in a form appropriate to the audience.

Objective:

- Ensure that the outreach efforts and materials are targeted appropriately to the various end users of the information: concerned citizens and constituents; the business and industry sector; agencies and managers; government at all levels; and the research community.

Introduction

Harmful algal blooms (HABs) have been increasing in prevalence in the United States for the past 30 years to the point where they occur along most of our coastlines and are common in many places. The impacts of these blooms are felt in many ways: human health is placed at risk; ecosystems are altered; marine mammals are injured or killed; and the fishing, aquaculture, and recreation industries suffer economic losses. The recent National Science and Technology Council (NSTC) report, *National Assessment of Harmful Algal Blooms in U.S. Waters,* stated "there appears to have been a major world-wide expansion in the frequency, geographic extent, and magnitude of HAB events and in the number of HAB species involved."

The challenge for the research community is to increase our understanding of harmful algal blooms and provide the tools to enable coastal communities and managers to reduce the impact of these events. Congress, in the FY 2001 Department of Commerce Appropriations Conference Report, directed the National Oceanic and Atmospheric Administration's National Sea Grant College Program "to develop a research plan to address the causes of harmful algal blooms and a prevention and monitoring program and submit it to the Committees on Appropriations by June 30, 2001."

Over the past decade, there have been several reports dealing with how to better understand and respond to the harmful algal bloom issue (see sidebar). The seriousness of the problem has been examined in detail and a strong case for action has been established. The report, *Marine Biotoxins and Harmful Algae: A National Plan,* identified the major impediments to progress in this area and provided a framework for action to be coordinated across several Federal and state agencies. The interagency Ecology and Oceanography of Harmful Algal Blooms (ECOHAB) research program, with the goal "To develop an understanding of the population dynamics and trophic impacts of harmful algal species which can be used as a basis for minimizing their adverse effects on the economy, public health, and marine ecosystems," was a direct outgrowth of those planning efforts. ECOHAB has made substantial progress toward this goal and has initiated regional studies and targeted projects to investigate and model the growth and toxin dynamics of the major toxic species along the U.S. coast.

However, as two recent reports, *Harmful Algal Blooms in Coastal Waters: Options for Prevention, Control and Mitigation* and the *National Assessment of Harmful Algal Blooms in U.S. Waters,* make clear, we must now "focus our goals and research expertise toward developing techniques for detecting and reducing the impacts of these events." There is now a critical need for a focused research program to directly address prevention, control, and mitigation (PCM) of

Previous reports on harmful algal blooms in the United States

Marine Biotoxins and Harmful Algae: A National Plan (1993)
ECOHAB, The Ecology and Oceanography of Harmful Algal Blooms: A National Research Agenda (1995)
Harmful Algal Blooms in Coastal Waters: Options for Prevention, Control and Mitigation (1997)
National Harmful Algal Bloom Research And Monitoring Strategy: An Initial Focus On Pfiesteria, Fish Lesions, Fish Kills And Public Health (1997)
National Assessment of Harmful Algal Blooms in U.S. Waters (2000)
Estimated Annual Economic Impacts from Harmful Algal Blooms (HABs) in the United States (2000)

harmful algal blooms, a program that would be the complement of the ECOHAB program and integrate its research findings into effective HAB management strategies, with the following goal:

Goal: To reduce the impacts of harmful algal blooms on public health, the economy, and coastal ecosystems

To achieve this goal will require an understanding of the many factors that regulate the dynamics of HABs, one of the emphases of the ECOHAB program, and the manner in which they cause harm; however, that knowledge by itself does not provide protection. Management strategies are needed that will reduce the impacts of HABs by either ***prevention*** – avoiding the occurrence of blooms or reducing their extent; ***mitigation*** – minimizing HAB impacts on human health, living resources, and coastal economies when they do occur; or by ***control*** – actions that directly reduce or contain the bloom population. Examples of prevention strategies might include reducing pollution inputs to a region in an effort to decrease the number or size of bloom events, or using new technologies to prevent the transport of bloom organisms in ballast water from one coastal area to another. Examples of mitigation strategies might involve moving fish cages from the path of a HAB, or reducing the quantity of fish food to minimize their susceptibility to a bloom. Examples of control strategies might be direct application of chemicals or other biological control agents that kill or disrupt HAB cells during blooms.

In the U.S., a significant constraint to the development of mitigation and control strategies has been the perception that we do not possess the skills, knowledge, or right to manipulate marine or freshwater environments on any significant scale. However, we are already doing exactly that. Physically or chemically altering the nature and integrity of aquatic systems, for example, by wetland destruction, nutrient enrichment, etc., has changed the environment in ways that have ultimately altered the species composition of the plankton. Indeed, this may be related to the apparent expansion in the number and frequency of HABs in the U.S. and worldwide. Direct intervention in HABs and attempts to mitigate their impacts should not be seen as a major departure from other coastal practices, but as an attempt to restore the balance that previously existed in coastal ecosystems.

This report, *Prevention, Control and Mitigation of Harmful Algal Blooms: A Research Plan*, outlines a forward-looking research program that complements the ECOHAB program by providing the means for academic, government, and industry scientists and engineers to combine their efforts with those of coastal communities and managers in order to lessen the impacts of HABs on our Nation's coasts. The core of the program was developed at a workshop on "Prevention, Control, and Mitigation of Harmful Algal Blooms," held in May 2001 in Silver Spring, Maryland, with participation by the academic research community, state and Federal agencies, and outreach professionals. If this ambitious effort is to be successful in reducing HAB impacts, there will need to be a comprehensive program with long-term fiscal support and participation not only by Sea Grant, but also by other offices within NOAA, and other Federal and state agencies. Given that we are finally reaching the stage where it may soon be possible to actually impact the course of blooms in the field, there is a compelling argument to move forward.

The remainder of the report is organized according to the major themes developed during the recent workshop. For each theme, the goal is presented, major issues are outlined, and research needs to address those issues are identified.

