PREVENTION, CONTROL AND MITIGATION OF HARMFUL ALGAL BLOOMS: MULTIPLE APPROACHES TO HAB MANAGEMENT

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ABSTRACT

The diversity of harmful algal blooms (HABs) and their impacts presents a significant challenge to those responsible for the management of threatened coastal resources. A recent review highlights the many different strategies adopted by countries and commercial enterprises worldwide to monitor and manage HABs in coastal waters. Here the objective is to provide a current perspective on some of these strategies, emphasizing the distinctions between management actions that fall into the categories of *mitigation, prevention,* and *control*.

Many of the management actions taken to respond to HABs can be termed mitigation – i.e., dealing with an existing or ongoing bloom, and taking whatever steps are necessary or possible to reduce negative impacts. Examples of this type of activity include the routine monitoring programs for toxins in shellfish, the towing of fish net pens away from the sites of intense HABs, and processing of shellfish in such a way as to reduce toxicity to an acceptable level. Prevention refers to actions taken to keep HABs from happening or from directly impacting a particular resource. There are three general categories of activities that can lead to bloom prevention. Examples are given of the effect on HABs from: 1) controls on the flow of materials into the coastal region (mainly nutrients and fresh water); 2) modifications of physical conditions (e.g., freshwater flow, tidal exchange); and 3) restrictions on activities, which might result in the accidental transfer of harmful algal species into environments where they do not naturally occur. Control is perhaps the most challenging and controversial aspect of HAB management. The concept refers to actions taken to suppress or destroy HABs - to directly intervene in the bloom process. This is one area where HAB science is rudimentary and slow moving. Five categories or strategies that can be used to combat HABs include: mechanical control, biological control, chemical control, genetic control and environmental control.

Overall, the topic of prevention, control and mitigation of HABs is broad and encompasses many different approaches and strategies. Some are well established, at least in the laboratory, and others are only at the theoretical or conceptual stage. Many require considerable research and testing before they can be fully evaluated.

INTRODUCTION

Algal blooms are diverse in many ways. Some are massive in scale, covering thousands of km^2 [e.g., 1], while others are small and localized [e.g., 2, 3]. Many are non-toxic, but some produce potent toxins that can poison human consumers of shellfish, kill wild and farmed fish in large numbers, and disrupt ecosystems at all levels, affecting even top predators such as sea lions and whales. Non-toxic blooms can also be harmful, typically when the blooms decay, leading to anoxia and large-scale mortalities of seaweeds, fish, and many other organisms. Many different species of algae can cause harm in this way, whereas only a few dozen species are known to produce toxins. Harm can also result from the smell or noxious character of algal blooms, driving tourists and residents from beaches and coastal waters, fouling fishermen's nets, or causing a general reduction in the enjoyment or commercial utilization of nearshore waters.

This diversity in blooms and their impacts presents a significant challenge to those responsible for the management of coastal resources threatened by harmful algal blooms (HABs). The strategies needed to protect fisheries, minimize economic and ecosystem losses, and protect public health vary considerably among locations and among HAB types. A recent review [4] highlights the many different strategies adopted by countries and commercial enterprises worldwide to monitor and manage HABs in coastal waters. Here the objective is to provide a current perspective on some of these strategies, emphasizing the distinctions between management actions that fall into the categories of *mitigation, prevention,* and *control*, as defined by Boesch et al. [5].

MITIGATION

Many of the management actions taken to respond to HABs can be termed mitigation – i.e., dealing with an existing or ongoing bloom, and taking whatever steps are necessary or possible to reduce negative impacts. Obvious examples of this type of activity are the routine monitoring programs for toxins in shellfish, as currently conducted in more than 50 countries [6]. The detection of dangerous levels of any of the HAB toxins in shellfish will lead to harvesting restrictions to keep contaminated product off the market. Another common mitigation strategy is the towing of fish net pens away from the sites of intense HABs. Though expensive and occasionally costly with respect to lost or damaged fish, this remains one of the primary tools used by fish farmers to combat HABs [7].

