Science for Solutions

NOAA COASTAL OCEAN PROGRAM
Decision Analysis Series No. 10

Special Joint Report with the National Fish and Wildlife Foundation

HARMFUL ALGAL BLOOMS IN COASTAL WATERS: Options for Prevention, Control and Mitigation

Donald F. Boesch, Donald M. Anderson, Rita A. Horner
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February 1997

U.S. DEPARTMENT OF COMMERCE
William M. Daley, Secretary

U.S. DEPARTMENT OF THE INTERIOR
Bruce Babbitt, Secretary

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Cover photo: The upper portion of photo depicts a brown tide event in an inlet along the eastern end of Long Island, New York, during Summer 1986. The blue water is Block Island Sound. Photo courtesy of L. Cosper.

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The Assessment Panel

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THE SECRETARY OF THE INTERIOR

WASHINGTON

Harmful algal blooms or as the public knows them, red and brown tides have become an increasing menace on our coasts over the last several years. While visiting the Texas coast last year, the serious impact these tides are having on our living aquatic resources and in the lives of people was brought home to me. At that time I asked the National Fish and Wildlife Foundation to see if the staff there could find out what could be done about this problem.

The report you have in your hands -- Harmful Algal Blooms in Coastal Water: Options for Prevention, Control and Mitigation -- is the result of my request, and is this Nation's first systematic attempt to find a solution to this growing problem. The report also represents the best in intergovernmental cooperation as the report was completed by a partnership with the National Oceanic and Atmospheric Administration, Department of Commerce, the Department of the Interior, and the National Fish and Wildlife Foundation.

What we have found is that while there are some steps that can be taken immediately, there are no simple answers to all the problems caused by these tides. This means we all must maintain a focus on this problem. For my part, I will ask the agencies of the Interior Department to put this report to work and to become an active partner in the search for and implementation of solutions.

I especially want to thank Dr. Donald F. Boesch of the University of Maryland, who chaired this important work and the impressive panel that he assembled to help him.

Well Done.

Bruce Babbitt

Foreword

I am pleased to release the assessment *Harmful Algal Blooms in Coastal Water: Options for Prevention, Control and Mitigation*, conducted for the National Fish and Wildlife Foundation, Department of the Interior, and the National Oceanic and Atmospheric Administration (NOAA), Department of Commerce. The report is the result of deliberations by a panel of experts, chaired by Donald F. Boesch of the University of Maryland, and is based on the outcome of workshops held in Port Aransas, Texas, Seattle, Washington, and Sarasota, Florida, from August through November 1996. Regional scientific experts, managers involved in reducing or mitigating the effects of algal blooms, and representatives of user constituencies participated in each of these fact-finding meetings by making presentations and participating in discussions. The assessment is intended to suggest the direction informed policy at Federal and state and local levels might take in dealing with the increasingly serious problem of harmful algal blooms.

The Department of Commerce is particularly interested in this environmental problem because it poses a significant threat to the Nation's health and economic well-being. Some of these blooms produce toxins that are harmful to human beings, fish, birds, and marine mammals. Additionally, significant economic losses have resulted from blooms that cause closure of fisheries, beaches, and water-related activities and the industries they support.

An interagency research effort to assemble the scientific knowledge to help understand and predict the occurrence of these blooms -- ECOHAB (Ecology and Oceanography of Harmful Algal Blooms) -- is underway under the leadership of NOAA's Coastal Ocean Program. NOAA is committed to expanding our interagency partnerships to explore ways to respond to the additional challenges posed in this report. Working together in this way, I believe we will move ahead toward finding solutions to this priority coastal ocean problem.

William M. Daley
Secretary of Commerce

ACKNOWLEDGMENTS

This assessment was supported principally by the National Fish and Wildlife Foundation and the National Oceanic and Atmospheric Administration (Coastal Ocean Program and National Sea Grant College Program). Drs. Jerry Clark and Don Scavia, respectively, represented these organizations and provided essential encouragement, guidance and assistance throughout the planning and execution of the project. Other sponsors providing financial or logistical support for the three regional meetings that were held included the University of Maryland Center for Environmental and Estuarine Studies, Texas Parks and Wildlife Department, Gulf Coast Conservation Association, University of Texas Marine Science Institute, National Marine Fisheries Service (Northwest Fisheries Science Center), University of Washington Sea Grant Program, Solutions to Avoid Red Tide, Mote Marine Laboratory and the Florida Department of Environmental Protection. Dr. Larry McKinney, Mr. Jim Ehman, Dr. Terry Whitledge, Dr. Usha Varanasi, Mr. Louie Echols, Major Gen. (ret.) Jim Patterson, Dr. Kumar Mahadaven, and Dr. Kenneth Haddad facilitated the participation of these organizations.

This assessment could not have been successful without the interest and cooperation of many technical experts, state agency representatives, resource users, businessmen, and citizens who participated in the three regional meetings as presenters, panelists or attendees. Their perspectives provided concerns and insights that could not be developed from written reports.

Ms. Miné Berg provided technical assistance at the regional meetings and in preparation of the report. Ms. Deborah Kennedy prepared the figures. Ms. Joyce Meritt and Ms. Joan Thompson helped with meeting planning, communication and travel arrangements. Dr. Grant Gross and Ms. Sydney Arny of the Chesapeake Research Consortium provided ready assistance and effective management of the project.

Finally, Drs. Sherwood Hall, Daniel Kamykowski, Maureen Keller, Kevin Sellner, Don Scavia, Karen Steidinger, Tracy Villareal, and John Wekell and General Jim Patterson reviewed the report and provided helpful suggestions toward its improvement.

To all of these individuals the authors extend their sincere thanks for their commitment, interest and assistance. The completion of this assessment would not have been possible at all, much less in the short time frame in which we acted, without their utmost cooperation.

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EXECUTIVE SUMMARY

This report is the product of a panel of experts in the science of blooms of unicellular marine algae which can cause mass mortalities in a variety of marine organisms and cause illness and even death in humans who consume contaminated seafood. These phenomena are collectively termed harmful algal blooms or HABs for short. As a counterpart to recent assessments of the priorities for scientific research to understand the causes and behavior of HABs, this assessment addressed the management options for reducing their incidence and extent (prevention), actions that can quell or contain blooms (control), and steps to reduce the losses of resources or economic values and minimize human health risks (mitigation).

This assessment is limited to an appraisal of scientific understanding, but also reflects consideration of information and perspectives provided by regional experts, agency managers and user constituencies during three regional meetings. The panel convened these meetings during the latter half of 1996 to solicit information and opinions from scientific experts, agency managers and user constituencies in Texas, Washington, and Florida. The panel's assessment limited its attention to those HABs that result in neurotoxic shellfish poisoning, paralytic shellfish poisoning, brown tides, amnesic shellfish poisoning, and aquaculture fish kills. This covers most, but certainly not all, HAB problems in the U.S.

The panel developed the following conclusions and recommendations as a result of its deliberations:

- Harmful algal blooms are increasing in frequency or severity in many U.S. coastal environments and worldwide. Beyond aesthetic impairment, such blooms pose increasing risks to human health, natural resources and environmental quality. Whether the increase in HABs is a direct result of human activities, cyclic or longer-term variations in climate, or other natural factors, the greater risks posed demand improved precautions for the protection of human health, more concerted efforts to manage activities which may cause HABs and renewed consideration of control strategies.
- It is obviously preferable to prevent HABs in the first place rather than to treat their symptoms. Many scientists have suggested that increases in HABs are somehow linked to increased pollution of the coastal ocean, particularly by plant nutrients. Indeed, there are few other causes, other than climate change, that could conceivably be responsible for such widespread increases in HABs during the last half of the 20th Century. Although pollution and nutrient enrichment are strongly implicated in worsening HABs elsewhere in the world, they have not been unequivocally identified as the cause of any of the HABs considered in this assessment. Nonetheless, conscientious pursuit of goals for reductions of pollution, including excess nutrients, which have been established for many U.S. coastal waters could well yield positive results in terms of reductions in some HABs. In other words, HAB reduction is yet another rationale for advancing existing

pollution reduction strategies. However, the reduction of the potentially most important pollutant, nitrogen, is a daunting challenge because of the importance of difficult-to-control nonpoint sources from agriculture and fossil fuel combustion. Careful assessment and precaution against introductions and along-coast transfers of HAB cells and cysts via ballast water and aquaculture-related activities also require attention.

- Although controlling HABs by the application of chemicals or flocculants or the introduction of biological control agents is fraught with difficulties related both to effectiveness and potential side effects, such controls deserve more careful attention than they have received heretofore. In addition to the need for expanded U.S. research on this topic, much can be learned from the experiences of Asian nations. Furthermore, control techniques should be evaluated in the context of risk assessments similar to those applied in evaluating chemical and biological controls in land-based agriculture. The applicability of controls may be limited to more managed and constrained circumstances, for example in association with aquaculture or within small bays.

- The conservative procedures used to protect public health from exposure to algal toxins have been largely successful to this point. The incidence of mortality and serious illnesses in the U.S. has been relatively low. However, in order to contend with potentially increased and more diverse risks from HABs in an era of declining governmental resources to support labor-intensive monitoring, more sophisticated and reliable detection methods are now required, in addition to the immediate expansion of simple methods using volunteer observers. In addition, the medical community should be better informed and prepared to treat individuals suffering HAB toxicity. Individuals visiting or living on the shore or consuming seafood also need to be better informed about the risks, but not unduly alarmed. Responsible public education and communication must receive increased attention.

- The expanded research being initiated by federal agencies on the Ecology and Oceanography of Harmful Algal Blooms (ECOHAB) should seek to contribute understanding toward prevention, control and mitigation strategies. However, a factor limiting the evaluation, much less application, of prevention, control and mitigation strategies has been the lack of focused research programs in these areas. Federal and state agencies with responsibilities for resource management, environmental protection and public health should support applied research directly addressing prevention, control and mitigation, including: evaluation of the effectiveness and side-effects of chemical, physical and biological control agents; development of better detection and measurement of toxins and HAB species for application in monitoring; ballast water treatments; and determination and treatment of the effects of chronic exposure on human health.

INTRODUCTION

Over the last several decades many areas of the world, including the United States, have experienced a growing trend in the incidence of harmful algal blooms (Anderson 1989; Smayda 1990). The episodic proliferation of unicellular marine algae, some of which produce toxins, can cause mass mortalities in a variety of marine organisms and cause illness and even death in humans who consume contaminated seafood. Some harmful algal blooms can be dense enough to discolor the water, while others may produce deleterious effects even if toxic algae are present in low concentrations. Some are spatially extensive and persistent, while others are patchy and episodic. Harmful algal blooms have long occurred in some regions, such as along the west coast of Florida and the extended coastlines of Maine and Alaska, but may be expanding or lasting longer there. Others, such as those occurring in Texas and Long Island bays, have developed only in recent years. Blooms now threaten virtually every coastal state, cover greater expanses of our coastlines, and involve a multitude of species (Anderson 1995).

Not all harmful algal species produce toxins. Dense blooms of non-toxic species can kill marine organisms indirectly by shading, through oxygen depletion, or even mechanical irritation. Harmful algae comprise species from several different groups: dinoflagellates, diatoms, micro-flagellates, cyanobacteria and chrysophytes. An important factor in some microalgal blooms is the production of toxins that in human consumers result in paralytic, diarrhetic, neurotoxic, and amnesic shellfish poisoning (PSP, DSP, NSP, and ASP); and ciguatera fish poisoning (CFP). Toxins may also affect marine mammals and birds. For example, neurotoxins associated with blooms along the west coast of Florida caused significant mortalities of endangered manatees in 1996 (Steidinger et al. 1996). In addition to risks to human health and natural resources, significant economic losses regularly result from closure of fisheries and beaches to protect human health: $7 million from a single PSP outbreak in Maine; $25 million from closures related to an NSP outbreak in North Carolina; $20 million per event from losses to the tourist industry and local governments for Florida red tides; and $15-20 million as a result of closures in harvesting razor clams and Dungeness crabs due to a single event of ASP in Washington and Oregon.

To resolve these issues, federal agencies, including the National Oceanic and Atmospheric Administration, Environmental Protection Agency, the National Science Foundation, and the Office of Naval Research, are initiating a strategic research program on the ecology and oceanography of harmful algal blooms (ECOHAB). To guide this initiative, scientific research and monitoring needs were assessed and a national research agenda developed (Anderson 1995). However, issues related to the management of HABs have not received comparable attention. What are the environmental management options for reducing the incidence and extent of harmful algal blooms (**prevention**)? What actions can be taken in response to blooms to quell or contain them (**control**)? What steps can be taken to reduce the losses of resources and economic values and minimize human health risks that do occur (**mitigation**)? This assessment of prevention, control and mitigation options seeks to answer these questions and to provide guidance for policy makers and resource managers at national, state and local levels.

The specific objectives are to:

- determine the state of understanding of the causes of harmful algal blooms in major regions of the United States;
- compare and evaluate the current management efforts related to these blooms;
- evaluate and recommend steps which could be taken to reduce the incidence and severity of harmful algal blooms;
- identify feasible actions which should be further developed or evaluated to control the spread of harmful algal blooms once they occur, and
- evaluate and recommend procedures for reducing the impact of harmful algal blooms, including more effective monitoring, fishery closures, aquaculture practices, and public health advisories.