Detection and Characterization of Harmful Algal Blooms: Organisms

Detection of harmful algal species in discrete water samples is critical to understanding the phenomenon of harmful algal blooms and in turn is essential for the prevention, control, and mitigation of such events. Historically detection of these organisms has relied on microscopic methods for distinguishing morphological characters, although such approaches may not discriminate among toxic and non-toxic strains (e.g., *Alexandrium tamarense*, *Pfiesteria piscicida*) or genetically different strains that may be unique to some geographic area.

Current advances in the development of molecular probes are bringing new sensitivity to organism detection. Probes may include lectins, antibodies, and methods to detect unique DNA or RNA targets (Scholin *et al*., in prep). These have the potential to allow for discrimination of unique strains and even for assessment of the metabolic activity of target species. Remote sensing techniques, including satellite and airplane overflights, as well as *in situ* devices, hold great promise for detecting selected taxa (Millie *et al*., 1997). These are active areas of research that promise rapid advances in the coming years. Within the framework of prevention, control and mitigation, further development and integration of these methods into monitoring, research, and management strategies is essential.

It should be noted that detection of a HAB species is not equivalent to a taxonomic identification of the same organism. The identification of an organism relies on a variety of characteristics ranging from genetic to morphologic, which considered together allow a taxonomic designation to be assigned to an organism. Detection of an organism, on the other hand, generally employs one of the taxonomic characteristics considered to be most reliable, as well as effectively and efficiently applied (e.g. rDNA sequence), to reveal or demonstrate the presence of a taxon in a sample. For example, a molecular probe is used to detect a particular taxon in a sample, while the sequence information upon which the probe is based, generally along with morphological characteristics, are used to identify the organism.

Goal: Improve identification, detection, and quantification of harmful algal species / strains and their presence in coastal ecosystems in order to provide accurate and timely information on the occurrence of HAB species.

Issue: Rapid and effective methods for the identification, detection, and enumeration of harmful algae are not fully developed for all species. Thus, decision-makers do not have critical information needed during harmful algal events.

<u>Specific Research Needs</u>

- Improve our ability to quantify the abundance of harmful algal species/strains in natural populations.

Development of tier-based testing recognizes that different methods of identification and detection (e.g. light microscopy, electron microscopy, molecular diagnostics, etc) are necessary and may vary for different taxa.

- Improve our understanding of strain and species diversity of harmful algae, especially the differences between geographically separated populations.
  Techniques for cell identification and detection with cell-specific probes, microscopic methods, etc. have been developed through different research programs in different regions. The applicability of these methods and the connection between toxin production and cell identification must be determined for specific situations. All modern methods need to be validated against generally accepted methods.
- Develop of molecular/taxonomic standards for the identification of HAB species.
  The deposit and storage of cultures and other reference material that is available to all workers is important. Training tools are needed at multiple levels including live cultures, preserved samples, images and genomic sequences. The maintenance of these resources should be institutionalized.
- Refine appropriate techniques and promote their application within the capabilities of the end user.
  This includes both development of in situ monitoring systems and remote sensing, as well as the simplifying of systems for public use.

Biotechnology is already providing new means to detect potentially toxic organisms and monitor the development of harmful algal blooms, and there is the promise of further rapid advances. For example, when *Pfiesteria* was first discovered, the identification and verification process was cumbersome, took 2-3 weeks, and could be carried out by only a few highly-trained researchers who were capable of culturing fish in Biohazard Safety Level 3 facilities and carrying out the subsequent microscopy. However, North Carolina and Maryland researchers were able to develop the first molecular probe for *Pfiesteria* and successfully applied it in 1998 to verify a *Pfiesteria*-caused fish kill in North Carolina. The major advantage of the molecular probe is that the presence of *Pfiesteria* can now be verified within 24-48 hours, in time to allow rapid and informed management responses. In addition, the use of these and similar detection methods that are under development with Maryland researchers and in other mid-Atlantic states should substantially reduce the costs of detection and require much less training, which in turn should lead to more widespread use by state agencies and private industry (such as aquaculture) not only for response to suspected bloom events, but also for routine monitoring activities.

A second example relates to the serious problem of paralytic shellfish poisoning (PSP) in Alaska. PSP-toxic shellfish harvested in the wild make several people sick every year and occasionally cause death, but there has been no rapid method to test for PSP-causing dinoflagellates. Additionally, because of the vastness and remoteness of the Alaska coast, routine monitoring of all potential shellfish areas is not possible. Now, though, an assay kit that was developed by California researchers and a Washington-based company is being field-tested along the Alaska coast by Alaskan researchers. The hope is that eventually these kits may make it possible for individual shellfish harvesters to detect toxic events themselves in locations too remote to justify routine monitoring.

Issue: Current monitoring methods are often based on cell numbers, which may not be a reliable indicator of toxin level or concentration. Managers need to know how cell numbers relate to harmful effects.

Specific Research Needs

- Define the relationship between cell concentration and toxin level.

    The number of cells is not a reliable indicator of toxin presence for most species, but it is often used as a measure to evoke action because it is often the most rapidly measured parameter. The relationship among cell abundance, nutritional status, environmental parameters and toxin concentration needs to be elucidated.

Issue: Modeling and prediction of harmful algal blooms require data sets over large temporal and spatial scales.

Specific Research Needs

- Improve the methods for remote sensing of harmful algal blooms.

    The relationship between cell numbers and other available data, including information from remote sensing, in situ monitoring, water quality information, etc., must be defined.

Detection and Characterization of Harmful Algal Blooms: Toxins

The 1993 report, *Marine Biotoxins and Harmful Algae: A National Plan*, concluded that the lack of sensitive assays and specific toxin standards were the major impediment to effective management of harmful algal blooms. This remains true today. Toxin identification and characterization have lagged behind the development of cell or organismal identification techniques, which already are a central part of many programs. It must be recognized, however, that the hazard associated with toxic blooms is the toxin. The occurrence of the organism itself is not necessarily a predictive measure of its harmful effects.