Another strategy to mitigate the impact of HAB toxins in shellfish is to process those shellfish in such a way as to reduce toxicity to an acceptable level. A clear example is the removal of scallop viscera and the marketing of only the adductor muscle, which generally contains little or no HAB toxins. Another example is provided by the Commission of European Communities (CEC) decision (91/492/EEC) which establishes

conditions for harvesting and processing the cockle *Acanthocardia tuberculatum* from areas where PSP levels exceed the 80 µg STX eq 100 g^{-1} safety limit. If the cockles are processed and canned in the manner specified (which involves washing, heat treatment, and removal of certain tissues), toxicity can be reduced to levels below the detection limit, as determined by mouse bioassay [8]. These and other details on seafood processing to reduce toxin levels are reviewed in Anderson et al. [4], including a new chemical method for decontamination of PSP toxins in shellfish developed by Lagos et al. [9]. This procedure involves immersion of contaminated product (e.g., live animals or shucked meats) in an alkaline solution, followed by boiling. Washing steps are required to remove toxins released into solution. This method is reported to yield 99% decontamination of mussels that had an initial toxicity of 6800 µg STX eq 100 g^{-1}.

These are but a few examples of many different mitigation strategies. In effect, we use these strategies to live with HABs and to manage around them. The question often arises, however, as to whether we can be more pro-active. Can we do something about these blooms before they happen or can we do something to destroy or suppress them while they are occurring? These questions highlight the "prevention" and "control" aspects of HAB management that will be the focus of the remainder of this discussion. The intent is not to provide a thorough overview of these topics, but rather to highlight important issues by providing examples of successful or promising strategies.

PREVENTION

Prevention refers to actions taken to keep HABs from happening or from directly impacting a particular resource. Several problems are immediately apparent in this regard. For one, we do not have all of the knowledge we need about why HABs form in many areas, so it is obviously difficult to regulate or control those factors. This argues for substantial and sustained research on all aspects of HABs, including their ecology, physiology and oceanography. All too often managers and agency officials view these topics as fundamental or basic science issues that have little direct practical utility, but in reality, such knowledge is essential for the design and implementation of effective prevention and control strategies.

Another problem that arises with regard to HAB prevention is that even if we know that certain environmental factors are influencing the population dynamics of a specific HAB organism, there are limitations on what we can feasibly do to modify or control those factors. For example, we might know that a particular HAB is strongly influenced by the outflow of a river system – that it is associated with a buoyant coastal current, for example, but we are unlikely to be able to justify the alteration of that river flow solely on the basis of HAB prevention. As discussed below, it is nevertheless important to factor the possible impacts on HABs into large-scale policy decisions on such topics as pollution reductions or alterations in freshwater flows due to agricultural and drinking water demands.

There are three general categories of activities that can lead to bloom prevention. These include:

1. Controls on the flow of materials into the coastal region (mainly nutrients and fresh water).
2. Modifications of physical conditions (e.g., freshwater flow, tidal exchange).
3. Restrictions on activities, which might result in the accidental transfer of harmful algal species into environments where they do not naturally occur.

Alteration of Nutrient Inputs

The rapid increase in the input of plant nutrients, particularly nitrogen compounds, into coastal waters throughout the world reflects the growing disposal of sewage from expanding populations, increased use of chemical fertilizers in agriculture, and increased fossil fuel combustion. Of considerable concern, particularly for coastal resource managers, is the potential relationship between the apparent increase in HABs and the accelerated eutrophication of coastal waters due to human activities [10, 11]. Linkages between HABs and eutrophication have been noted within the past several decades, though the linkages remain circumstantial and thus are not universally accepted. For example, enhancement of red tides and HABs by pollution has been inferred from data showing that both parameters increase in parallel. A number of examples of increases in blooms or primary production in coastal waters in parallel with nutrient increases are provided by Smayda [10].

Those requiring more proof of this causality can now consider newer data demonstrating that HABs tend to decrease when nutrient loadings are reduced [11]. In other words, reversals in the increasing trends in HAB incidence that occur when government policies reduce pollution loading strengthen the case considerably that those nutrients were responsible for the increases in the first place.

The earliest example of this relationship was seen in the Seto Inland Sea in Japan, where the number of visible red tides (high biomass blooms) increased seven-fold between 1960 and the mid 1970's. This increase paralleled the increase in industrial production and chemical oxygen demand (COD) from domestic and industrial wastes. In 1973, Japanese authorities instituted the Seto Inland Sea Law to reduce COD loadings to half of the 1974 levels over a three-year period. As a result, the number of red tides began to decrease in 1977, dropping to levels approximately one-third of the peak frequency. This lower level of bloom incidence has been maintained to the present [12]. These data demonstrate a general increase in phytoplankton abundance due to over-enrichment of coastal waters, followed by a proportional decrease in blooms when that loading was reduced. Interestingly, toxic blooms (in this instance, those that caused fish mortalities or other fisheries damage) also decreased after the loadings were reduced.