The assessment was conducted by a Panel of experts—the authors of this report—representing a range of experience in the related scientific and management issues in different parts of the United States. The members of the panel were selected by the panel chair, Donald F. Boesch, in consultation with the principal sponsors of the assessment, the National Fish and Wildlife Foundation and the National Oceanic and Atmospheric Administration.

The Panel performed the assessment through three regional meetings which addressed the most important types of harmful algal blooms:

- Port Aransas, Texas: August 21-22, 1996; brown tides in Texas and Long Island.
- Seattle, Washington: September 30-October 1, 1996; paralytic and amnesic shellfish poisoning and blooms causing fish kills in the Pacific Northwest, California, Alaska and New England.
- Sarasota, Florida: November 13-14, 1996; neurotoxic shellfish poisoning (red tide) in the Gulf of Mexico and southeast.

Regional scientific experts, managers involved in reducing or mitigating the effects of algal blooms, and representatives of user constituencies participated in each of these fact-finding meetings by making presentations and participating in discussions. A list of these individuals is provided in Appendix 1.

The assessment is intended to suggest informed policy at federal and state levels as it relates to environmental protection, resource management, public health, research and development, and investment of financial and capital resources. Specific recommendations are highlighted by bold facing. A second major goal is to provide background, comparative contexts, and practical advice for managers responsible for living resources, environmental protection, public health and tourism and recreation. In addition, the assessment aims to serve a useful role in public education and awareness. Finally, it provides a frame of reference for better relating research to policy and management information needs. The inputs of regional managers and resource users were particularly influential in broadening the assessment beyond strictly scientific issues.

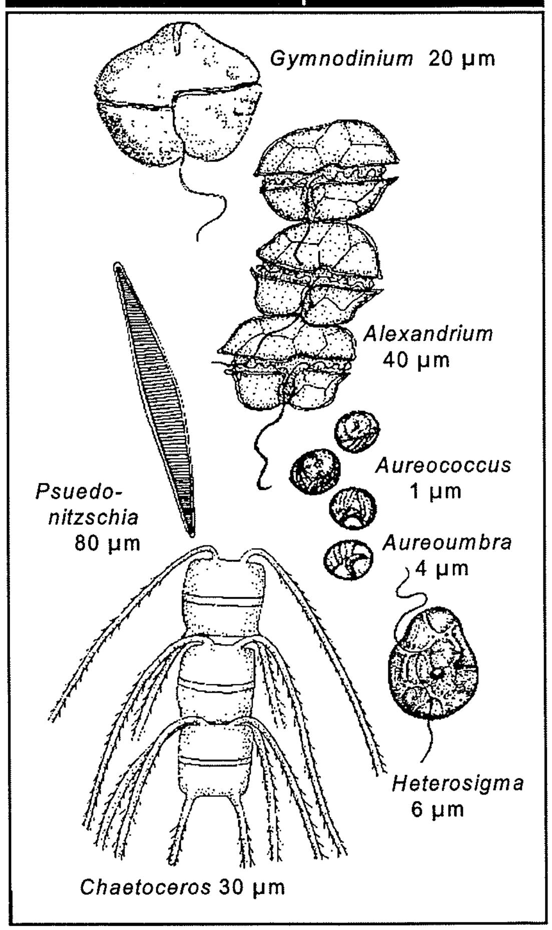
WHAT ARE HARMFUL ALGAL BLOOMS?

The term "harmful algal blooms" (shortened for convenience here to HABs) has been used by the scientific community to describe a diverse array of blooms of both microscopic and macroscopic marine algae which produce: toxic effects on humans and other organisms; physical impairment of fish and shellfish; nuisance conditions from odors and discoloration of waters; or overwhelming effects on ecosystems such as severe oxygen depletion or overgrowth of bottom habitats. Although the use of the terms "bloom" or "red tide" conjure up an image of algal populations so dense as to be visible, this is not always the case with HABs. Concentrations of only a few cells per liter of some microalgae may produce harmful toxic effects.

This assessment focused on blooms of microscopic algae occurring in the coastal waters of the United States which produce toxic effects and impairment of fish and shellfish production, either directly or indirectly, via degradation of habitats. The focus was on a relatively few species of microscopic marine algae which cause the following:

- Blooms producing neurotoxic shellfish poisoning (NSP). These are caused by the dinoflagellate *Gymnodinium breve* and occur along the coasts of the Gulf of Mexico, and rarely, the southeast Atlantic coast.
- Blooms causing paralytic shellfish poisoning (PSP). Various species of the dinoflagellate genus *Alexandrium* are responsible for PSP in New England, northern California, the Pacific Northwest and Alaska.
- "Brown tide" blooms (BTB) caused by very small golden brown algae. These seem to be a recent occurrence in relatively enclosed waters of southern New England, particularly Long Island (New York) and Texas. *Aureococcus anophagefferens* is responsible for brown tides in southern New England and a similar species, *Aureoumbra lagunensis*, blooms in Texas bays and lagoons.

The Culprits



- Blooms of various species of the diatom genus *Pseudo-nitzschia* produce domoic acid that causes amnesic shellfish poisoning (ASP). Domoic acid poisoning may also be experienced by humans, mammals, and birds from consumption of fish and other invertebrates. Toxin-producing species of *Pseudo-nitzschia* occur on the northwest, east and Gulf coasts, but no confirmed cases of ASP have occurred in humans in the U.S.

- Blooms which result in catastrophic losses of cultured and wild fish, particularly in the Pacific Northwest, but do not cause illness in humans. Such blooms are caused both by the raphidophyte flagellate *Heterosigma akashiwo* and by a few species of the diatom genus *Chaetoceros*, which clog fish gills.

In the following section, knowledge of the causes and consequences of these harmful algal blooms is reviewed. They are treated in the order listed above, with the long-studied NSP and PSP-causing blooms treated first, followed by those which are emerging concerns and less well-studied.

Several other types of harmful algal blooms were not addressed in this assessment but deserve mention. These include blooms of a variety of dinoflagellates: the epibenthic *Gambierdiscus toxicus* which is responsible for ciguatera fish poisoning in tropical waters; the "phantom dinoflagellate," *Pfiesteria piscicida,* known to cause fish mortalities in east coast estuaries (Burkholder et al. 1992); and endoparasitic dinoflagellates which infect commercial crab species. Blooms of cyanobacteria or "blue-green algae" in east coast estuaries from the Chesapeake Bay to Florida Bay and excessive growths of macroalgae ("sea weeds"), which foul beaches, shade seagrasses, and deplete oxygen, also cause harm.

Causes and Consequences

Neurotoxic Shellfish Poisoning

Massive fish kills off the west coast of Florida have been known since 1844 and, according to the writings of sixteenth-century Spanish explorers, the Tampa Bay Indians long noted the seasonality of fish kills now associated with red tide blooms. Shellfish toxicity was documented in 1880 and aerosol-related respiratory symptoms in human inhabitants were described in 1916. Between 1844 and 1996, red tides (discoloration, fish kills, respiratory irritation, or shellfish poisoning) have occurred in 58 years. Since 1946, when the causative toxic dinoflagellate, *Gymnodinium breve*, was first discovered, red tide has been observed in 42 of the 50 intervening years.

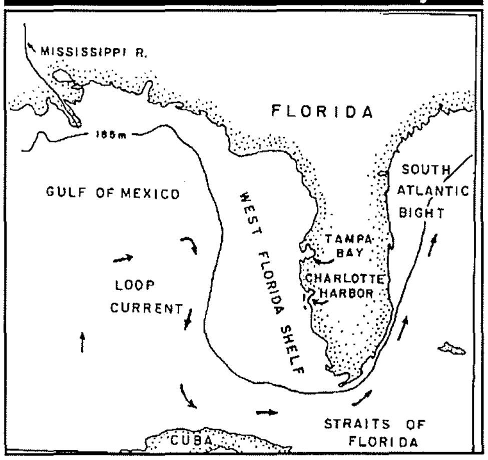
Throughout the Gulf of Mexico and the U.S. South Atlantic Bight, *G. breve* is found in low background concentrations (1-1,000 cell/l) except in areas off the west Florida and Texas coasts where local circulation may play a role in concentrating cells. While *G. breve* blooms have occurred in many different areas within the Gulf of Mexico, from Yucatàn in the south, along the Tamaulipas and Texas coasts, and recently to Alabama, Mississippi and Louisiana waters, they are most frequent along the west coast of Florida. Blooms there are especially frequent from Clearwater to Sanibel Island, occurring in 21 of the last 22 years. These blooms on the southwest Florida shelf served as a source for cells innoculating the U.S. South Atlantic Bight (Florida east coast and North Carolina) in 1987-88 (Tester et al. 1991).

Florida red tides affect humans, wildlife, fishery resources and the regional tourist-related economy. As *G. breve* cells die and break up, they release a suite of powerful neurotoxins, known collectively as brevetoxins. Shellfish management regulations include a biotoxin control plan that is implemented during red tides to reduce the risk to humans from consumption of toxic molluscs. While some illness related to shellfish consumption occasionally has occurred, in general the highly cautionary regulations have been quite effective in preventing neurotoxic shellfish poisoning. While it is known that aerosols from red tides produce respiratory ailments in many humans exposed, the long-term consequences are poorly known, in part because statistics on individuals treated for respiratory and other associated maladies are not maintained. Also, it is difficult to assess long-term effects of acute exposure among tourists who leave the area. Fish kills, bird kills and occasional invertebrate kills are common sights during red tides. In 1996 more than 150 manatees, an endangered species, died due to brevetoxin exposure during a prolonged red tide along the southwest Florida coast (Steidinger et al. 1996).

The economic impacts of the Florida red tides are not well-documented but estimates of $15-20 million were published in the early 1970s when the blooms lasted for at least three months and impacted several counties. The 4-6 month red tide in North Carolina during 1987-88 was estimated to have cost the coastal community there $25 million (Tester and Fowler 1990). The 1995-96 west Florida red tide, an unusually prolonged one, had severe financial consequences for shellfish growers, beach resorts and tourist-dependent businesses and may have adversely affected real estate values. Although these impacts have not been comprehensively quantified, hoteliers and restauranteurs in the region testified to unprecedented reductions in business volume.

G. breve blooms are initiated on the continental shelf or at the shelf edge, rather than in nearshore waters where they produce the most deleterious effects. Low concentrations (<1,000 cells/l) of the organism occur in offshore waters throughout the year. Bloom initiation is characteristically associated with intrusion of deeper, offshore waters onto the shelf. This phenomenon is best known for the west Florida shelf where blooms may occur any time of the year, but typically occur in late summer and fall when more than 70% of the observed outbreaks have been initiated. Bloom concentrations first appear offshore (18-74 km) and are associated with fronts. Much as weather fronts mark the convergence of air masses, ocean fronts separate waters of different temperature and salinity characteristics. These fronts are caused by the onshore-offshore meanders of the Loop Current, part of the Gulf of Mexico current system through which water flows along the edge of the shelf and then through Florida Strait, eventually to become the Gulf Stream.

Florida's Red Tide Country



G. breve may grow rapidly in the dynamic nutrient regimes and light conditions along frontal gradients, dividing up to once a day, but usually once every 2 to 5 days (Steidinger et al. in press), gradually building high densities. *G. breve* is well-adapted to such environments and can grow throughout the water column where there is sufficient light. It has a high photosynthetic capacity and can assimilate nutrients (both organic and inorganic) at low light levels. Once growth occurs, it takes 2 to 8 weeks to develop into a bloom of fish-killing proportions ($1\text{-}2.5 \times 10^5$ cells/l) depending on physical, chemical and biological conditions. Because of rapid growth and ability to out-compete or otherwise exclude other phytoplankton species, *G. breve* can develop almost monospecific surface blooms covering a surface area of 10,000 km^2 or more. Although biomass concentration is patchy, chlorophyll *a* values (a good surrogate for biomass) from 10 to >100 mg/ m^3 make the resultant discolored surface water detectable by satellite color sensors. The Coastal Zone Color Scanner which provided data between 1978 and 1986 was able to detect chlorophyll *a* from *G. breve* cells at densities as much as three orders of magnitude less than are present when discolored water is detectable by the human eye, about 10^6cells/l (Tester and Steidinger in press). New satellite-borne ocean color sensors, which have been recently launched or should be operational in the near future, thus offer prospects for routine bloom detection. Of course, the ability to detect subsurface patches and distinguish *G. breve* blooms from those of other algae will limit the use of this technology.

The fate of a *G. breve* bloom, whether it will grow denser or larger and, very importantly, whether it will be transported onshore and impact beaches and bays, is determined largely by the currents on the continental shelf, which are driven by winds, impingement of the Loop Current on the shelf, and the fact that the ocean level typically slopes ever-so-slightly down from north to south. On the west Florida shelf, currents are complex and include gyres, larger eddies, and filament-like incursions of offshore water across the shelf. These physical processes are capable of moving blooms onshore, to the north along the Florida panhandle (via a large clockwise gyre on the northern part of the shelf), or south toward the Florida Strait. During some periods there may be little net flow, allowing blooms to be maintained within the midshelf zone and occasionally inoculate or re-inoculate the nearshore region. The annual cycle of wind stress, northward during the summer and southward in the fall, is responsible for the persistent upwelling (summer) or downwelling (fall) found over the west Florida shelf, which can concentrate or disperse blooms and transport them toward or away from shore depending on the site and timing of the bloom. Once in nearshore waters, transport of the blooms is affected by longshore flows and tidal exchanges with bays.