Toxins must be recognized in broader terms of the diversity of their chemical structures and the breadth of their biological effects. Modern instrument methods such as tandem mass spectroscopy and multidimensional nuclear magnetic resonance offer new potential in the detection and identification of trace amounts of individual toxins. However detection methods should address the applications of the users, be it rapid detection or high throughput methods. Both qualitative and quantitative methods need to be considered, with the end goal of obtaining a tier-based or multi-level approach for toxin analysis. At the lower tiers, the emphasis is on ease of use, whereas at higher tiers, more emphasis is placed on accuracy and identification of individual toxins. Accurate information on the full spectrum of effects, and the amount of toxin leading to these effects is generally unavailable for many toxins. Further, the metabolism of many toxins is undefined. Susceptible populations, such as the very young, the very old, and the immuno-compromised, need to be identified to ensure the protection of the public health and marine resources. Finally, these problems must be investigated for the full spectrum of possible food sources, including organisms consumed by cultural and ethnic minorities.

Goal: Identify and characterize toxins and their effects on human and coastal ecosystem health.

Issue: Many of the toxins and metabolites of HAB species are still unknown. Consequently, decision-makers lack critical information during harmful algal events.

Specific Research Needs:

- Identify the structure of unknown toxins.
  The toxins of many HAB species have not been identified or are only partially identified, for example, Pfiesteria *and* Pfiesteria*-like organisms,* Dinophysis*,* Heterosigma*, Cyanobacteria, etc.*
- Identify toxin metabolites and the routes for biotransformation of toxins.
  This includes both the conversion of one chemical form to another (cryptic toxins) and the depuration/metabolism/elimination from human and marine resources.

Issue: The lack of sensitive and specific detection methods and toxin standards still remains the primary impediment to progress in the research and management of HABs

Specific Research needs

- Develop methods of toxin quantitation that are appropriate to the application.

Tier-based testing is an accepted approach, but needs methods appropriate to each of the tiers. This includes development of methods for rapid identification, based on either structure or activity, development of high throughput methods for larger sample sets, and chemical confirmation of specific toxins. Appropriate methodologies must be developed to be able to collect and identify specific toxins in biological fluids, tissues, algal cells, and water.

- Production of chemical reference materials.

  This should include calibrating solutions, internal controls in biological matrices, preparations for exposure studies in live organisms, and the distribution of these materials to research and management communities.

Issue: Insufficient information on the effects of toxins impedes the effective management and protection of marine resources and public health

Specific Research needs:

- Elucidate the biological mode of action of toxins and their total spectrum of effects in humans and other target species.

  Many toxins have a diverse spectrum of action in physiological processes. Understanding the chronic and acute effects is important.
- Define the levels of toxin exposure that lead to an adverse effect.

  The effect levels for toxins must be determined for relevant routes of exposure and related to the internal doses or body burdens in affected organisms.
- Define mechanisms for preventing exposure or mitigating the action of toxins after exposure.

  This includes elucidating population differences in susceptibility, as well as the development of education, diagnostic, or treatment techniques useful in public health.

Prevention and Mitigation of Harmful Algal Bloom Impacts

HABs can have a major impact on natural resources, strongly influencing utilization of those resources. The most obvious example is the occurrence of human illness and death from consumption of shellfish that have become toxic from ingestion of toxic HABs. To protect human health, state agencies are required to regulate harvesting of shellfish, but decisions are often made in the absence of information about how shellfish accumulate and depurate toxins or data about a particular toxic event. Similarly, HABs cause mortality of fish, birds, marine mammals, and turtles. Little is known about the mechanisms by which toxins cause mortality, what impacts this has on fisheries or protection of endangered species, and how the impacts can be minimized. Finfish and shellfish in mariculture facilities are particularly susceptible to HAB-related mortality, but can also promote HAB formation if nutrient effluents are not managed properly. Conversely, human resource utilization can cause or influence the occurrence and persistence of HABs. Human activities can increase nutrient inputs through changes in land-use patterns or changes in the hydrology of an area, facilitating occurrence of HABs. The cells and/or resistant resting cysts of HAB species can be transported to new areas in ballast water or in live shellfish, where they may thrive and threaten human and ecosystem health. Thus, natural resource managers, elected officials and the public must have an understanding of the causes and impacts of HABs that can be used as a basis for preventing or minimizing their adverse effects on the economy, public health, and marine systems.

Goals: Ensure a safe and sustainable seafood supply by developing fisheries and aquaculture management strategies to minimize the impacts of HABs.

Ensure the public can use and enjoy coastal waters safely, free from exposure to HABs, thereby protecting public health and economic vitality.

Provide information and tools so that coastal managers and policy makers can consider HABs in their decision-making processes at local and regional levels.

Prevent the spread or enhancement of HABs from human activities.

Issue: Habitat alteration, such as increased nutrient loading resulting from changes in land-use practices, altered hydrology, or reduced shellfish populations can foster the development of HABs

<u>Specific Research Needs</u>

- Determine the relationship between HABs and land-use practices.
  Water shed land use changes and coastal modifications cause increases in runoff and nutrient inputs into rivers, estuaries and the coastal ocean. As a consequence water quality suffers, yet the causal relationships between altered water quality and HABs are not well established.
- Assess the role of altered hydrology in causing HABs and develop policies to reduce impact.
  HABs often develop in areas with limited circulation or long residence times. Human activities, such as dredging a channel to open an inlet or construction of hard

structures that impede water circulation, can change hydrology in ways that either reduce or increase the risk of HAB formation.

- Evaluate the potential for establishing or enhancing shellfish communities to restore natural phytoplankton populations and reduce dominance of HAB organisms.

  Filter feeding shellfish provide the natural function of removing large quantities of phytoplankton from the water and can in part ameliorate the stimulatory effect of excess nutrients. In areas where shellfish abundance has declined, restoration may reduce the likelihood of HABs.