These toxic blooms have always been a small fraction of the total bloom number, so the decreasing trend was less obvious, but still apparent [11].

A second example is from Tolo Harbor, Hong Kong, where increasing population growth in the watershed in the late 1970s and early '80s coincided with a dramatic increase in the number of visible red tides. The implication was that the increased pollution loadings from those population increases simulated red tide occurrence [13]. Sewage inputs to Tolo Harbor were later diverted from Tolo Harbor and discharged elsewhere. Although red tides still occur at a relatively high frequency, data presented by Yung et al. [14] suggest that the community composition may have shifted after these diversions – from dinoflagellate to diatom dominance. It is tempting to link the increase in blooms to pollution and the decrease (or at least the change in bloom-type) to the diversion of sewage. As pointed out by Kueh [15], however, there are other possible explanations for the trends in bloom incidence, including large-scale biological or climatological phenomena that operate in approximate ten-year cycles.

Repeated incidence of high-biomass blooms such as those described above for the Seto Inland Sea and Tolo Harbor provide evidence for a broadly based stimulatory effect of anthropogenic nutrients on phytoplankton in coastal waters. The legislative or policy changes implemented in the Seto Inland Sea and Tolo Harbor [14] demonstrate that control of sewage discharges has the potential to prevent certain types of HABs. Many countries are implementing sewage reduction strategies, and this trend should be encouraged. Nevertheless, there are other important sources of nutrients to coastal waters, and these are proving much more difficult to control, given the increased population pressures and the need to feed a growing world population. In particular, the steady expansion in the use of fertilizers for agricultural production represents a significant and worrisome source of plant nutrients to coastal waters.

A striking example of the impact of fertilizer usage on HAB incidence is seen with the northwestern Black Sea, which experienced heavy pollution loading in the 1970s and '80s from the eight countries within that watershed. This was reflected in significant increases in inorganic and organic nutrients over that 20-year interval: NO_3^- was 2.5-8 times higher, and PO_4^{3-} was up to 20-fold higher [16]. A consequence of this enrichment was an increase in the frequency and magnitude of algal blooms. In the 1960s, high biomass blooms were rare**,** but during the two decades of intense eutrophication pressure, blooms became recurrent, with cell densities greatly exceeding past abundance levels [16]. During the 1980s, 49 major blooms were reported, of which 15 had >10 million cells L^{-1} [17]. Anoxia, fish mortalities, and other impacts were frequent. A noteworthy characteristic of this interval was the decreased abundance of diatoms and larger algae and their replacement by flagellates and nanoplankton. In a striking reversal, algal blooms began to decrease in 1991, both in number and in size, and this trend has continued to the present. Diatoms became more dominant, and nanoplankton and flagellates decreased. From 1991-1996, there were only three blooms with cell concentrations in excess of 10 million cells L^{-1}. This reduction in blooms coincided with significantly decreased nutrient loading to the Black Sea due to reduced fertilizer usage as a result of reduced economic subsidies that accompanied the breakup of the former Soviet Union [17]. This raises the question of whether we will see a recurrence of the planktonic ecosystem changes in the coming years, leading to the high biomass blooms and fish mortality events that characterize the early 1980's. The extent to which the system reverts to the deteriorated conditions of the past will be determined by the pace of economic recovery, as well as the willingness of governments and farmers to make efforts to control non-point source pollution.

Some countries are making good strides towards more efficient fertilizer application methods or are instituting other controls that help to capture the nitrogen and phosphorus before they enter rivers and streams. However, many other countries continue to expand their use of fertilizers at a rapid rate, a trend that is facilitated in part by the relatively low cost of nitrogen fertilizers. There are also trends towards the production of more beef and other meat products that are inefficient in nitrogen assimilation, resulting in extremely high nitrogen usage per kilogram of food produced, compared to production of vegetables and grains. As pointed out in Smil [18], the net result is that the magnitude of human alteration of the global nitrogen cycle is huge - much larger than the changes we are making to the atmospheric CO_2 and greenhouse gas problem. There are obviously many benefits to the world population that derive from our ability to turn atmospheric nitrogen in to fertilizer salts. One wonders, however, how long it will take for policy makers throughout the world to recognize the negative aspects of our increasing reliance on nitrogen to produce the crops needed to feed the growing world population. In effect, we are feeding the world, but in doing so, are over-enriching the coastal ocean.