G. breve is essentially a continental margin species which can utilize low levels of nutrients very efficiently. Dense blooms do not persist at salinities below 24 ‰ (parts per thousand), conditions that occur in estuaries and coastal waters receiving fresh water from rivers. The offshore initiation of red tide blooms cannot be readily prevented. An important question, then, is the degree to which a bloom being moved into nearshore waters can be prevented from persisting or intensifying by reducing nutrient inputs from the land, including those of human origin. *G. breve* can utilize land-based nutrients and grow rapidly in the coastal waters provided the salinity does not fall below 24 ‰. Evidence suggests that dense blooms inshore cannot be sustained without inputs of "new" nutrients (Steidinger et al. in press). If so, human inputs of nutrient could be responsible for extending the duration and impacts of red tides once blooms enter the nearshore zone, including bays and canals.

Dissipation or termination of red tide blooms occurs when blooms are transported out of the area or when the integrity of the water mass is weakened by mixing and dilution. Both declining water temperature and increasing wind stress contributed to the dissipation of the 1987-1988 *G. breve* bloom off North and South Carolina (Tester et al. 1991). Unfortunately, the roles of density-dependent growth factors, nutrient limitation, and grazing pressure in the decline of red tide blooms are not well known.

PARALYTIC SHELLFISH POISONING

Paralytic shellfish poisoning (PSP) is a significant problem on both the east and west coasts of the U. S. Caused by several closely related species in the genus *Alexandrium*, PSP toxins are responsible for persistent problems due to their accumulation in filter feeding shellfish (e.g., Shumway et al. 1988), but they also move through the food chain, affecting zooplankton, fish larvae, adult fish, and even birds and marine mammals (Anderson and White 1992; Geraci et al. 1989; Shumway 1995). On the east coast, PSP is a serious and recurrent problem from Maine to Massachusetts. Connecticut, Long Island (New York) and New Jersey occasionally experience the toxin (or *Alexandrium*) at low levels, but these areas seem to define the southern extreme of this organism's geographic distribution. The offshore waters of Georges Bank experienced a serious PSP outbreak several years ago, leading to the extended closure of the surfclam fishery and the demise of a fledgling roe-on scallop fishery. On the west coast, PSP is a recurrent annual problem along the coasts of northern California, Oregon, Washington, and Alaska. Overall, PSP affects more coastline than any other HAB problem.

It is likely that seasonally recurring outbreaks of PSP are linked to the existence of a dormant cyst stage in the *Alexandrium* life history. This strategy allows the species to deposit dormant cells in sediments where they survive through harsh winter conditions and then germinate to initiate new outbreaks in subsequent years. Prior to 1972, for example, PSP was restricted to the far eastern sections of Maine ("down east") near the Canadian border. That year, however, a massive red tide occurred that stretched from southern Maine through New Hampshire and into Massachusetts, causing high levels of toxicity in those areas for the first time in recorded history. Virtually every year since that event, this region has experienced PSP outbreaks, a result of the successful colonization of the area by *Alexandrium* spp. A similar expansion, with subsequent recurring outbreaks of *Alexandrium,* occurred in the Puget Sound region of Washington in the late 1970's, an area with no prior history of shellfish poisoning (Nishitani and Chew 1988). Long-term climatic variability, which affects temperature, upwelling, and currents or allows cysts to survive in areas where they did not before, may be factors in such range extensions.

PSP occurs over a large geographic range, so a variety of physical mechanisms underlie the spreading of *Alexandrium* blooms. In southern New England, for example, localized blooms occur in small, isolated salt ponds and embayments, whereas in the southwestern Gulf of Maine, linkage has been documented between the abundance and distribution of *Alexandrium* and a buoyant coastal current that travels from north to south in that region (Franks and Anderson, 1992). Fresh water enters the Gulf of Maine from several large rivers in southern Maine, and the freshened coastal waters flow south in a manner that is influenced by the amount of rainfall and snowmelt, the local wind stress, and the underlying circulation of the Gulf of Maine. Toxic *Alexandrium* populations are closely associated with this buoyant water mass. The long distance transport of *Alexandrium* cells in this coastal current are responsible for PSP outbreaks in southern Maine and Massachusetts, and may even be linked to shellfish toxicity on Georges Bank (Anderson and Keafer 1992). The hydrographic mechanisms underlying PSP blooms in down-east Maine are more poorly understood than those described for the region to the southwest.

Similarly, on the west coast, blooms can be either localized in distribution (i.e. restricted to the inland waters of Puget Sound or the fjords of Alaska) or wide spread along the Pacific Ocean coast. In northern California, it is hypothesized that the onset of PSP toxicity is linked to the onshore movement of warm, stratified waters following the relaxation of coastal upwelling (Horner et al. in press). The relaxation events or downwelling, brought about by a change in wind speed or direction, carry established *Alexandrium* populations toward shore, resulting in rapid increases in toxicity in nearshore shellfish. There is currently no evidence that this also occurs in Washington or Alaska.

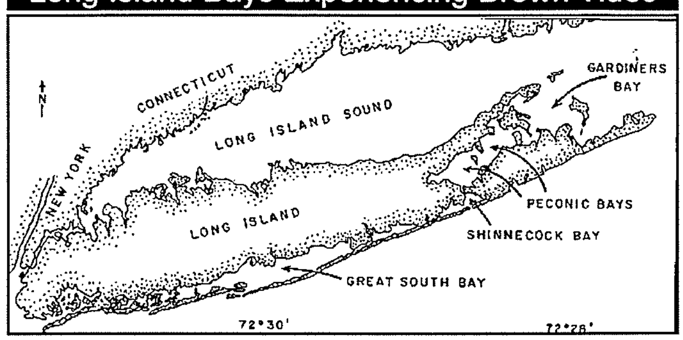
These are but a few of the physical mechanisms underlying PSP outbreaks in the U.S. Some areas are well-studied, and others are virtually unknown. *Alexandrium* blooms generally do not involve large cell accumulations that discolor the water and may be below the water surface where they are not visible. Low density populations can cause severe problems due to the high potency of the toxins produced by these species. Furthermore, *Alexandrium* species can grow in relatively pristine waters, and it is difficult to argue that anthropogenic nutrient inputs are stimulating the blooms. These characteristics are important when considering mitigation and control strategies.

The economic impact of these outbreaks is significant, though difficult to estimate in total. Most of the states listed above operate shellfish monitoring programs, each of which costs $100,000-$200,000 per year. Estimates of the losses to shellfisheries and other seafood-related industries are few, but one listed the costs of a single PSP outbreak in Maine at $6 million (Shumway et al. 1988). Some estimates place the value of the quarantined surfclam resources on Georges Bank at several million dollars per year. This resource has been closed to harvest since 1989. On the west coast, the shellfish industry in Alaska, which produced 5 million pounds of product in 1917, has been greatly reduced (except for aquaculture) as a direct result of persistent product contamination of butterclams by PSP (Nevé and Reichardt 1984). There is a highly restricted recreational shellfish industry since many of the state's resources remain permanently closed due to the high costs associated with monitoring the state's vast coastline. The value of the sustainable, but presently unexploited, shellfish resource in Alaska is estimated to be $50 million per year (Nevé and Reichardt 1984). In addition to the risks of PSP from molluscs, there are PSP and domoic acid poisoning risks from consumption of Dungeness and other crabs.

BROWN TIDES

In 1985, a massive bloom of the very small microalga *Aureococcus anophagefferens* occurred in the coastal bays of Long Island, New York. Concurrent with the blooms around Long Island, blooms were recorded in Narragansett Bay (Rhode Island) and Barnegat Bay (New Jersey) (Sieburth et al. 1988, Olsen 1989). The blooms reached very high densities and were commonly referred to as "brown tide" due to the striking discoloration of the water (Cosper et al. 1990). A similar event occurred in Texas a short time after an extremely cold, windy event in December 1989. Sub-freezing temperatures coincident with low tides killed millions of finfish and benthic organisms in Laguna Madre (Buskey and Stockwell 1993). The decomposition of the dead biomass produced an order of magnitude increase of inorganic nitrogen nutrients relative to normal levels (Whitledge 1993). Consequently, high densities of the species being described as new to science as *Aureoumbra lagunensis* developed resulting in the formation of a "brown tide," which enigmatically has persisted until this day, seven years later.

Long Island Bays Experiencing Brown Tides

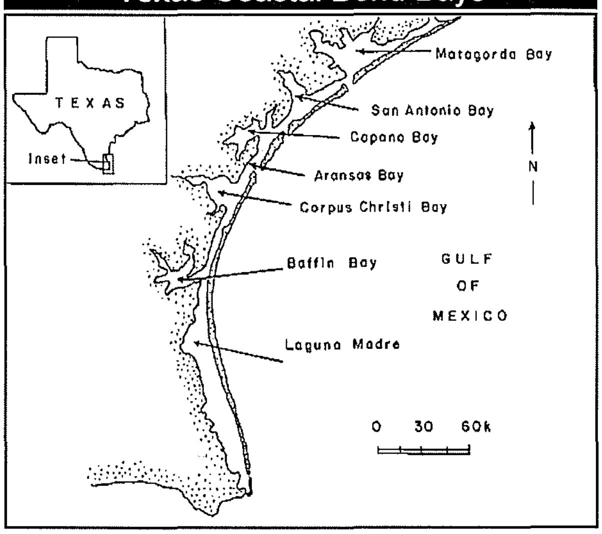


The blooms in Texas and Long Island had substantial ecological and economic effects. In both regions the dense algal blooms resulted in decreased light penetration and reductions in the extent of seagrass beds, especially in Texas where 20 percent coverage has been lost in water depths below one meter (Onuf 1996). In Long Island waters, brown tide blooms (BTBs) had a severe impact on commercially valuable bay scallops, affecting bays which contribute more than 80% of New York State's bay scallop harvest (Cosper et al. 1987). This fishery is worth an estimated $2 million per year. In addition other shellfish, including the commercially valuable hard clam, have also been affected.

The brown tide has recurred in Long Island embayments several years since 1985 and various theories exist regarding its formation, such as increased freshwater flow following drought, low oxidized nitrogen concentrations, high iron availability, capacity of *Aureococcus* for growth on organic nitrogen sources, decreased exchange with ocean water, and variations in rainfall and groundwater inputs (Nixon et al. 1994; Cosper et al. 1990). In contrast to the Long Island BTB which has an annual cycle of retreat and redevelopment, *Aureoumbra* has bloomed continually since 1989 in Texas embayments and lagoons with a limited water circulation and exchange. Restricted circulation promotes nutrient and biomass accumulation by retaining dissolved and particulate materials in the ecosystem, thereby maintaining availability of vital elements. In the presence of these regenerated nutrients, the growth rate of the BTB organism exceeds advective losses and bloom development occurs quickly and persists for long periods of time.

However, the causes of an initiation of a BTB may be different than the factors responsible for the increased prevalence of blooms. The existence of the bloom may even enhance some processes for self-perpetuation. One example of this is continual regeneration of nutrients from existing biomass. Nevertheless, the persistence of a bloom in the longer term also requires additional influx of nutrients from terrestrial or atmospheric sources. Physical mixing of the water column and resuspension of sediments are factors that must be considered as potential mechanisms of bloom persistence. There is some evidence that there may be a benthic phase or a mixing-related resuspension of cell aggregates that enhances or maintains a BTB (Stockwell et al. 1993). Aside from nutrient regeneration and mixing processes, one of the prime "maintenance" mechanisms is lack of grazing by water column and benthic populations (Buskey and Stockwell 1993). These processes control levels of phytoplankton biomass under normal conditions. Both the Long Island and the Texas brown tide organisms were found to retard zooplankton grazing in field and laboratory samples through an apparent release of inhibiting substances (Buskey and Hyatt 1995). Interestingly, micro-zooplankton grazing was reduced only when chlorophyll concentrations exceeded 10 μg/l (Buskey et al. 1996). Based on discussions during the Port Aransas meeting, other factors which could govern the persistence of BTB include decreased competition from the natural phytoplankton assemblage and lower-than-normal loss rates via sinking (e.g., via intensified mixing and resuspension) and viral infections.