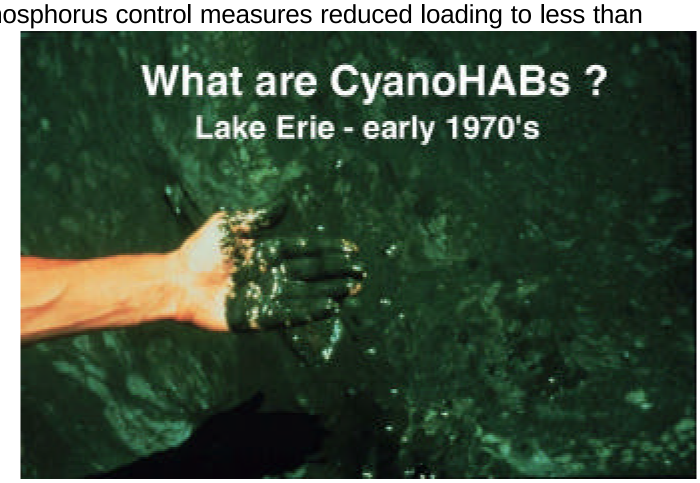
- Assist managers in controlling nutrient loading in coastal areas susceptible to HABs by providing decision support tools, including predictive models, GIS applications and other methods.

  There are a wide variety of potential nutrient sources in coastal areas, including non-point sources, such as agricultural runoff or effluent from individual septic systems, and point sources such as sewage treatment and aquaculture facilities. There will need to be close partnership among federal (for example, EPA and the Department of Agriculture), state, and local agencies dealing with nutrient over-enrichment issues.

Great Lakes Algal Blooms

Harmful algal blooms are not only a problem for the Nation's marine coasts. Recent research has linked health problems and ecological problems to blue-green algae (also known as Cyanobacteria) blooms that occur in the Great Lakes. Blue-green algae blooms are common in the U.S. and are most frequently associated with eutrophication and nutrient enrichment from sewage treatment plants and agricultural runoff. Most forms of blue-green algae float at the surface and are most prevalent during the warmest times of the year. As a result they are a very common source of complaints from boating, fishing, and swimming enthusiasts, and are considered a nuisance form of algae. They are also frequently associated with taste and odor problems at water treatment plants. However, we have recently learned that blue-greens can also produce toxins that, in high concentrations, have caused deaths in South America and Asia. In the U.S. they have been associated with waterfowl kills and health problems in people and animals that have come in contact with them.

For example, in the Great Lakes, blue-green algal blooms were a huge problem in Lake Erie during the 1960s and 1970s when phosphorus loading approached 30,000 metric tons per year. However, improved sewage treatment and phosphorus control measures reduced loading to less than 11,000 metric tons per year and led scientists to believe that the problem had been solved by 1980. Then very unexpected blooms occurred in Saginaw Bay and western Lake Erie in the mid-1990s and some of these were producing the toxin "microcystin." It appears from several research studies that these blooms are linked to nutrient loading, nutrient releases by zebra mussels, and selective feeding by zebra mussels, but much more work needs to be done. It is also unclear what triggers the algae to produce the toxins, for they are not in production all the time. These are significant issues in all freshwater and low salinity systems where blue-green algae bloom due to nutrient enrichment and/or zebra mussel interactions, and in particular in those areas where people or animals come in contact with the algae or use the water as a drinking water supply.



Issue: HABs may be initiated from cells or resting stages after transport in ballast water or live organisms (primarily shellfish) and by sediment dredging

Specific Research Needs

- Assess the threat of HAB species transport by live shellfish and ballast water and the likelihood that subsequent growth will occur in receiving waters.
- Assess the potential for bloom initiation by sediment dredging.
- Develop methods of preventing transport of HAB species and treating ballast water.
- Identify other possible introduction mechanisms.

Issue: HABs can cause mortality in fish, shellfish and higher trophic levels.

Specific Research Needs

- Determine types of toxins, mechanisms and levels of exposure resulting in fish, bird, marine mammal, and turtle mortality.
- Identify other mechanisms by which HABs harm higher trophic levels.

  For example, the brown tide organism, Aureococcus anophagefferens*, may be harmful when it is abundant because it replaces normal food sources for some shellfish, but is itself nutritionally inadequate.*
- Investigate the harmful effects of HABs/toxins on reproduction and early life history stages.
- Develop techniques for managing shellfish and fish aquaculture to minimize impacts from HABs.

  Some species used in aquaculture may be less susceptible to HABs because they do not consume HAB species, depurate toxins quickly, or are not harmed by toxins. Further, locations for aquaculture facilities can be chosen to decrease the likelihood that HABs will be encountered. Developing methods of rapid detection for early warning will allow rapid harvesting or moving of pens.

Issue: HABs that produce toxins can cause human illness and mortality.

Specific Research Needs

- Determine rates of accumulation and depuration of toxins, and the environmental and biological factors that influence those rates, for different species and life-stages consumed by humans.

  The animals that usually become toxic first are those that directly filter the toxic phytoplankton out of the water. They may in turn be consumed by other animals that also become toxic. Since food web linkages are often poorly known, it is often difficult to predict which food items will pose a threat to human health due to accumulated toxicity. For example, Dungeness crabs on the west coast of the US can become highly toxic, but since they are not filter feeders, the mechanism by which they become toxic is not known. The factors that control the depuration process are not known for most species.
- Develop methods for rapid detection of toxin levels in species consumed by humans.

  As outlined in the previous section on "Detection and Characterization of Harmful Algal Blooms: Toxins," development of rapid detection methods must be consistent with the aim of protecting human health.

- Refine guidelines to govern the opening and closing of fisheries for human consumption by replacing cell-based action levels with toxin-based action levels, and incorporating sampling protocols that take into account toxin accumulation and depuration rates.
- Provide information targeted to specific cultural and ethnic groups and to other groups, such as children, who are more susceptible than others to algal toxins.
- Ensure that Hazard Analysis and Critical Control Point (HACCP) guidelines that take into account HABs and aquaculture operations are kept up to date.
- Develop toxin action levels and regulations to protect human health from exposure due to contact with coastal waters or aerosols (boating, swimming, etc.).

    Although most human illness and mortality due to HAB toxins result from consumption in food or water, there are other routes of exposure that involve contact with water or aerosols.

Issue: HABs frequently move across state boundaries and a regional response to HAB events is required.

Specific Research Needs

- Recommend regional standards and methodology so that incidents crossing jurisdictional boundaries are dealt with in a uniform manner.
- Foster regional coordination of information exchange and dissemination to stakeholders and decision makers.
- Facilitate regional rapid response contingency planning.

    HABs often occur unexpectedly and problems develop rapidly. Emergency response planning by agencies and individuals responsible for protecting human and environmental health will facilitate a rapid, effective response that will minimize both impacts and economic and social costs.