Freshwater Flows

Another topic that falls under the Prevention category of HAB management involves modification of freshwater flows. Human activities can profoundly affect the amount of fresh water entering the coastal zone, and this can affect HABs. In addition to the obvious role fresh water plays in diluting pollution loads as they enter marine systems, it also affects the stratification of coastal waters, which has always been an important determinant of phytoplankton community composition. Buoyant coastal currents can be critical in the development and transport of certain types of HABs [e.g., 19], and as a generalization, stratified waters are often thought to favor the growth of dinoflagellates and other motile groups that can access the higher nutrients typically found below the nutrient-deplete surface layer.

Another area where changes in freshwater flow may be affecting the patterns of HAB incidence is in the Bohai Sea of China. Due to droughts and water diversions for drinking water and agriculture, several of the rivers that used to flow freely into the Bohai are now dry for many days every year. This affects the dilution of

pollution loads in nearshore waters, and reduces stratification. The Bohai is one of several regions in China where the number of HABs has increased dramatically in recent years. It is not known how the changes in freshwater inputs have contributed to this trend, but it seems probable that they have. It is of note that China has plans to divert the flow of several rivers that presently discharge in the south to deliver water to the Bohai region. These types of large-scale fresh water diversion projects could have a major affect on HAB events. One hopes that comprehensive plankton and water quality monitoring programs will be sustained in that region so that the effects of these public works projects can be documented and lessons learned.

Dams can also affect HABs, again through effects on fresh water. Dams can decrease the availability of silicate to downstream waters due to sediment trapping within the impounded waters. A decrease in the amount of silicate reaching coastal waters, concurrent with increases in nitrogen and phosphorus due to domestic and agricultural pollution could lead to dramatic shifts in the important nutrient ratios that regulate phytoplankton community composition [e.g., 10].

CONTROL

Control is perhaps the most challenging and controversial aspect of HAB management. The concept refers to actions taken to suppress or destroy HABs - to directly intervene in the bloom process. This is one area where HAB science is rudimentary and slow moving. Five years ago, Anderson [20] wrote a commentary highlighting the virtual lack of research activity on bloom control, in contrast to aggressive policies to control tests and nuisance species in terrestrial agriculture. A number of reasons were listed for this "reticence" or reluctance to explore control strategies. For each of the points commonly used to argue against bloom control, there are reasonable counterpoints. These opposing viewpoints can be summarized as follows:

Argument #1: *HABs are complex phenomena in highly dynamic environments. Many are large, covering thousands of km^2.*

Counter argument: This may be true for some HABs, but is not a valid generalization across all types. Some blooms are highly localized, and even some of those that are large may have originated from much smaller populations at an earlier time, such as those linked to specific cyst seedbeds. Furthermore, no one is arguing that all HABs can or should be controlled – just those that are feasible given reasonable expenditures of money and effort relative to potential benefits and impacts.

Argument #2: *HAB phenomena remain poorly understood – "We can't control what we don't understand".*

Counter argument: Some HAB phenomena in certain regions have been studied for more than three decades. While it is true that not everything is known about these outbreaks, a great deal is understood, and one might argue that it is time to begin discussing control or suppression strategies. There will always be scientific uncertainty; the challenge is to determine when sufficient knowledge exists to support the formulation and evaluation of treatment strategies.

Argument #3: *The solutions may be worse than the HAB problem being treated.*

Counter argument: This is an argument that is frequently invoked in discussions of control possibilities, but those who use it often fail to acknowledge the damage cost of the HABs. For example, if it were possible to treat a Florida red tide or New York brown tide at an early stage when those blooms are relatively small and localized, might the potential impact of the bloom event be much lower than would be the case with the widespread, long-lasting blooms that might derive from these initial populations? In other words, what impacts are we willing to accept on a small scale in order to prevent bloom impacts that might be much more widespread and long-lasting?