Texas Coastal Bend Bays



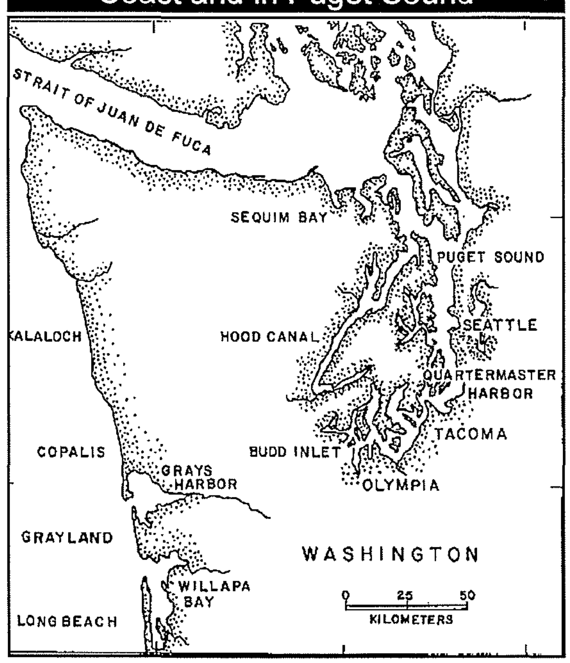
Other than reductions in the extent of seagrass beds due to reduced light levels, Texas brown tides have not been linked with obvious reductions of other living resources. Whether due to population rebound following the 1989 freeze-related mortality, the effects of reduced fishing pressure associated with conservation-related regulations, or the contributions of restocking efforts, all or any of these factors have allowed populations of highly prized game fish, such as red drum and spotted sea trout, to increase to higher levels than before the BTB (McEachron and Fuls 1996). How these species are fished has, however, also changed. As a result of the heightened turbidity of previously clear waters, lures that depend on visibility are not as effective, making fishing less attractive to sport fishers. There is some evidence that larval fish populations are reduced in areas experiencing a BTB and survival is only 15-20% of controls in laboratory and fish hatchery exposures to BTBs. Whether this is of any consequence to the stocks or whether there are delayed effects which may result in a future decline in adult populations are unknown at this point.

AMNESIC SHELLFISH POISONING

Domoic acid has been detected in finfish and shellfish resources on both the east and west coasts. This neurotoxin, produced by diatoms in the genus *Pseudo-nitzschia*, may cause permanent short-term memory loss in victims, hence the name amnesic shellfish poisoning (ASP). Another term often used for the syndrome is domoic acid poisoning (DAP) because amnesia is not always present and there have been no confirmed cases of ASP in humans in the U.S.

Toxic *Pseudo-nitzschia* species are present in the northeast and Gulf of Mexico and low levels of domoic acid have been detected in shellfish on the east coast, but not at levels that necessitate quarantine. On the west coast, however, domoic acid poisoning has been a serious problem affecting razor clams and Dungeness crabs in California, Oregon, and Washington.

HABs Occur on Washington's Pacific Coast and in Puget Sound



The west coast has two different environments to consider in terms of harmful algal bloom development. The Pacific Ocean coast is associated with upwelling events in spring and warmer, thermally stratified water in late summer and fall. On the other hand, inland waters of Puget Sound and the fjords and inlets of Alaska are enclosed areas with restricted water exchange.

Domoic acid production has been confirmed for three species of *Pseudo-nitzschia* on the west coast: *P. australis*, *P. multiseries*, and *P. pungens*. Domoic acid poisoning first became a noticeable problem in 1991 when pelicans and cormorants in Monterey Bay (California) died or suffered from unusual neurological symptoms similar to ASP. Many tons of anchovy catches were recalled or diverted following this episode. That same year, domoic acid was identified in razor clams and Dungeness crabs on the Oregon and Washington coasts. Since 1991, *Pseudo-nitzschia* spp. and domoic acid have recurred in Monterey Bay, but at relatively low cell numbers and concentrations. Blooms are common in late summer and fall when the upwelling season has ended, sea surface temperatures are warmer, thermal stratification is evident, and concentrations of inorganic nutrients are low. On the Washington coast, razor clams on some beaches continue to contain low levels of domoic acid, but the source is not known. Meanwhile a bloom of mixed *Psuedo-nitzschia* species occurred in Hood Canal (an arm of Puget Sound) in November-December 1994, resulting in toxin levels of about 10 μg/g in mussels and 14 μg/g in phytoplankton (Horner et al. 1996). Closure limits are 20 μg/g.

In western Washington, the economic impact for the 1991 domoic acid event was estimated to be between $15 and 20 million based on lost tourist visits (at $25 per digger trip); lost or delayed retail sales and lower prices of oysters that were never toxic but were avoided by confused consumers (halo effect), lost employment, bankruptcies of local businesses, potential adverse health effects (there were no confirmed illnesses due to domoic acid), and costs to the state health department for increased testing.

BLOOMS RESULTING IN WEST COAST FISH KILLS

Catastrophic losses of cultured and wild fish sometimes occur due to species of phytoplankton that do not cause illnesses in humans. Blooms of the raphidophyte flagellate *Heterosigma akashiwo* have caused kills of pen-reared salmonids in Washington in 1989 and 1990, and wild fish in 1994. Losses to the fish growers, including higher insurance rates as well as lost production, are about $4-5 million per year when blooms occur. The mechanism by which *Heterosigma* kills fish is not known, but may involve an ichthyotoxin (R.A. Cattolico, presentation to the Panel, 1996), or production of superoxide hydroxy radicals or hydrogen peroxide (Yang et al. 1995). *Heterosigma* blooms cause problems at high cell densities, usually exceeding 10^7 cells/l. Blooms often start in shallow back bays of Puget Sound and spread into the sound, carried by tides and currents. This species is a vertical migrator, usually occurring in surface waters during the day and at depth during the night. Vertical stability of the water column is probably an important factor in maintaining blooms.

Fish kills are also caused by the diatoms *Chaetoceros convolutus* and *C. concavicornis* (possibly also *C. danicus*) which do not produce a toxin, but have long setae armed with short secondary spines. Chains of cells apparently become lodged between secondary lamellae in the fish gills and cause blood hypoxia as a result of mucus production. *Chaetoceros* blooms kill at low cell densities, sometimes as low as 10^4 cells/l. These diatoms may be restricted to near-surface waters or mixed throughout the water column depending on local hydrographic conditions. Most fish growers have their own phytoplankton monitors who sample at the pen sites on a daily basis from April through September. They also rely on reports from other phytoplankton monitoring programs. Economic losses are about half a million dollars per event.

NATIONAL TRENDS

The foregoing sections highlight several of the major HAB phenomena that affect the U.S. For Florida NSP red tides there is no evidence of increased frequency of blooms, but the 1995-96 persistent bloom left the impression in many that these blooms are lasting longer and covering more area. Similarly, the recent occurrence of *G. breve* blooms in Texas, North Carolina, Louisiana, Mississippi, and Alabama where there they have historically been extremely rare or unknown raises concerns about their proliferation. Although PSP events have been experienced for hundreds of years in northeastern and northwestern Canada, these outbreaks now affect extensive areas in New England and Washington State where fewer problems existed 20 years ago. Brown tides have become persistent problems in Texas and Long Island bays, but were unknown to those regions 7 and 12 years ago, respectively. ASP has emerged as a concern on the east and west coasts, but was unknown to science before 1987.

The nature of the HAB problem has thus changed considerably over the last two decades in the United States. Where formerly a few regions were affected in scattered locations, now larger geographic areas, including most coastal states, are threatened, in many cases by more than one harmful or toxic algal species. These trends are not unique to the U.S., as a global expansion of the HAB problem over the last several decades has been suggested by several analysts (Anderson 1989; Smayda 1990; Hallegraeff 1993). Given the many different manifestations of HABs and their impacts and the increased monitoring and reporting in recent years, it is difficult to tabulate these events to document statistically an increasing trend. Most international experts would agree, however, that the number of toxic blooms, the economic losses from them, the types of resources affected, and the number of toxins and toxic species have all increased dramatically in recent years, lending credence to our general observations of trends for U.S. waters.

There are many potential reasons for the increased incidence of HABs (Anderson 1989), some of which simply reflect our improved ability to detect toxins at low levels or to network with colleagues familiar with particular toxin syndromes. Nevertheless, based on abundant evidence that the events are more numerous and more dangerous, one has to suspect that human activities may be involved via growth stimulation due to nutrient inputs; alteration of the "integrity" of coastal ecosystems through pollution, habitat destruction, and harvesting of resources; climate change; or dispersal of HAB species or strains via shipping and other materials transportation. In addition, the increased use of coastal waters for aquaculture might provide other mechanisms for the transport of harmful algal cells and their growth in new areas, but aquaculture also leads to increased monitoring to ensure that a safe product is produced.

The implications of expansion of HABs are significant, not just because of the economic costs of severe and recurrent blooms, but also because state and federal agencies responsible for protecting the public health and the viability of fisheries industries are forced to struggle with a broad array of toxins and potentially toxic resources. In addition, subtle and significant ecosystem impacts are only now beginning to be considered or recognized. These may be caused by the movement of toxins through food webs or by selective mortality of critical components of these webs. Effects on marine mammals and birds which are at the top of food chains have been observed and it is conceivable that entire year-classes of finfish and shellfish species could be impacted if toxic blooms devastate larval or juvenile populations.

If one accepts that the expansion of HABs is real, and that it has many causes, both natural and human-assisted, what can be done about them in a practical sense? What information is needed to efficiently manage the affected fisheries resources, protect public health, support aquaculture development, and contribute to policies for the protection and management of coastal environments? If human activities are making the HAB problem worse, how can that be demonstrated, and what steps should be taken to minimize further impacts? These are important practical issues, and the apparent trends in HAB incidence make them even more pressing. Management of these phenomena and other impacts are considered in subsequent sections in the context of prevention, control and mitigation. It should be clear from this brief review that there is considerable disparity in the knowledge of causes of different types of HABs. This variation in understanding has obvious implications regarding the feasibility of these management approaches.

PREVENTION

As used here, **prevention** refers to environmental management options for reducing the incidence and extent of harmful algal blooms before they begin, not controlling or mitigating them after they occur. The options are problematic both because of uncertainties about what environmental factors cause the blooms and because of the difficulties of regulating those factors. Other than actions taken to moderate the effects of society on global climate change, the potential options are limited to controls on materials flowing into the coastal region (mainly nutrients and fresh water, but potentially trace elements and toxic pollutants as well), modifications of physical conditions which might favor HABs (e.g., poor water circulation), and restrictions on activities which might result in the inadvertent transfer of harmful species into environments where they do not now occur.

ALTERATION OF NUTRIENT INPUTS

There has been a rapid increase in the loading of coastal waters of developed nations with plant nutrients, particularly nitrogen, since World War II, coincident with the growing disposal of sewage from expanding populations, increased use of chemical fertilizers and animal production in agriculture, and increased fossil fuel combustion (producing nitrous oxides which fall back on the earth). Consequently, it is tempting to attribute the apparent increase in HABs to human eutrophication (e.g., Smayda 1990); indeed there is strong evidence for this for some HABs in Europe and Japan (see papers in Smayda and Smimizu 1991). It is now well-documented that anthropogenic nutrient enrichment is responsible for increase phytoplankton production and biomass, decreased water clarity, loss of submersed aquatic vegetation due to shading, and sometimes severe oxygen depletion in many U. S. coastal waters. While this is a prime suspect for blooms that become harmful when high concentrations of algae develop, it is less likely a factor for those blooms which are harmful when cells are present at low densities (e.g., for PSP). There may be a good *prima facie* case to implicate human nutrient inputs where blooms are recent or worsening phenomena (e.g., brown tides).

Too Much of a Good Thing?

Nitrogen is a critical element for life. The availability of nitrogen controls the productivity of ecosystems and explains why coastal regions produce more harvestable resources than the open ocean. However, growing evidence is demonstrating that human activities (including the use of artificial fertilizers, planting of nitrogen-fixing crops, fossil fuel burning, and the mobilization of nitrogen stored in soils and trees) have at least doubled the global rate of nitrogen entering the land-based nitrogen cycle. Excess nitrogen is causing serious and long-term environmental consequences including increased concentrations of the greenhouse gas nitrous oxide, formation of photochemical smog, losses of mineral nutrients essential for long-term soil fertility, acidification of soils and waters, and increased transport of nitrogen by rivers into estuaries and coastal waters (Vitousek et al. in press). Riverine nitrogen fluxes in temperate zones of the North Atlantic Ocean basin have increased from pre-industrial times by 2 to 20 fold (Howarth et al. 1996). These increases result mainly from nonpoint sources, particularly agriculture and the atmospheric deposition of oxidized nitrogen from fossil fuel combustion. Algal blooms, depletion of dissolved oxygen, and loss of seagrasses are among the consequences of the resulting over-enrichment of the coastal marine environment.

The accumulation of biomass that accompanies the appearance and growth of some HABs requires that a considerable amount of vital nutrients be available. However, the types of nutrients preferred differs widely among various microalgae. Recent evidence indicates that when a certain preferred nutrient substrate, such as nitrate, is depleted from the water column HAB species are often capable of using other substrates for their nutrition (Carlsson and Granéli in press). Thus, not only the quantity of any one or two particular nutrient(s), but the relative proportions of a whole array of nutrients (quality of the total nutrient pool), may influence the development of a nuisance bloom.