Control of Harmful Algal Blooms

Human efforts to control insects, diseases, and fungi are common agricultural practices on land, and control of freshwater HABs has been a significant component of public utility management of drinking, agricultural, and recreational water supplies, but similar attempts to control unwanted plants or animals in the ocean are rare or more limited in scope (Anderson 1997). Physical, chemical, and biological control measures have been used in freshwater systems for small and large-scale control of HABs due to their significant public health, economic, and ecosystem impacts (Chorus and Bartram 1999). Given that HABs in the ocean have similar impacts, these phenomena would appear to be legitimate targets for control efforts, and other countries - notably Japan and Korea - have invested heavily in research on the topic. However, research on this topic has been minimal in the United States, presumably because of over-riding concerns about costs, effectiveness, and environmental impacts. Other than one unsuccessful attempt to control a red tide bloom in Florida 45 years ago, field testing of methods to control major blooms in the marine environment has not been seriously considered in the United States. Furthermore, no federal agency has been given the responsibility for marine pest management in the way that the U.S. Department of Agriculture has been given this responsibility for agricultural pests.

Approaches to direct bloom intervention can be grouped into three categories: *mechanical, physical/chemical, and biological control*. Mechanical control involves the use of filters, pumps, and barriers (e.g., curtains, floating booms) to remove or exclude HAB cells, dead fish, or other bloom-related materials from impacted waters. *Physical/chemical* control involves the use of chemical or mineral compounds to kill, inhibit, or remove HAB cells. *Biological control* involves the use of organisms or pathogens (e.g., viruses, bacteria, parasites, zooplankton, shellfish) that can kill, lyse, or remove HAB cells.

Bloom control efforts need not be massive and worrisome. For example, not all blooms are large in scale – many are small and localized. Where the times and places of bloom initiation can be discreetly defined, control efforts applied then and there could cover a small area but potentially have a significant impact on bloom magnitude and spatial extent. Reduction in the size of a bloom in one year might result in smaller blooms in future years due to a decrease in cysts or surviving cells that might serve as a bloom inoculum. Control efforts might also be justified in emergency situations where an endangered species or other valuable resource is threatened by a HAB, and when the benefits from prompt and effective intervention would outweigh possible negative environmental impacts. The recent discovery of the highly invasive macroalgal species *Caulerpa taxifolia* (see photo at right) in southern California (Jousson et al., 2000) might be an example where drastic control measures are justified by the extreme threat to coastal resources, as proven in the Mediterranean where this introduced species has overgrown hundreds of kilometers of coastline.

Goal: Develop environmentally acceptable strategies for direct intervention in ongoing HAB events for the purpose of eliminating toxic or harmful cells or inhibiting their growth

Issue: Various mechanical bloom control strategies have been identified, but it is not known the extent to which these can be applied to particular HAB species in specific environments or habitats.

Specific Research Needs

- Investigate the scope and effectiveness of available methods for physical removal or exclusion of particular HAB species in different habitats.

  Pumping of surface algal scums from inshore areas has proven be an effective mechanism to temporarily protect recreational users of freshwater lakes from exposure to toxic cyanobacteria and filtration has been used effectively in purification of drinking water supplies. Aeration for de-stratification has also been effective in reducing toxic cyanobacterial blooms. Barrier systems might be able to exclude HAB cells, dead fish, or other bloom-related materials from water intakes, beaches, recreational areas or aquaculture sites.
- Working from technologies used in other disciplines, explore new options for physical removal or exclusion of HAB cells, foam or dead fish and other bloom-associated debris from aquaculture sites, beaches, recreational waters, or drinking water supplies.
- Explore the release of toxins and the mitigation of their effects during physical treatment of HABs of various types.

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Issue: Chemicals are likely to be non-specific and thus kill co-occurring algae and other organisms. They are also likely to kill toxic cells and release toxins into the environment where they may cause a greater harm than before they were released.

Specific Research Needs

- Identify chemical control methods and evaluate their effectiveness on particular HAB species, while minimizing damage to co-occurring organisms.

  Chemicals have been used to treat blooms in drinking water supplies and other enclosed freshwater systems. These include copper compounds, barley straw, and chemical oxidants such as chlorine, peroxide, ozone, and chloramines (Chorus and Bartram 1999). Another interesting approach to bloom control in freshwater lakes and ponds utilizes a blue dye to limit penetration of the wavelengths of light required for photosynthesis, and thus the growth of algae. However, all these methods have the potential to indiscriminately kill many co-occurring algae and other organisms.
- Investigate the fate of toxins released during chemical control efforts, and explore strategies to minimize the impacts.

  Attempts to use chemicals to directly control HAB cells in blooms may have unintended consequences. For example, it was not known to what extent toxins were released from the cells following the use of copper sulfate in the 1957 Florida Gymnodinium breve control effort treatment, and there were concerns that there *could have been fish or other marine animal mortalities similar to those the control operation was attempting to prevent.*

Issue: Application of clays may be able to flocculate and remove HAB cells from the water column, but the environmental impacts remain uncertain and the feasibility for use on different bloom types and hydrographic systems is unknown.

Specific Research Needs

- Investigate the relative removal of different planktonic organisms during clay treatment.
- Investigate the release and impacts of toxins from flocculated cells, the physical and toxic effects on benthic organisms from sedimented toxins and cells, the release or uptake of nutrients and other materials by the clay, and the consequences of organic loading from sedimented cells and clay on near-bottom oxygen conditions.

  Physical/chemical approaches such as the use of clays and other flocculants to remove cells from the water column are potentially more benign than strictly chemical control efforts. Indeed, Korea dispersed clay as a flocculant to protect fish farms from HABs on a large scale – applying more than 60,000 tons of clay over 100 km^2 during a widespread bloom of the fish killing alga Cochlodinium polykrikoides *in 1996 (Na et al., 1996). Likewise, chemical flocculants (e.g., aluminum compounds such as alum) are used extensively in freshwater systems to remove unwanted cells from lakes and ponds.*
- Determine the hydrodynamic properties of clay/cell aggregates with respect to transport, settling, and resuspension.
- Explore engineering and logistical approaches to clay/flocculant dispersal at various scales needed for bloom control.
- Initiate pilot studies of clay flocculation in the field on a scale sufficient to assess cell removal efficiencies and environmental impacts in natural systems.
- Transfer technologies used in treatment of fresh water to coastal HAB control.