Argument #4: *It's simply too risky and too difficult to control a HAB.*

Counter argument: This statement reflects the view that it's always easier to study the problem than it is to pursue direct solutions, since scientists are more comfortable pursuing basic research results than they are attempting difficult, controversial, and highly visible studies such as those on bloom control that may lead to failure. The counter argument here is that this is not the approach taken by other scientific disciplines such as agricultural pest control, where there have been significant successes.

Overall, there seems to be a general concession by the HAB community that blooms cannot be controlled, that the problems are too difficult and complex. Given this view, progress in this area will be slow unless steps are taken in the following areas:

- We need to change the "mindset" of HAB scientists to make them more willing to undertake risky studies that may include failures. To do this, the community must be more supportive of those who attempt these types of studies. This support could take the form of more tolerance to proposals submitted seeking funding for this type of work, offers of assistance and advice to make the research team

stronger, and a willingness to keep an open mind on the topic. The simple fact is that there has not been sufficient research on any of the possible bloom control strategies to support a conclusion that they are not feasible, yet many still cling to this preconception.

- We have to set practical goals for bloom control. This means that one needs to start small, with mesocosm and pilot-scale treatments rather than moving immediately to large-scale bloom control. A series of small successes under relatively controlled conditions will do much to alter the receptivity of scientists and managers to the concept of bloom control.

- We need to provide targeted funding for control research. This could best be done through a program on prevention, control and mitigation, for example, which would be distinct from other programs such as those on the ecology and oceanography of HABs. It is important that funding for PCM research be kept separate, in that it also should not come at the expense of funding intended for other HAB disciplines.

- We need to enlist the help of those experienced in mitigating the impacts of terrestrial or aquatic pests. There is a great deal of knowledge and technology that can be of great benefit to those working on HAB control. A joint workshop or working group might be an excellent way to foster this type of interaction.

The challenges and inertia associated with bloom control are significant, yet with these types of approaches, it should be possible to focus the energies and expertise of a subset of the HAB community on control research. Only after that research is completed should we then conclude that it is or is not possible to control HABs.

Experience From Other Disciplines

Harmful algae are not the only "pests" that threaten marine resources. It can therefore be instructive to examine the actions taken by other disciplines in response to outbreaks of potentially damaging organisms. In particular, those concerned with introduced or invasive species have long considered the concept of control. Workers in that field recognize five categories or strategies that can be used to combat an invasive species [21]. These include: mechanical control, biological control, chemical control, genetic control and environmental control. Several of these have already been applied to HAB species. For example, one form of mechanical control is the removal of HAB cells from the water using clay flocculation. This strategy has been employed with good success in Korean waters threatened by red tides of *Cocchlodinium polykrikoides* [22]. For invasive invertebrate species, mechanical control sometimes involves the harvesting of water hyacinths and other destructive plants from waterways. One advantage of this approach is that the target plant is physically removed from the water, minimizing environmental impacts. Clay flocculation of HABs, on the other hand, relies on the sedimentation of clay/cell flocs to bottom sediments, where negative impacts or eventual escape of the flocculated cells are possible. Direct removal of HAB cells through filtration, air sparging, or other approaches has not yet been attempted.

There are a variety of organisms that could theoretically be used to control HABs, but in reality, biological control has many logistical problems and is far from the application stage. Introduction of non-indigenous species or strains poses unknown risks and may be irreversible. Biocontrol is used extensively in agriculture, such as in the release of sterile males or the use of pheromones to control insect pests [23], but there is still considerable opposition to the concept of releasing one organism to control another. This concern is likely to be greatly magnified if the marine environment is to be the site of the release, as there is little precedence for such activities. Despite frequently cited examples where such an approach has had negative long-term consequences on land (such as with the introduction of the mongoose to oceanic islands or the giant toad to Australia [24], there are cases where the approach has been both effective and environmentally benign [23, 25]. The concept deserves some consideration in marine systems.