For example, as one moves away (in time or space) from a new nutrient source, the mouth of a river, for example, algae typically deplete inorganic nitrogen (nitrate and ammonium) first and leave other substrates behind (Butler et al. 1979). Later in the bloom sequence, the dissolved and particulate organic matter produced from the initial uptake is often available to support subsequent blooms either directly (through dissolved organic matter uptake) or after remineralization of the organic matter to ammonium. Even in regions where total nitrogen inputs have been reduced, a change in the relative amounts of organic and inorganic nitrogen in the remaining nitrogen pool may affect bloom development. The brown tide blooms evidenced in Long Island embayments may be a prime example of this as they typically develop during summer, after the concentration of inorganic nitrogen in the water has been depleted to very low levels. This was similarly observed for Narragansett Bay (Smayda and Villareal 1989). In such instances, a more effective control program for nutrient inputs to the coastal waters could reduce the accumulation of HAB biomass and possibly the duration of the bloom conditions. Immediate effects may not be evident, however, due to the possible existence of sedimentary nutrient reservoirs.

Nutrients that may be responsible for the large biomass accumulations include various inorganic and organic forms of nitrogen, phosphorus, and other growth factors such as iron. Intensities of nutrient loadings, the proportion of the various plant nutrients, remineralization rates, and grazing pressures all potentially affect which algal species will bloom. Some of the Long Island bays presently experiencing BTBs had earlier experienced dense "green tides" (reviewed in Ryther 1990) as a result of runoff from duck farms. Although the duck farms sources have been greatly reduced, the concentrations and composition of nutrients (e.g., proportions of inorganic and organic forms of nitrogen) may now favor the proliferation of *Aureococcus* as opposed to green algae.

At present, it cannot be concluded with certainty that any of the HABs considered here would be eliminated with rigorous control of anthropogenic nutrient inputs, but it is possible that such inputs may be factors in bloom intensity and persistence for BTB, *Heterosigma*, and *Gymnodinium breve* blooms. Nutrient management strategies may be particularly useful in preventing some HABs in estuaries and embayments that have restricted water circulation. Nutrient reduction strategies are being pursued in many of these more enclosed water bodies for reasons other than HAB prevention. Notable among these are the Comprehensive Conservation and Management Plans (CCMPs) developed under the National Estuary Program (NEP) for many of the nation's estuaries, including the HAB-affected Peconic Bay, Albemarle-Pamlico Sound, Tampa Bay, Sarasota Bay, Charlotte Harbor, Corpus Christi Bay/Laguna Madre and Puget Sound. Although implementation of these plans is often lagging—particularly with regard to nitrogen which is difficult to control because of its multiple sources, high solubility, and growing atmospheric inputs—considerable progress has already been made in reducing point-source loadings of nutrients in such estuaries as Tampa Bay and

Sarasota Bay (Sarasota Bay National Estuary Program 1995), where water clarity and the conditions for growth of seagrasses have improved.

Point and non-point source reductions of nutrient inputs into coastal waters should be rigorously pursued as a key element of estuarine and coastal management where restricted flushing of the receiving waters or sheer magnitude of the loadings suggest that there are negative impacts of eutrophication. The potential benefits of reductions of nutrient loadings in terms of decreased frequency and severity of HABs should be made a more explicit consideration in relevant estuarine and coastal management programs, such as those in the National Estuary Program.

REGULATING FRESHWATER FLOWS

Flows of fresh water into many coastal ecosystems are subject to human alteration through water use and diversion and modifications of the watershed, e.g. deforestation, impoundments and stream channelization. Flows are, to a certain degree, subject to human control and regulation. Can, then, freshwater flows be managed in such a way as to reduce the frequency, extent, and severity of HABs?

Regulation of freshwater inflows might be an important consideration only with the Gulf of Mexico red tide organism, *G. breve*. Although *G. breve* tolerates a wide salinity range, it seems only to proliferate in consequential blooms at salinities above 24 ‰. Resource managers in Florida are concerned that projected reductions in freshwater flow into Gulf Coast estuaries, as a result of growing demand for potable water, may result in increased salinities and deeper intrusion of red tides into these estuaries. Incursion of *G. breve* blooms into Texas bays and unusual blooms along the Mississippi and southeastern Louisiana coasts in the fall of 1996 also seemed to be associated with higher than normal salinities. These observations suggest that managing inflows of fresh water, when available, may prevent encroachment of red tide into estuaries. However, it must be kept in mind that nutrients, which may stimulate blooms, are also delivered with fresh water.

It should also be pointed out that *Heterosigma* blooms in Puget Sound and *Alexandrium* blooms in the southwest Gulf of Maine seem to occur when freshwater influx increases (in the latter case in combination with onshore winds). In contrast to the shallow estuaries of the Gulf Coast, however, management of freshwater flows to prevent such blooms is not a feasible management action.

Limiting the intrusion of red tide into Gulf Coast estuaries by maintenance of reduced salinity conditions should be an expressed consideration in freshwater flow allocation and estuarine management.

MODIFICATION OF WATER CIRCULATION

For some HABs in relatively confined coastal waters, there is concern that restricted water exchange may allow blooms to persist. For example, the Texas bays and lagoons plagued by brown tide have poor water circulation and exchange as a result of the small astronomic tidal range and restrictions by occluded passes, tidal flats and causeways. Consequently, the residence time of water in parts of the Laguna Madre is about one year. For these reasons, some environmental and fishing advocates have suggested that brown tides could be reduced or eliminated by increasing circulation through the removal of currently in-place causeways and replacing them with high-rise bridges. Another suggestion was to open passes through the long, uninterrupted stretch of Padre Island to increase direct exchange between Laguna Madre and the Gulf of Mexico. It is not clear that such passes would have the desired effect, either on sufficiently reduced residence time or on the blooms themselves. Cells could still be present in the smaller bays off Baffin Bay where the bloom seems to be reinitiated periodically. Increased circulation could move the cells to new areas. Furthermore, there may be other undesirable and possibly unpredictable consequences (e.g., increasing storm surge) of opening new passes. There would also be considerable engineering challenges, not to mention costs, in keeping these passes open and providing required infrastructure. Similar re-engineering of coastal hydrodynamics has also been a topic for discussion for Long Island estuaries, although they are better flushed than the Laguna Madre.

Major modifications of water circulation for preventing HABs are not presently justified by available knowledge, but the effects of water exchange on HABs should be an expressed consideration in managing features such as inlets, channels and causeways which affect circulation.

RESTRICTING INTRODUCTIONS

Ballast Water

Introductions of organisms from one region to another via ships' ballast waters have had significant impacts on coastal ecosystems. In some cases, nonindigenous species have become established which, because of a lack of predators or competitors, dramatically proliferated in the new environment. Most of the species for which ballast-water introduction has been documented are marine invertebrates (NRC 1996), although evidence has been presented that toxic dinoflagellates have been introduced into Australian waters via ballast water (Hallegraeff 1991) and genetic tracers suggest that there have been transfers among strains of some HAB species between widely separated parts of the

"Stemming the Tide"

In its recent report of this title, the National Research Council (1996) assessed potential control strategies for reducing the risk of introductions of nonindigenous species by ship's ballast water. Changing ballast at sea is currently the favored technique, but is limited by vessel safety considerations and the lack of ability to remove all ballast and associated biota. Development of shipboard treatment is recommended, with the most promising techniques (based on safety, effectiveness and operational feasibility) being fine screening and application of low concentrations of biocides.

world (Scholin and Anderson 1993). These genetic methods are, however, unable to indicate whether this dispersal occurred in the very recent past (i.e. within the last 50 years) or several million years ago. HAB species are more likely to survive ballast-water transport if they form cysts and reside in ballast tank sediments. Kelly (1993) incubated a variety of planktonic algae from ballast sediments collected from ships entering ports in the state of Washington, but none of these was a known HAB species. There is yet no evidence that any of the HAB species considered here has been introduced via ballast water into areas where they now cause problems, but two issues should be kept in mind. First, the behavior of many HABs suggests that seeding of areas where blooms have not occurred or re-seeding where blooms have died out is important. This suggests that even short-distance transport of cysts or planktonic organisms themselves could stimulate blooms. Second, even though the nominal species may be indigenous, the introduction of new genetic strains of the organism that prosper better in the receiving environment or are better able to escape pathogen control than the indigenous populations could also lead to blooms.

More attention should be directed to evaluating the role of ballast water transfers as a mechanism for inoculating areas with HAB species. Particular attention should be directed to the transfer of spores and cysts in ballast tank sediments. Where significant risk is demonstrated, appropriate control strategies should be required as suggested by the National Research Council (1996). Some of the strategies recommended by the NRC, e.g., fine screening, may not be as effective for organisms less than 50 μm in size as for larger invertebrates.

Except where the potential for introduction of HAB species is extremely low, engineering or operational strategies developed to reduce ballast-water introductions of invertebrates should be designed to ensure the destruction or elimination of HAB species and their cysts.

Shellfish and Finfish Transfers

There is a potential for introducing HABs into waters in which the algal species or specific strain is not resident when shellfish and finfish (including eggs and fry) are transported from site to site during normal stocking procedures. No specific cases of introduction of HAB species in contaminated shellfish seed (small bivalves transplanted for grow-out) have yet been documented. Although it is possible that algal species could survive ingestion by the bivalve, introduction via shellfish seed is improbable given the conditions of transfer. On the other hand, transfer of stock with large volumes of sediment, seaweed, or detrital material attached to shells is more likely to result in algal transfers as well. Precautions should be taken when transporting shellfish from a bloom-prone region to one which is not, particularly if substantial sediment is included and the alga of concern forms cysts.

State agencies should carefully consider and appropriately regulate the risks of inter- and intra-state transfer of HAB species via shellfish seeding and transfer operations. Where such risks exist, it is prudent to prohibit such transfers or require an intermediate transfer step whereby shellfish can be 'depurated' or washed prior to introduction into the receiving environment.

Alexandrium cysts
D. Anderson photo

Dredging

One mechanism for HAB dispersal or proliferation is through dredging and disposal of marine sediments containing resting stages of HAB species. Large numbers of cysts or spores are often found in bottom sediments of areas subject to HABs, maintained in a resting state either because of internal (e.g. maturation) or external (e.g. low temperature, low light, anoxia) inhibition of germination (Anderson et al. 1987). Dredging or other activities that displace sediments can thus disperse a harmful species to new areas or initiate a bloom near the dredge site. Dispersal can occur through the transport of dredged material by barge or by the resuspension of sediments by dredging activities and subsequent dispersal by currents. Bloom initiation can result when cysts are exposed to favorable environmental conditions during dredging or spoil disposal. For example, in many areas, 90% or more of the cysts of toxic *Alexandrium* species are buried below the sediment surface, typically in anoxic sediments (Anderson et al. 1982). Since cyst germination requires oxygen, most of these buried cysts will remain dormant and never germinate unless they are resuspended, as might occur during a dredging operation. A bloom might then occur at or near the dredge site, or in distant waters where the spoil is dumped. Dredging during certain seasons will be less likely to result in cyst germination than at other times, and care with sediment resuspension and transport can minimize dispersal. At present, there are no federal regulations in this regard, although the Army Corps of Engineers requires testing for a host of other chemical and biological parameters prior to approval of a dredging permit.

State and federal agencies must take HAB cysts into account when regulating coastal zone activities such as dredging or dredge spoil disposal. Effective policy decisions on these issues will require current information on the regional distribution and abundance of HAB cysts and a knowledge of the physiological and environmental controls on cyst germination in that region. Surveys for cysts may be required prior to issuance of permits.

CONTROLS

Efforts to control insects, diseases, and fungi are common agricultural practices on land, but similar attempts to control unwanted plants or animals in the ocean are rare or more limited in scope. The significant impacts of HABs on public health, the economy, and ecosystems provide rationale for considering similar controls, but research on this topic has been extremely limited, especially in the United States, presumably because of over-riding concerns about environmental impacts, costs, and effectiveness. Forty years ago, attempts were made to control the Florida red tide dinoflagellate *Gymnodinium breve* through the large-scale application of copper sulfate to 16 square miles of ocean using crop-dusting aircraft (Rounsefell and Evans 1958). Copper sulfate is commonly used to control freshwater algae in lakes and reservoirs. The results of that aerial treatment were initially effective, but several of the treated areas developed new red tides several weeks later. The conclusion reached at the time was that the use of copper sulfate for bloom control should only be considered in local situations to give short-term, temporary relief from blooms. Since that time, HAB control has not been seriously considered in the United States, although other countries—notably Japan and China which farm the ocean heavily—have invested in research on the topic. Control of HABs remains largely untested on major blooms, however, as field applications have been restricted to shallow ponds used for shrimp and fish mariculture or on waters in the immediate vicinity of fish cages.

General approaches to direct control include: 1) chemicals that kill or disrupt red tide cells during blooms; 2) clays or other materials that flocculate algal cells and other particles in the water column into larger particle aggregations, which thereby sink more rapidly to the ocean floor; and 3) biological agents such as zooplankton grazers or lethal pathogens such as viruses, bacteria, or parasites.