Issue: Although the use of biological control agents to treat HABs may have great potential, there are significant environmental and logistical concerns that must be addressed.

Specific Research Needs

- Determine if bacteria, viruses, and parasites exist that can be effective pathogens to targeted HAB species.

  Parasites and bacteria also have potential as biological control agents for HABs. An intriguing example is the Gymnodinium mikimotoi - *killing bacterium described by Ishida (1999). A strain isolated at the end of a* G. mikimotoi *bloom exhibits strong algicidal activity against only this dinoflagellate species and has the advantage of being a native species already present in the HAB species' environment.*
- Evaluate the specificity and dynamics of pathogen/algal interactions.

  Viruses, for example, have the potential to be highly specific and effective control agents. They tend to be host-specific, suggesting 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, as often occurs in a HAB.

- Investigate the environmental impacts of the release of any non-indigenous organism used in biological control.

    Biological control is used extensively in agriculture, but there is still opposition to the concept of releasing one organism to treat another on land or in the sea. This is in part because the introduction of non-indigenous species or strains poses unknown risks, and may cause irreversible damage. There are examples where such an approach has had negative long-term consequences, yet there are also cases where the approach has been both effective and environmentally benign (e.g., sterile male releases for control of the Mediterranean fruit fly). The biological control concept thus deserves some consideration in marine systems.

- Explore the role of shellfish and other grazers in regulating HAB dynamics, including the possible value of seeding or restoration efforts as mechanisms for bloom control.

    Bivalves such as clams or oysters might be effective as biological control agents based on their ability to filter large volumes of water. For example, it has been suggested that restoration efforts that would return bivalves to their historical peak abundances in Great South Bay, New York, might control the initiation of brown tides (Schaffner 1999; Bricelj et al. 2001). In an analagous manner, combined culture of bivalves in shrimp ponds might control the algal blooms that cause anoxic events and mortalities in those shallow systems. The small organisms (zooplankton and ciliates) that co-occur with algae and eat them as food might also be cultured and used for control of HAB cells; however, there are daunting logistical problems involved in growing sufficient numbers of these organisms to control an actual bloom (e.g., Steidinger 1983).

- Investigate the role of invasive species in selecting for or promoting particular HABs (e.g., the zebra mussel and *Microcystis* blooms in the Great Lakes).
- Investigate the engineering and logistical requirements for field applications of biological control agents.
- Evaluate the fate and impact of toxins released during biological control efforts.
- Initiate mesocosm-level studies of biological control in natural HAB communities.

    Despite considerable success in laboratory investigations, this approach to direct bloom control is a long way from applications in natural waters. More work is clearly needed to pursue the possibility that bacteria, parasites, or viruses can be important in sustaining HABs or are important in their declines. Studies thus far have been confined to basic scientific investigations of the nature of the interactions. No practical efforts have yet been attempted to use these pathogens to control HABs.

Socioeconomic Impacts of Harmful Algal Blooms

There are social and economic costs to HAB events, ranging from short-term to long-term, that must be taken into consideration by policy and decision makers. For example, closure of a body of water or beach due to HAB-related fish kills and toxic aerosols can have substantial effects on tourism and fishing. A recent study reported that about one-third of visitors planning to visit a coastal area would stay home or go to another coastal location if a *Pfiesteria* outbreak were to occur (Falk, 2000). In some cases, the negative public reaction to HAB events can be severe and prolonged, and misinformation can cause scares unnecessarily, creating heavy pressures on management agencies and increasing economic losses. Some of the costs are direct, such as those related to health issues and agency monitoring programs, and lost sales of fish and shellfish products; others may be indirect and harder to quantify, such as negative investment decisions in coastal aquaculture due to the threat of HAB events or lost recreational opportunities. The recent report *Estimated Annual Economic Impacts from Harmful Algal Blooms (HABs) in the United States* gave a conservative estimate of the economic impacts of HABs in the U.S. for the period 1987-1992 as $49 million annually. This estimate did not include all instances of HAB events or include economic multipliers. Socio-economic costs are difficult to arrive at in part due to reporting limitations, although these have improved in recent years, as well as a lack of detailed data on local market characteristics and interactions among market sectors. It should also be recognized that certain single HAB events may alone approach or exceed the costs arrived at during the six-year period described above. For example, the 1976 red tide event in New Jersey is estimated to have caused losses of about $1 billion in 2000 dollars. Similarly the 1997 outbreak of *Pfiesteria* in the Chesapeake Bay is estimated to have cost the seafood industry $46 million in lost sales, mostly on species that were not even affected by *Pfiesteria*.

The socio-economic impacts from HABs are large and diverse at the local level, and significant at the aggregated, national level. Importantly, many HAB events are recurrent, and HABs show signs of expanding in geographic scope and severity as the nation’s use of coastal areas for commerce and recreation expands. In order for managers to make better decisions on how to manage blooms, additional research is needed to understand the nature and extent of public and industry reactions to HABs, the interactions among market sectors, and to develop methods of reporting that provide some consistency from different locales.

Goals: Improve understanding of public and commercial reactions to HABs in order to manage bloom events for maximum safety and minimum disruption.

Improve the ability of policy makers and managers to manage HABs by taking the true costs into account.

Issue: Due to largely unknown costs and benefits associated with bloom events, managers typically must manage each event with a maximum expenditure of energy and resources. This may be creating inefficiencies in the management of HABs.

Specific Research Needs

- Analyze the array of costs and benefits associated with HABs in various areas, taking into account the type of HAB event, magnitude, geographic extent, and duration, as well as the public and market sectors affected to provide a better basis for decision-making.

Issue: The nature of public and commercial sector reactions to HAB events is not well understood. This can lead to widespread concern that puts enormous pressures on management agencies and may lead to extensive additional economic costs.