CHEMICAL CONTROL

Attempts to use chemicals to control directly HAB algal cells in blooms encounter many logistical problems and environmental objections. The use of copper sulfate in the 1957 Florida red tide control effort (Rounsefell and Evans 1958) highlights several of these problems, the most significant being that the chemicals are likely to be non-specific and thus will kill co-occurring algae and other organisms indiscriminately. Efforts to find a "magic chemical bullet" that will somehow kill only a specific, targeted HAB species may be futile, as it is difficult to imagine a unique physiological target for a chemical that is characteristic only of one phytoplankton species. For example, about 35 years ago the Bureau of Commercial Fisheries conducted a major program to screen chemicals that could be used for controlling Florida red tides. Approximately 4,700 compounds, predominantly organic in nature, were evaluated (Marvin 1964). Of these, only 6 were found to be suitably potent against *G. breve* without causing excessive mortality of other marine organisms. Unfortunately, when these six were re-tested against *G. breve* using natural seawater culture medium, cell mortality proved to be low and variable, possibly because natural seawater contains chemicals inhibiting the effectiveness of the toxicants tested. More testing was planned, but the lack of subsequent published data suggests that this program was terminated before further tests could be conducted. The failure of this program to identify a promising chemical does not mean that such chemicals do not exist, but rather that the process of finding one is long and laborious.

Chemical control of blooms is thus an area where some careful research is needed. Even if a chemical with ideal properties is found, environmental objections to its application are likely to be significant. Each candidate chemical will require extensive testing for lethality, specificity, persistence, and general safety, and each must meet regulatory concerns, such as those imposed on industrial discharges, regarding acute and longer-terms effects in coastal environments. Although direct chemical control of HABs may not be a strategy of choice given other more benign alternatives, the success of this approach in terrestrial systems (e.g. application of herbicides and pesticides) suggests that it should not be completely ruled out, in discrete applications where collateral effects are minor or confined.

While it is not prudent to invest in a major search for chemical compounds that might destroy HAB cells, a small-scale effort could be justified concentrating on chemicals and application procedures that are already accepted for use in the control of aquatic weeds and pests such as the water hyacinth or Eurasian milfoil. Furthermore, before significant effort is expended to evaluate chemical control strategies, risks to other resources must be evaluated and the receptivity of federal and state agencies and the general public to this approach assessed on a regional basis. In addition, the persistence and effects on co-occurring organisms of toxins released by chemicals which disrupt algal cells should be evaluated.

FLOCCULANTS

A flocculant is a material that, when added to water, scavenges co-occurring particles as it falls to the sediments below. Inorganic flocculants (e.g., aluminum sulfate or various ferric salts) are commonly used to purify fresh water in reservoirs. Macromolecular flocculants are synthetic molecules that collect particles by means of a process called bridge formation. Huge polymer molecules are very effective in this regard, the most common being polyacrylamide (Shirota 1989).

One non-chemical flocculant that shows considerable potential is clay. The natural water-clearing properties of clays are evident during and immediately after storms when the seawater near the mouth of rivers becomes turbid from clay minerals eroded from land. This turbidity decreases dramatically several days later and the seawater can become very clear. This is a result of flocculation. The clay particles adsorb inorganic and organic materials, algae, and other particles to form a "floc" which continues to grow in size as it accumulates particles, and eventually falls to the bottom sediments.

Japanese (reviewed in Shirota 1989) and Chinese (Yu et al. 1994 a,b,c) researchers have studied the theory behind clay as a flocculant in seawater, and both groups have tested a variety of natural and treated clays on HAB species in culture. Depending on the treatment used, removal of

95-99% of the targeted cells in cultures has been accomplished following additions of clay. In field trials, the Japanese have used clay to treat natural HAB blooms on several occasions. On a small scale, clay was dispersed in the vicinity of culture cages where fish were dying during a *Cochlodinium* red tide (Shirota 1989). This was deemed very effective by the fishermen, as virtually no fish mortality was observed and the bloom was eliminated. Japanese workers also looked into application of the clay from aircraft as a strategy for large-scale bloom treatment and concluded that airborne dispersal of clay is feasible, but expensive (Shirota 1989). Chinese workers are now applying clay flocculation methods to the treatment of unwanted algae in shallow mariculture ponds (Yu et al. 1994 a,b,c), but it is not yet known whether costs are low enough and removal efficiencies high enough for use in more open coastal waters.

The principal environmental concern about the use of clay as a flocculent relates to the effect of sedimented particles on bottom-dwelling (benthic) organisms. Filter-feeding benthic organisms, for example, are known to stop filtering when suspended sediment concentrations are elevated. However, benthic organisms inhabiting sediments, as opposed to rock or reef substrates, are generally well-adapted to survive the deposition of fine sediments provided it is not overwhelming. Another concern is that clay treatment might deposit so much algal biomass that oxygen depletion becomes a problem in bottom waters. Furthermore, no studies have been conducted on the possible impacts of flocculation and sedimentation of toxin-containing organisms, either in the release of their toxins or in possible encystment in bottom sediments. If clay is to be seriously considered as a bloom control strategy, an area for future study is clearly the fate and effects of sedimented toxins, as well as the effects of the clays themselves on benthic organisms

Possible Effects of Clay Sedimentation

Evidence that clay/organic aggregates falling down on organisms inhabiting bottom sediments are not detrimental is found in the studies of Portmann (1970) and Howell and Shelton (1970) who investigated the effects of clay from pottery operations on the bottom fauna of two bays near Plymouth, U.K. As a result of the area's pottery industry, China clay was distributed over 48 square kilometers, accumulating in bottom sediments at the very high loading of 188 kg per square meter. Fish and benthic organisms were abundant in the area, however, and many seemed to thrive with the clay substrate. Shirota (1989) reports that clay/organic floc is an excellent food source for sea cucumbers, so it is likely that some benthic animals would benefit from the nutrition in the material carried to the bottom with the clay.

The application of clays to flocculate and thereby remove cells of HAB algae from the water column may constitute a relatively benign control strategy under feasible circumstances. Rates of removal of cells due to clay flocculation, degree of release of toxins from flocculated cells, physical and toxic effects on benthic organisms, and the consequences of organic loading from sedimented blooms on near-bottom oxygen conditions will require further evaluation.

BIOLOGICAL CONTROL

A variety of organisms could conceivably be used to control HABs, but in reality, biological controls have many logistical problems and are far from operational. Introduction of non-indigenous species or strains pose unknown risks and may be irreversible. Biological control is used extensively in agriculture, such as in the release of sterile male insects or the use of pheromones to control insect pests (Hokkanen and Lynch 1995), but there are concerns about the concept of releasing one organism to control another. Such concerns are likely to be greatly magnified in the marine environment, because there is little precedent 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 acceptable (e.g., sterile male releases for control of the Mediterranean fruit fly). Biological controls of marine HABs could be via predators (animals which graze on planktonic algae), parasites, or microbial pathogens.

Zooplankton

One obvious group of organisms to consider as biological control agents is the small animals (zooplankton) which co-occur with algae and eat them as food. In nature, zooplankton grazing may be an important factor limiting the growth of algal populations and thus preventing blooms. Martin et al. (1973) suggested that marine ciliates could be cultured and used for control of *G. breve* cells. Likewise, Shirota (1989) indicated that the Japanese considered the use of zooplankton such as the copepod *Acartia clausi* in controlling HABs. However, both Shirota (1989) and Steidinger (1983) provide calculations that illustrate the logistical impracticality involved in growing zooplankton predators in the laboratory in sufficient quantity to control blooms. Both authors arrive at estimates that are unrealistic with respect to cost, space, and facilities. Grazing control for the Texas brown tide is being evaluated for isolated embayments and lagoons (Buskey et al. 1996) where the volume to be treated may not be as prohibitive. But here too the density of grazers required is probably not achievable. While zooplankton grazing may be a factor that normally keeps blooms in check, the suggestion that zooplankton can be added or stimulated in order to control blooms once they occur is problematic because of the more rapid growth of populations of microalgae than those of their animal grazers.

Viruses

Viruses have the potential to be highly specific and effective control agents. They are abundant in coastal seawater and have recently been recognized as having significant effects on the dynamics of phytoplankton blooms. In Norway, the collapse of a bloom of the coccolithophorid *Emiliania huxleyi* occurred simultaneously with the appearance of many viruses in the surrounding water and inside the algal cells (Bratbak et al. 1993). Similarly, Nagasaki et al. (1994 a,b) linked the collapse of a *Heterosigma* bloom to the appearance of virus particles within the cells. Viruses have also been observed inside many cells during brown tides on Long Island (Sieburth et al. 1988; Milligan and Cosper 1994) and there is some indication that a virus may have affected the Texas brown tide in a portion of Corpus Christi Bay (D. Stockwell, personal communication).

On a theoretical level, there are a number of features which make viruses attractive as biological control agents (Suttle 1995). First, viruses replicate rapidly, releasing hundreds of viral particles when a host cell is disrupted. During a HAB, the rate of viral propagation would potentially be accelerated because infection depends upon the frequency with which the virus encounters host cells. 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—the ultimate "magic bullet". In reality, however, viruses are sometimes so host-specific that they are unable to infect different genetic strains of the same host species. A bloom population of an algal species in nature is often a mixture of different genetic strains of that species. This is perhaps the reason many viruses co-exist with their host species, rather than destroying them. Because one can expect a co-existence to have developed between viruses and HAB species over time, viral control of an established bloom will likely require the introduction of a virus or viruses which are isolated from a location or time where the bloom is not present (perhaps even from other parts of the world). Whether such viruses exist is a primary question, and whether they could be used effectively in control remains unknown as well.

Another limitation is that environmental regulations concerning the release of a viral pathogen might be highly restrictive, given the uncertainties involved. The ability of some viruses (e.g. HIV) to switch hosts would support concerns that a control strategy might have unexpected consequences within the community of planktonic organisms. Some effort should be devoted to further exploration of this avenue of biological control, but the probable limitations of this strategy should be recognized as well.

Parasites

There are a variety of different parasite species which can infect marine organisms, including algae. For example, the dinoflagellate *Amoebophrya ceratii* is a well known intracellular parasite of other, free-living dinoflagellates (Nishitani et al. 1984). The highly virulent nature of parasite infection of dinoflagellates has led to the suggestion that these might be effective in controlling HAB populations (Taylor, 1968).

A key issue with respect to biological control is that of host specificity, as the technique would be ideal if an introduced parasite would only attack the targeted HAB organism and then die-off after the demise of the bloom. This is, however, an area where little is known with respect to HAB species. Resolution of these specificity issues is needed, although an argument can be made that absolute host specificity should not be a requirement. In agriculture or in pest management (e.g., mosquitoes), biological and chemical control agents are seldom species-specific and in many cases have been employed without unacceptable side effects.

Bacteria

New work by Japanese scientists suggests that bacteria could play an important role in controlling HABs. An intriguing example is the *Gymnodinum mikimotoi*-killing bacterium described by Ishida (in press). A bacterial strain isolated at the end of a *G. mikimotoi* bloom exhibits strong and very specific algicidal activity against this dinoflagellate species. Cultures of *G. mikimotoi* are completely destroyed within 24-38 hours of the time the bacterium is introduced to a culture. A second example of a potentially specific bacterial-algal relationship was reported by Furuki and Kobayashi (1990) who found that a *Cytophaga* species (bacterium) isolated from the declining phase of a *Chattonella* (alga) bloom was lethal to that alga and could be cultivated in sea water only when that sea water was spiked with disrupted cells of *Chattonella*. As in many other areas involving biological control of HABs, the status of studies on bacteria thus far has been confined to basic scientific investigations of the nature of the interaction. No practical efforts have yet been attempted to use bacteria to control HABs.

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 must be made to understand the dynamics of infection and replication. The environmental impacts of the release of non-indigenous organisms need to be carefully considered before biological controls can be used in practice.

OPTIONS FOR CONTROL

The concept of HAB control is a scientifically challenging and politically charged topic that has not received serious attention from the scientific community in the United States. Each of the strategies described above has potential benefits and disadvantages, but all require significant research and risk assessment before they can be applied on a larger scale to control naturally occurring algal blooms. In theory, they can be applied to an established bloom for short-term, temporary control, or at specific places and times in the early stages of bloom development in an attempt to reduce the size of the seed or inoculum populations. The latter strategy is especially appealing if a discrete initiation zone actually can be identified for a HAB, in which treatment might result in long-term reduction in bloom size or frequency.

With both the Long Island and Texas brown tides it may be possible to define such initiation zones. In Texas, the Baffin Bay system appears to be a location where blooms are sustained from year to year, with adjacent waters being more sporadic with respect to biomass development. Around Long Island, areas such as Flanders Bay in the Peconic Bays are often the first to show signs of the brown tide, with adjacent waters blooming in subsequent weeks. In Florida, *G. breve* blooms seem to have an offshore initiation zone (Steidinger 1983; Tester and Steidinger in press), although it may be large. In the Gulf of Maine, the Casco Bay area is thought to be a source region for blooms of *Alexandrium tamarense* that affect several hundred miles of coastline (Franks and Anderson 1992). Where the times and places of bloom initiation can be discretely defined, control efforts applied then and there could cover a small area but potentially have a significant impact on bloom magnitude and spatial extent.

Furthermore, since neither the Texas nor the Long Island brown tide organisms nor *G. breve* have been shown to have a dormant, benthic stage in their life histories, these species appear to rely on the persistence of sparse populations of cells in the water column for the "seed" population that initiates future blooms. Reduction in the size of a bloom in one year through control efforts in an initiation zone might thus reduce the geographic extent of a bloom that year, and reduce the size of future blooms as well.

In some situations, it may be worthwhile to consider controlling an established bloom as it threatens nearshore fisheries or coastal aesthetics, rather than focusing on source populations. For example, should control measures along the west coast of Florida be considered at times when the red tide is established in nearshore waters, even though it is likely that the problem is more widespread and will likely recur? Short-term relief from dead fish, toxic shellfish, and airborne aerosols might be desirable to citizens, tourists, and local businesses, even if winds and currents bring another bloom to those waters a few weeks later. Clearly, policy decisions of this type require a thorough understanding of bloom transport and growth dynamics, and of the cost, effectiveness, and environmental impacts of control strategies.

An obvious question central to the Panel's deliberations is whether HABs can and should be controlled. The first issue, that of feasibility, can only be addressed through detailed laboratory, mesocosm, and field studies using the most promising of the approaches listed above. The more important question is whether control should even be attempted—whether the benefits outweigh the potential impacts. One argument is that any discussion of controls is premature because there is insufficient knowledge of the physiology, oceanography, and bloom dynamics of HAB species on which to base control strategies. We cannot control what we do not understand. In addition, there is the concern that human efforts to control these natural phenomena may have undesirable consequences. Steidinger (1983) argued that Florida red tide control, even if it were feasible, should be carefully considered before it is pursued because the red tides and associated fish kills may have an ecological function similar to fires or other perturbations in terrestrial ecosystems, which help to maintain biological diversity and productivity. Conversely, it can be argued that human activities may be stimulating HABs in the first case, thus remedial intervention may be justified. In any case, the high likelihood that any attempt to control a HAB will have consequences to other organisms requires a precautionary approach to application of chemical, physical or biological controls.

It is easy to understand why individuals who are economically or personally affected by HABs would strongly advocate control strategies. However, the drive to control HAB phenomena must demonstrate that the problems are severe, long-lasting, and worth the cost and potential environmental impacts of the control strategy. Even then, it must be recognized that there are presently no proven control techniques and that bloom dynamics and environmental conditions may limit or exclude the application of effective controls. Certain types of HABs seem the most amenable to control—such as those in isolated embayments or those which totally dominate planktonic ecosystems so that few co-occurring species will be impacted by the treatment. Likewise, blooms for which discrete initiation zones can be identified seem appropriate for consideration in this regard. Concerns and reservations about controls increase when blooms produce toxins which might be released during treatment or when blooms are widespread.

A START?

The severe impacts of the protracted 1995-96 red tide along the Florida Gulf Coast on coastal residents and businesses led concerned citizens to establish Solutions to Avoid Red Tide (START). Perhaps the first grass-roots organization formed specifically to address HABs, START is "dedicated to funding and promoting efforts to control and manage toxic red tide, keeping it from area waters and beaches" and has expressed concern that little effort is being expended on research on possible solutions. START's activities have heightened attention to prevention and control strategies by managers, scientists, and the public.

It is premature to conclude whether HAB control strategies are feasible, applicable or advisable, because the knowledge base and experience are not sufficient to provide the information needed to judge effectiveness and weigh benefits against costs. Research on potentially feasible control methodologies should thus be pursued, concurrent with field and laboratory studies to better understand the ecological mechanisms underlying HABs.

MITIGATION

Under **mitigation** we consider the steps that can be taken to reduce the losses of resources and economic values and to minimize human health risks that occur as a result of blooms that are otherwise not prevented or controlled. These include better monitoring and surveillance to reduce the risk of ingestion or exposure to toxins, improved forecasting to allow more time to protect resources and avoid risks, restoration of affected resources, and a variety of alternative actions to minimize effects which might occur. Because prevention and controls are unlikely to provide much relief from HABs in the near term, special attention should be given to more immediate improvements in mitigation of their effects.

MONITORING AND SURVEILLANCE

Coastal states that experience toxic phytoplankton blooms are mandated under the National Shellfish Sanitation Program of the Interstate Shellfish Sanitation Commission (ISSC) to have shellfish monitoring programs designed to protect public health. While these programs have proven highly effective, they are not meant to address the biology of the causative organisms and their bloom dynamics. In recent years not only has there been an extension in the range of known HAB species, but previously unknown toxic species have emerged as well. Further, increased pressure on shellfish resources by non-traditional user groups (such as immigrants who harvest previously unutilized seafood species which are not monitored for HAB toxicity) coupled with increased demand for underutilized species has put severe pressures on monitoring programs already facing extreme financial and personnel limitations.

Difficulties in sample collection, transport and testing of shellfish are compounded in many areas by the lack of staff, especially in regions with extensive coasts or remote regions. Some regions have been successful in developing a volunteer network to help collect samples. Even with such assistance most state programs lack adequate funding for increased sample analyses.

Monitoring of offshore waters poses an extreme situation. Collection of samples from Georges Bank, for example, is complicated by the great distance from the shore, large area, and the fact that these are federally controlled waters. Dockside monitoring of offshore shellfish catch has been suggested, but appears infeasible. The

Thin Line of Protection

Representatives of the Washington Department of Health and the California Department of Health Services spoke to the Panel about the difficulties of maintaining adequate surveillance while the variety of HAB threats was increasing at the same time that financial and human resources devoted to monitoring programs were static or declining. The numbers of samples collected in California has greatly increased through use of volunteers, but this has stressed the fixed resources available for laboratory analysis. Consequently, there is a great need for more rapid, automated analysis. In Washington, an outbreak of domoic acid in razor clams along the ocean coast was fortuitously detected because curious field agents decided to collect a few unscheduled samples. The fishery was closed on an emergency basis two weeks into the season and exposure of large numbers of people to the toxin was narrowly averted. Because of budget pressures experienced by state agencies throughout the country, there is widespread concern among those charged with protecting public health from HABs that the line of protection of public health is becoming alarmingly thin.

shellfish involved (usually surfclams and mahogany quahogs) have a short shelf life and this, coupled with the potential problem of disposal of tons of toxic shellfish, make dockside testing after harvest an unreasonable alternative to regular monitoring. A further complication is the individual variability of toxicity in these shellfish. Samples have been collected with individual toxicity ranging from non-detectable to over 2,000 μg saxitoxin-equivalents/100 g of tissue. Further complicating monitoring is the species-specific and tissue-specific binding and elimination of toxins. Other regions with offshore blooms present similar difficulties.

Phytoplankton monitoring has been proposed as an early warning system in several areas. For example, a program of citizen collection of phytoplankton samples from piers has been developed in California (G. Langlois, presentation to the Panel, 1996) and is now being implemented in New England. While this may provide a good indicator assessment for fish farms in the Pacific Northwest and *G. breve* in the Gulf of Mexico, it should be pointed out that it has not been possible to correlate the presence or abundance of the causative organism with outbreaks of PSP toxicity during the past forty-plus years in Maine (Shumway et al. 1988). In Alaska, Hall (1982) found that this may reflect inadequate sampling frequency rather than inadequacy of the general approach. In spite of these limitations, Canadian shellfish growers recently argued for the maintenance of some type of phytoplankton monitoring program, noting that it serves as an early warning system to allow them to identify toxin-free periods for harvesting and marketing product (Bates and Keizer 1996). Implementing a volunteer patrol (coastal and beach) to observe and map discolored water or dead fish has been suggested as an early warning system for the eastern Gulf of Mexico. This would help meet the need for accurate, up-to-date information requested by local businesses and the general public.

There is a chorus from the management and private sectors to produce a rapid, reliable, inexpensive (<$5.00 ea) "dip-stick" test for the various HAB toxins, although these sectors may fail to realize that the largest cost of toxicity monitoring will remain sample acquisition and processing rather than the analysis itself. Obviously, "dip-stick" tests will need to be sensitive and specific. There are test kits under development for at least five toxin groups, yet none is currently reliable for management purposes. Fast through-put, laboratory-based monitoring awaits the development and approval of receptor-based assays or ELISA tests using toxin antibodies. Future possibilities for monitoring include the use of *in situ* sensors, species-specific probes, and, for some HABs, air-borne optical instrumentation.

Research and development agencies should support development of "dip stick" tests for phycotoxins and assist the ISSC and Food and Drug Administration to speed their testing and approval for routine use in HAB risk management. Further development of phytoplankton monitoring approaches should also be pursued, to help focus monitoring of toxins or toxicity levels.

FORECASTING

Effective forecasting of the occurrence, intensity and distribution of HABs depends on understanding the interplay of underlying physical and biological processes. The ECOHAB (Ecology and Oceanography of Harmful Algal Blooms) program to be implemented by federal science agencies offers the prospect of developing the understanding of key processes, emphasizing the development of predictive models and forecasts. Ideally, information on the life cycle requirements, cell physiology and behavior of the HAB species in a region should be available to develop a conceptual model of bloom dynamics. That knowledge, coupled with local meteorological and circulation models (even first order empirical, statistical models) could help identify conditions both necessary and sufficient for bloom initiation. Pertinent field conditions most easily measured by automated *in situ* devices, sensors on moorings and remotely operated vehicles (ROVs), remote sensing (sea surface temperature, ocean color), and air-borne spectral radiometers hold promise for detecting or tracking spatially explicit bloom phases for some species. However, some algae produce harmful effects at fairly low cell densities or occur at depth in the water column and would escape such detection. Some HABs result in discolored water patches that can be visually observed by overflights in such areas as the Texas and Long Island bays and Puget Sound, and by satellite in open shelf areas in the Gulf of Mexico and the U.S. South Atlantic Bight. These patches can be tracked, correlated with local wind and current conditions, and mapped. Coupled with forecast models, these satellite, aircraft of in-situ observations can be used to re-initialize or correct models to yield more accurate near real-time predictions.

> **The development of forecast models integrated with near-real time sensing systems should be pursued as an important goal of research programs on the ecology of HABs.**

ACTION ALTERNATIVES

Accurate Information and Public Education

Public confusion concerning algal bloom has in the past resulted in over-reaction, causing harm to fishery or tourism industries that had little or no relationship to a particular bloom. Conversely, a cavalier or too lax attitude in come cases could result in illnesses, or even deaths. Not all HABs pose similar health risks. Public health officials and health care providers need accurate and up-to-date information. The public also requires responsible reports to guide their consumer and recreational choices. Any HAB mitigation strategy should include an educational component for researchers, resource managers, public health officials, health care providers and user groups. Providing relevant information on the potential causes and effects of HABs to the medical community as well as the general public should act to reduce the level of anxiety, promote realistic expectations and allow individuals to develop their own contingency plans. Timely dissemination of accurate information to the press by managers and scientists should be a priority. The press, in turn, should accept the obligation of reporting this information promptly and factually, avoiding sensationalism.

Aquaculture and Fishery Harvesting

Efforts to mitigate the impacts of HABs on shellfish and finfish farms are both difficult and complicated. One of the few opportunities available for mitigation for shellfish growers during

HABs is short-term filtration of water to hatcheries, but this is not a practical solution in the long-term. Moving shellfish crops to another area is usually not possible and, if the shellfish are already contaminated with harmful cells, e.g. *Alexandrium*, moving them may contaminate the other area. Floating net-pens used to raise fish, however, can be moved from affected areas to uncontaminated waters, but this often entails regulatory approval or permitting, logistically challenging movement of the pens and the fish in them, and the assumption that clean water will be available at the new site. Such movements are costly, dangerous and labor intensive. Fish growers usually stop feeding their fish at the first sign of a bloom in order to reduce fish activity and metabolism, but this is also costly in terms of reduced growth of the fish. Fish farms sometimes are able to pump harmful algae-free water from depth into their pens, but this assumes that the farm has the necessary pumping equipment and the bloom remains in the surface water. This is not always the case, e.g., *Heterosigma* is a vertical migrator and *Chaetoceros* can often occur throughout a 50-m, well-mixed water column.

Both finfish and shellfish farmers from all geographic regions of the U.S. have repeatedly expressed a need for more advanced warning from regulatory agencies when blooms occur. For example, determination of the most likely bloom areas in Long Island bays provides valuable information for shellfish reseeding operations. Finfish farmers in the Pacific Northwest also would benefit from an expedited permitting processes for relocating their stocks when HABs occur.

Some shellfish hatcheries have added potassium permanganate or copper sulfate to the water (both algicides) to kill blooms. Ozonation is also being investigated for "depuration" of shellfish contaminated with brevetoxin. Although ozonation has some promising applications, its widespread effectiveness and reliability remain to be demonstrated.

Human Health

Few primary care and emergency-room physicians in HAB-prone areas are familiar with symptoms of algal toxicity, thus hindering quick and reliable diagnosis and treatment. Consequently, there is reason to believe that human health effects of algal toxicity are under-reported. Better information on symptomology and treatment should be provided to health-care providers, particularly where the exposure of large numbers of people cannot be prevented by regular public health precautions, for example where beach-goers and coastal residents are exposed to toxic aerosols. In such cases, the longer-term consequences of acute exposure, for example after a vacationer goes back home and suffers a respiratory infection or other malady, are particularly problematic. The chronic exposure to algal toxins (as might be experienced by a beach resident in a red tide region, or a subsistence shellfisher) deserves increased attention by the medical research community.