Specific Research Needs

- Undertake research that helps explain the public's perceptions and attitudes regarding HABs and use this understanding to guide the responses of public officials, to nullify misperceptions and to direct accurate information to targeted groups.

    Improving the understanding of public and commercial reactions to HABs can improve managers' ability to manage the actual blooms, correct misinformation and allay fears, and minimize economic costs, while still protecting the public health.

- Develop information delivery methods targeted at specific cultural and ethnic populations.

Issue: Local market characteristics and interactions among markets are poorly understood, thereby limiting the accuracy of economic cost estimates resulting from HABs at the local and national levels.

Paralytic Shellfish Poisoning Outbreaks

In August 2000, nine people in Washington State became ill from Paralytic Shellfish Poisoning (PSP) after consuming recreationally harvested shellfish from closed waters of Carr Inlet in South Puget Sound. Seven of the nine cases were Cambodian-Americans. An investigation revealed that despite the fact that they knew PSP could make them ill, they proceeded to harvest and consume the shellfish.

Three weeks earlier state health officials had closed Carr Inlet when PSP results surpassed the required closure level of 80 µg of PSP toxin. A significant public education and media campaign accompanied the closure.

Janet Jensen/The News Tribune/2000
Reprinted with permission from The News Tribune, Tacoma, WA

The mussels contained exceedingly high toxin levels (13,769 µg of PSP toxin per 100 gm of shellfish tissue), resulting in extremely acute symptoms in some patients. Three of the nine illnesses were very severe, with two patients becoming completely paralyzed, requiring respirators and intensive care. Immediate intubation was essential to save their lives.

Excessively high levels of PSP toxin in molluscan shellfish are commonplace in Washington State. PSP levels in excess of 500 µg occur repeatedly each year. In addition, Washington State is home to many large and varied ethnic populations, making public notification and education a significant

Specific Research Needs

- Analyze a variety of local market structure characteristics and the interactions among the markets.

  Improving the understanding of market forces and interactions will provide additional information necessary for tallying the overall impacts of HABs at the local and national levels. This information is needed to plan and budget for future HAB events as well as to provide information critical to industry for development and other investment decisions.

Monitoring And Prediction of Harmful Algal Blooms

The widespread expansion of HABs throughout U.S. coastal waters has led to increasing stress on government agencies responsible for protecting public health and providing timely, accurate information to citizens, policymakers and businesses dependent on the health of these waters. Over the last twenty years, harmful algal species have increased in number and extended their range—many species have multiple strains, which can often complicate detection. Moreover, the movements of such blooms are difficult to predict at present — they can move across large areas, subject to changing climatic and environmental conditions.

State and local agencies that did not need to monitor or once monitored their waters for one or two potentially dangerous species have been forced to expand monitoring efforts as new species have inexplicably appeared. These efforts have significantly raised costs of monitoring and analysis; agencies are under pressure to act, often on limited information and funding. Under the National Shellfish Sanitation Program of the Interstate Shellfish Sanitation Commission, states have conservative measures in place for closing shellfish waters in order to protect human health from consumption of contaminated shellfish. However, the inability to accurately predict the onset of many blooms before they occur can be detrimental to businesses in these regions, among them commercial harvesters, aquaculturists, recreational fishermen, seafood handlers and those in the tourism industry.

Clearly, there is a strong need for a monitoring and detection system that will enable local, state, and federal agencies to work together in developing early warning systems and providing accurate forecasts on bloom occurrence, development, and transport – such capabilities will make it possible to develop realistic mitigation strategies that minimize the risks to human health and reduce the economic impacts.

Goals: Develop a regionally based, nationally cohesive HAB monitoring program.

Provide forecasts to predict bloom events with a 1-5 day lead time to public health and resource managers

Develop national and regional contingency plans with funding so that the response to HAB events can be rapid and effective

Issue: HABS develop and move quickly over large areas, leaving little time for agencies and the public to respond to minimize impacts

<u>Specific Research Needs</u>

- Develop a regionally based, nationally cohesive monitoring program.

  A national program should take advantage of existing federal, state, and local monitoring and research programs, while providing overall coordination and direction for state and local efforts. These actions would add efficiencies to existing programs while building the national capacity for long-term (> 10 years) time series data in support of environmental research. National support is needed to foster the *institutionalization of existing and new monitoring programs to promote continuity and longevity. These monitoring programs should include marine and meteorological conditions relevant to the development and transport of harmful algal events. The synthesis of these data to relate environmental change to HAB events will further increase forecasting ability.*

- Develop forecasting methods for blooms.

  Forecasting is necessary to enable an alert time of 1-5 days prior to a bloom to provide opportunities for mitigation, provide notification for coastal managers to reduce public risk, minimize the risk to endangered and protected species, educate the public to reduce the potential for collateral damage, and enable the relocation and protection of aquaculture resources.

- Develop contingency and rapid response plans as well as funding mechanisms.

  National contingency plans and rapid response capabilities are needed to promote a uniform and coordinated response at regional and local levels. Real-time data is necessary for early warning systems or alerts, allowing tracking of their movements.

- Develop a regional, rapid-response communications network to facilitate coordinated sampling and interpretation of HAB events and provide early warning and data dissemination.

  There is a need for timely access to regional information and data, integrated with environmental factors to enhance predictive capabilities. This could be based on similar listserv programs such as the Gulf Mortality Network (GMNET).

Issue: Current monitoring methods are often cumbersome, slow, and imprecise. There is an increasing need for monitoring tools that are fast, simple to use, and inexpensive.

Specific Research Needs

- Develop, test, and implement alternative monitoring tools.

  These new tools provide information that reduces the ever-increasing level of resources and cost now borne by state regulatory agencies. Alternative monitoring technologies and methods should be developed to enhance existing options used for regulatory purposes. In addition, alternative monitoring methods should be developed that lend themselves to adaptive sampling plans, further reducing the cost and resources incurred by state monitoring agencies. This should also include integration of new technologies into current monitoring programs, such as molecular probes, remote sensing data, and in situ instrumentation.

Issue: It is very costly to monitor the toxin levels in all organisms that may pose a human health threat.

Specific Research Needs

- Identify sentinel species that can be used to provide early warning.