Recreation and Tourism

As reviewed under Causes and Consequences, HABs have significant economic impacts not only from the loss of fish and shellfish, but also as a result of impairment of the use and enjoyment of coastal areas and their resources. This includes: simple aversion to boating or fishing in turbid waters (as seen in the case of brown tides in Texas and Long Island); prohibition of recreational fisheries (for example, razor clam harvesting in Washington); halo effects on the sales of fish and shellfish in markets and restaurants as a result of public concern and misinformation about the safety or wholesomeness of the product; cancellation or abbreviation of vacations and recreational uses as a result of noxious blooms; and diminished property values. Beyond the dollars and cents, the quality of life of coastal residents and visitors has been considerably diminished by HABs, such as the extended 1995-1996 red tide on the Florida Gulf coast.

Representatives of the hospitality industry in Florida who met with the Panel indicated that they sometimes lost business because the public learned from the press that the entire region was being affected by red tide, when the outbreak was in fact patchy and localized. Similar problems have been observed for resort areas on the Texas coast during and following red tide (*Gymnodinium breve*) incidents. Better reporting through the popular news and information media, perhaps including daily or weekly advisories about the location and severity of red tide, based on a well-organized network of observers would improve this situation as well as reduce the exposure of the uninformed visitor when blooms are severe. In order to avoid unwarranted panic, however, this information service would have to be accompanied by a carefully developed educational effort.

Red Tide, Tourism & Economy

At the Panel's Sarasota meeting, hoteliers, restauranteurs, and sport-fishing businessmen related the significant impacts on their businesses of the unusually persistent red tide during 1995 and 1996. Overseas tourists had vacations ruined by noxious beachfront conditions. Many U.S. tourists canceled their reservations based on news reports, even during times when beaches were not affected. Restaurants also reported sharp drop-off of customers and revenues, presumably out of groundless fear for the safety of seafood. Charter boat operators also experienced numerous cancellations, even though the fishing grounds were unaffected. The costs to the regional economy have not been totaled, but must have been many millions of dollars.

Beyond the physical discomfort caused by brevetoxin aerosols, beach use is also affected by the sight and smell of windrows of dead fish on the beach. Although this has not been routinely done, it should be feasible to reduce the stranding of dead fish on limited sections of beach by the use of floating booms, such as those used for oil spill control, or net enclosures. An additional problem and cost is the removal of dead fish from the beaches. During the 1995-96 red tide outbreak, many tons of dead fish were removed from beaches. In addition to the costs of physical removal, disposal into landfills required the payment of tipping fees and consumed landfill capacity. Similar disposal problems confront fish farmers in the Pacific Northwest when *Heterosigma* or diatom blooms result in significant fish mortality. A Sarasota County commissioner asked whether the dead fish could be macerated and disposed of offshore. The Panel was unable to examine all aspects of the feasibility of this option but noted that existing regulations may pose obstacles. Clearly, alternative disposal options should be evaluated using a common-sense, relative-risk approach.

A variety of estimates of economic impacts from HABs are presented in the literature and were offered to the panel during its three regional meetings. However, there is a consistent lack of comprehensive assessments of regional economic impacts of HABs. This is important information not only for determining where best to focus efforts to reduce avoidable economic impacts, but also for determining the justifiable costs of prevention and control efforts.

Endangered Species

HABs have now been determined to be responsible for the mortality of at least three endangered marine mammals: Florida manatees (brevetoxins) and humpback whales and bottle-nosed dolphins (saxitoxins). While it may prove difficult to mitigate these impacts, greater understanding of the nature and extent of these impacts is required. Stranded and ill marine mammals and birds should be routinely examined for symptoms and presence of algal toxins. The 1996 manatee mortality incident clearly indicates that much more monitoring of at-risk species is required. Coupled with improved knowledge about the distribution of and environmental factors associated with HABs, this may reveal management options to reduce exposure, for example by regulating freshwater flows to protect manatees from red tide.

Federal and state agencies with resource stewardship and public health responsibilities, working in conjunction with outreach officers from universities and research institutions, should develop and widely distribute clear and factual leaflets and public advisories concerning HABs and their risks. Special materials should be distributed to health care providers, which present information about symptoms and treatments. During HAB events, agencies should provide regular reports to the public via the news media concerning the distribution and intensity of outbreaks and recommended precautions.

Technical assistance to resource users should be increased to provide timely advisories based on forecasts and monitoring and advice on practical steps that can be taken to minimize losses. In areas with finfish net-pen aquaculture, permitting processes should be streamlined to allow timely tactical relocation of pens.

Economic studies should be undertaken to document regional and national costs of HAB impacts and made available to inform policy-makers.

RESTORATION

Restoration efforts have thus far been limited to reseeding efforts (bottom planting of hatchery-reared juvenile scallops) in the Peconic Bay system (New York) after mortalities resulting from BTB. These efforts have been only partially successful. The bay scallop comprised a multimillion dollar fishery on Long Island prior to the first occurrence of *Aureococcus* blooms in 1985. Three successive years with brown tides caused extensive mortality of adult scallops and severely limited larval recruitment; the impact of the brown tide is magnified by the short lifespan of the bay scallops. By the fall of 1988, virtually no native stock remained in the Peconic Bays and the fishery was essentially eliminated.

Tettelbach and Wenczel (1993) and the Long Island Green Seal Committee attempted to reseed bay scallops at three sites. Enough scallops survived at one of the sites to spawn, but another bloom of *Aureococcus* apparently prevented successful recruitment. Heavy recruitment was noted in 1991 after similar reseeding efforts; however, these scallops were quickly obliterated by a shell-boring parasite and another summer brown tide. A good crop of scallops realized in 1994 raised the hopes of baymen that the worst was over, but, due to a major brown tide in 1995, both 1995 and 1996 were poor seasons and the outlook for 1997 is dim. Transfer of bay scallop spawners has been successful (Peterson et al. 1996) and could, theoretically, be successful in restocking areas affected by brown tides. However, in the Peconic Bays areas of optimum scallop growth often coincide with areas of intense BTBs. Furthermore, it is currently not possible to predict with any degree of certainty the likelihood of a bloom, making restocking with spawners risky.

The other cases in which the living resources themselves may be damaged include fish kills from Gulf of Mexico red tides or loss of fishery resources resulting from larval mortality or declines in seagrasses in Texas estuaries affected by BTB. In Texas, hatchery stock enhancement of some finfish species is already being conducted, although as discussed under the Causes and Consequences section it is not clear that these stocks have yet suffered. Nonetheless, it may be feasible to restore lost seagrass beds in Texas and Long Island estuaries, but not until the BTB subsides and light conditions improve.

Restoration of resources damaged by harmful algal blooms is limited to restocking of shellfish and replanting of seagrasses, but such efforts will not be successful until the threats of recurrent blooms subside.

CONCLUSIONS

RISKS

Harmful algal blooms are increasing in frequency or severity in many U.S. coastal environments and worldwide. Beyond aesthetic impairment, such blooms pose increasing risks to human health, natural resources, and environmental quality. Whether increasing blooms are a direct result of human activities, cyclic or longer-term variations in climate, or other natural factors, **the greater risks posed demand improved precautions for the protection of human health, more concerted efforts to manage activities which may cause HABs, and renewed consideration of strategies to control blooms once they occur.**

PREVENTION

It is obviously preferable to prevent HABs in the first place rather than just to treat their symptoms. Many scientists have suggested that increases in HABs are somehow linked to increased pollution of the coastal ocean, particularly by plant nutrients. Indeed, it is difficult to imagine another cause, other than climate change, that could be responsible for the widespread increases in HABs witnessed during the last half of this century. Although pollution and nutrient enrichment are strongly implicated in worsening HABs elsewhere in the world, they have not been unequivocally identified as the cause of any of the HABs considered in this assessment. Nonetheless, **conscientious pursuit of goals for reductions of pollution—including excess nutrients—which have been established for many of the bays and estuaries of the United States could well yield positive results in terms of reductions in HABs**. In other words, HAB reduction is yet another rationale for advancing existing pollution reduction strategies. However, the reduction of the potentially most important pollutant, nitrogen-containing materials, is a daunting challenge because of the importance of nonpoint sources of nitrogen from agriculture and fossil fuel combustion. **Careful assessment and precaution against introductions and along-coast transfers of HAB cells and cysts via ballast water and aquaculture-related transfers also require greater attention.**

CONTROLS

Although controlling HABs through the application of chemicals or flocculants or the introduction of biological control agents is fraught with difficulties related to effectiveness and potential side effects, such **controls deserve more careful attention than they have received recently**. In addition to the need for expanded U.S. research on this topic, much can be learned from the experiences of Asian nations. Furthermore, control techniques should be evaluated in the context of risk assessments such as those applied in evaluating chemical and biological controls in land-based agriculture. The applicability of controls will probably be limited to more managed and constrained circumstances, for example in association with aquaculture or within small bays.

MITIGATION

The conservative procedures used to protect public health from exposure to algal toxins have been largely successful to this point: the incidence of mortality and serious illnesses in the U.S. has been relatively low. However, **in order to contend with the increased number and diversity of risks from HABs in an era of declining governmental resources to support labor-intensive monitoring, more sophisticated and reliable detection methods are now required, in addition to the immediate expansion of simple methods using volunteer observers**. Moreover, the medical community should be better informed and prepared to recognize and to treat individuals suffering HAB toxicity. Individuals visiting or living on the shore or consuming seafood also need to be better informed about the risks so that they are cautious but not unduly alarmed. **Responsible public education and communication should receive increased attention**.

RESEARCH

Research being initiated by federal agencies on the Ecology and Oceanography of Harmful Algal Blooms (ECOHAB) should seek to contribute basic understanding of the causes and behavior of HABs which would inform prevention, control and mitigation strategies, particularly regarding:

a. the role of anthropogenic nutrient sources in stimulating and sustaining blooms and the potential effectiveness of nutrient control strategies in reducing blooms;

b. the effects on blooms of trophic alterations, such as changing grazing pressure, that result from human over-harvesting or habitat changes;

c. the importance of "seeding" in the genesis of blooms and mechanisms for inoculation;

d. critical stages of bloom formation and propagation that may be suitable targets for control strategies;

e. the role and potential impacts of parasites and predators in suppressing blooms;

f. molecular or other indicators of harmful algal species which may improve the sensitivity and reliability of monitoring;

g. remote sensing of blooms that provides advanced warning and supports tactical mitigation; and

h. modeling of physical and biological processes which may be applied in forecasting the occurrence and movement of harmful algal blooms.

Even with such advances in basic understanding, a critical factor limiting the evaluation, much less application, of prevention, control and mitigation strategies is the lack of focused, applied research on solutions. **Federal and state agencies with responsibilities for resource management, environmental protection, and public health should support research directly addressing prevention, control, and mitigation, including: evaluation of the effectiveness and side-effects of chemical, physical, and biological controls; development of better measurements of toxins and HAB species for application in monitoring; ballast water treatments; and effects of chronic exposure on human health.** Such a focused, applied research effort, in consort with the expanded research on ecology and oceanography of blooms, would substantially increase the Nation's ability to protect public health and natural resources.

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APPENDIX

SPEAKERS AND PANELISTS PARTICIPATING IN THE REGIONAL MEETINGS

PORT ARANSAS, TEXAS, AUGUST 21-23, 1996

Dr. Edward J. Buskey	Marine Science Institute, University of Texas at Austin Port Aransas, TX
Dr. Hudson DeYoe	Corpus Christi Bay National Estuary Program Corpus Christi, TX
Mr. Jim Ehman	Gulf Coast Conservation Association Houston, TX
Mr. Wallace Kelly, Jr.	Coastal Bend Guides Association Corpus Christi, TX
Mr. Walt Kittleberger	Lower Laguna Madre Foundation Port Mansfield, TX
Dr. Darcy J. Lonsdale	Marine Sciences Research Center, State University of New York, Stony Brook
Dr. Larry McEachron	Texas Parks and Wildlife Department Rockport, TX
Dr. Larry D. McKinney	Texas Parks and Wildlife Department Austin, TX
Dr. Robert Nuzzi	Suffolk County Department of Health Services Riverhead, NY
Dr. Christopher P. Onuf	National Biological Service Corpus Christi, TX
Mr. Robert B. Wallace, Jr.	Coastal Bend Bays Foundation Corpus Christi, TX

SEATTLE, WASHINGTON, SEPTEMBER 30-OCTOBER 1996

Mr. Brian Bernier	Global Aqua-USA Seattle, WA
Mr. Kevin Bright	ScanAm Fish Farm Anacortes, WA
Dr. Raymond Carruthers	U.S. Department of Agriculture Beltsville, MD
Dr. Rose Ann Cattolico	Department of Botany, University of Washington Seattle, WA
Mr. Frank Cox	Washington Department of Health Olympia, WA
Ms. Janet Kelly	Seattle, WA
Mr. Gregg Langlois	California Department of Health Services Berkeley, CA
Mr. Steve McKnight	Global Aqua-USA Seattle, WA
Mr. Dave Molenaar	Quinault Indian Nation Taholah, WA
Mr. Raymond RaLonde	University of Alaska Marine Advisory Program Anchorage, AK
Mr. Tim Sample	U.S. Food and Drug Administration Seattle, WA
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