  Identification of sentinel species and characterization of their toxin uptake and depuration rates established under different environmental conditions are needed to provide better focus and economy to monitoring efforts. Regulatory sampling could benefit greatly if toxin uptake and depuration kinetics were known for each species and each toxin in comparison with the sentinel species.

Issue: The amount of data generated by existing and future monitoring programs will quickly become overwhelming, or will be inaccessible to the end-user.

Specific Research Needs

- Apply data assimilation and modeling to HAB monitoring and forecasting.
  This will provide a critical connection between existing and future monitoring programs and our ability to provide predictive forecasting and tracking of HAB events.
- Provide standardized data products.
  Data reduction and synthesis can improve end products for managers and the public by providing standardized results (e.g. GIS-based maps, summary graphs, synoptic forecasts). These techniques will also be applied to the development of better adaptive sampling protocols by providing more selective spatial and temporal sampling information.

Outreach and Education Related to Harmful Algal Blooms

Outreach and public education should be an integral part of any research program, but particularly so for a research program such as Prevention, Control, and Mitigation of HABs where the primary audience is not other researchers. The results of the research must be made available to the public, the private sector, and the various agencies involved in dealing with harmful algal blooms. As was made clear once again during the recent *Pfiesteria* outbreaks in the mid-Atlantic, public perceptions of risk and the actions they take in response can have major economic impacts, over and above the direct impacts of HABs. It is critical that research results be delivered accurately and in a timely manner so as to increase public confidence and the utility of the results. Education represents a long-term delivery tool to increase public understanding of extreme environmental events such as HABs and their health effects on humans and aquatic ecosystems. It is expected that inherent in the planning of all research to be conducted under this Program will be consideration of how the results can be best delivered to the appropriate audience. The interactions between researchers and outreach personnel will be ongoing during the projects. The creation of new monitoring capabilities with information being available on a real-time basis presents a challenge to be sure the public is not overwhelmed, but instead is provided with tools that will help interpret the information. In addition, there is a great deal of existing information that needs to be transferred to the public and management communities. What is needed is a suite of products developed in coordination with researchers that would include, for example, workshops and symposia, reports and fact sheets, focus group presentations, and websites. Understanding how the general public typically obtains information on environmental/science issues, and tailoring the outreach and education materials accordingly, is the key to the effective delivery of accurate information.

Goal: Ensure that the results of the HAB prevention, control, and mitigation research program are delivered in a timely manner in a form appropriate to the audience.

Issue: Outreach techniques need to be appropriate to the needs of the end-users of the information.

<u>Targeted End-users and their Needs</u>

- Concerned citizens and constituents

  The outreach effort will provide summary information such as basic education on toxins, their causative organisms, and their human health effects to the general public, including educators and health professionals. Mass media delivery through television, radio and newspaper features is a potentially powerful tool. Efforts will be made to involve the public in monitoring projects according to their level of skill. There is a need to develop information delivery methods that can be targeted to specific cultural and ethnic populations who may not be well served by traditional communication channels.
- The business and industry sector

  The outreach effort will provide the link between product safety and development with

HAB research, helping to apply useful research information to industry development and business planning. Outreach personnel will aid the research effort by acting as a link to provide economically based data to assist in establishing research priorities and experimental design. The tourism/recreation and seafood industries will be aided by the development and enhanced distribution of relevant information about HABs and public health.

- Agencies and managers

  The outreach program will facilitate communication on regulatory issues relative to HABs and provide research-based information to other stakeholders, and will provide a link between agencies and research personnel and facilities. In addition, outreach personnel will provide training workshops appropriate to the end users (both high- and low-end), for example, to introduce new sampling techniques that are appropriate for toxin analysis or species identification to agency personnel.
- Government (local, regional, national)

  The outreach program will act as a link between research and governmental officials, summarize research-based information, and keep local, regional, and national officials informed about HAB-related environmental issues.
- Research sector

  The outreach program will summarize scientific publications for general public use, and will assist researchers with identification of appropriate methods and timing of outreach activities. In addition, outreach personnel will be available to facilitate networking within and outside the research community, identify and coordinate interaction between stakeholders and researchers in developing research questions, and generally provide input that will assist in the performance of research activities.

The recent *Pfiesteria* outbreak illustrated some of the many possibilities for outreach materials to be useful in getting the message out to the public. After *Pfiesteria* killed fish and sickened people in the Mid-Atlantic region, Sea Grant programs from New York to North Carolina teamed up to produce video programs, design web sites, publish handbooks and distribute other information to help everyone from seafood processors to journalists to consumers understand the risks of noxious algae and dinoflagellates.

Two videos were produced. North Carolina Sea Grant produced "*Nature Out of Balance*," a documentary on harmful algal blooms with a focus on *Pfiesteria* in an ecological and human health context. The purpose of the program was to answer questions posed by public citizens and policy-makers, and it addressed the role of science and citizens in a water quality issue. Maryland Sea Grant prepared a documentary entitled "*The* Pfiesteria *Files*" that not only explained the scientific challenges surrounding Pfiesteria, but also detailed the responses of people, including the media, to this most puzzling of organisms.

Maryland Sea Grant took the lead in designing a regional web site that focuses on *Pfiesteria* and other harmful algal blooms, providing links to information available throughout the region and beyond. Maryland also helped take the lead in preparing a resource notebook for journalists and others interested in basic information about *Pfiesteria* and other harmful algae, including facts on biology, ecology, human health and seafood safety. North Carolina Sea Grant developed a commercially published guide for educators, "*Algae: Source Book for Teaching About Harmful Algal Blooms*," through a Federal-state-university partnership.

And Delaware Sea Grant produced "*Understanding Mid-Atlantic residents' concerns, attitudes and perceptions about harmful algal blooms*: Pfiesteria piscicida," based on a survey of 3,500 coastal residents from New York to the Carolinas. The results showed that *Pfiesteria* outbreaks might dramatically affect consumers' travel choices, reducing tourism in an affected area by at least 40 percent, with a significant impact on coastal communities. Seafood sales also might plummet with nearly two-thirds of respondents saying they would eat less locally harvested seafood if *Pfiesteria* had been reported in their state waters.

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