Zooplankton that graze on HAB species have been proposed as biological control agents [26, 27], but this has never been attempted because of the logistical impracticality of growing and maintaining zooplankton predators in sufficient quantity. Viruses, parasites, or bacteria are more promising control agents. Viruses are abundant in marine systems, replicate rapidly, and tend to be host-specific, suggesting that a single algal species such as *Heterosigma akashiwo* [28, 29] or *Aureococcus anophagefferens* [30] could be targeted. In reality, however, viruses are sometimes so host-specific that they are often unable to infect different genetic strains of the same host species. If HABs are genetically heterogeneous, only part of a population will be affected. Parasites [31] and bacteria [32] also have potential to control HAB species, but specificity is again an issue. There are numerous examples of bacterial strains which exhibit strong and apparently specific algicidal activity, but no field applications have yet been attempted. Clearly, the environmental impacts of the release of non-indigenous organisms will need to be carefully considered and discussed before a biological control strategy could be fully implemented for HABs.

Chemical control relies on toxic chemical release, including the potential development of species specific chemical control agents. Chemical control was attempted in 1957 against the Florida red tide organism now called *Karenia brevis* using copper sulfate delivered with crop dusting airplanes [33]. Although successful in destroying several large patches of red tide cells, this treatment was not considered a success because the red tide re-appeared several weeks later, following the transport of offshore populations to the treated areas. In addition, there was the unquantified but probable collateral mortality of co-

occurring organisms due to the broad lethality of copper. This single effort at chemical control of HABs has not been followed by other attempts, presumably because of the general feeling in the HAB community that it will be difficult and perhaps impossible to find an environmentally acceptable chemical that would target a particular HAB species but not cause widespread mortality of other organisms.

Experience with several invasive invertebrate or plant species suggest that under certain circumstances, the concern over collateral mortality might be outweighed by the benefits of chemical control, at least for some situations. One such example occurred in the summer of 2000, when the Mediterranean green seaweed, *Caulerpa taxifolia*, was discovered in a lagoon in Southern California, USA. This was considered an extraordinarily worrisome situation, since this same species has overgrown huge expanses of the Mediterranean coast since its first accidental introduction about ten years ago [34]. Recognizing that they had to act decisively and quickly, authorities treated the algal beds with liquid chlorine [21]. Although high mortality of the *Caulerpa* followed, individual plants did survive this treatment. The infestation, however, is considerably smaller, and additional efforts were needed to eradicate survivors. It remains to be seen whether this introduction or invasion of *Caulerpa* was prevented.

A similar emergency control effort was mounted in March 1999 against the Asian fouling mussel (*Mytilopsis sallei*) when it was discovered in large densities in three marinas in Darwin, Australia [35]. These marinas were treated with liquid chlorine and copper sulfate. The treatments killed all of the targeted mussels, and a considerable amount of other marine life. This is the same type of "collateral" mortality that many HAB scientists cite as an argument against chemical control. Were these *Mytilopsi* treatments successful? One might argue that the complete destruction of the mussel was worth the effort, despite the mortality of other organisms, since the invasive species was totally eliminated. Even in the case of *Caulerpa*, where there were survivors, the chemical treatment might also be considered partially successful, since it at least slowed the invasion process, and presumably the next treatment might be on a smaller scale.

These two efforts highlight an important issue – namely that drastic control measures might be deemed environmentally acceptable if the situation is considered an emergency. In the context of HABs, this might not be the case for recurrent blooms of toxic or harmful species that are manageable in some way, such as with harvesting quarantines for shellfish. On the other hand, we can wonder what steps should be taken if a particularly toxic or dangerous algal species is detected in a bloom for the first time near a major aquaculture center, for example. Quick action to destroy most of the blooming organisms might prevent not only the immediate impacts, but impacts in future years if that species is not allowed to colonize the area, such as with cysts. Likewise, one wonders what might be considered if large numbers of the endangered Florida manatee were once again dying due to toxic algae, as occurred several times in the past [36; Jan Landsberg, pers. comm.]. If this were in a localized estuarine site, it might be possible to treat that bloom without adverse impacts on the manatees or the ecosystem. Right now, decisions like these are very difficult, in large part because there is insufficient information about the effectiveness and the impacts of different forms of bloom treatment. In the future, however, it may be much easier to decide whether the treatment is acceptable or not if there is a database from laboratory, mesocosm and field studies of different control strategies. The issues surrounding this type of treatment have not been thoroughly debated among the HAB community and the affected resource managers, so it is premature to attempt such drastic treatments at this time. However, it does seem appropriate to keep the concept alive, and to recognize that certain types of events might be sufficiently worrisome and dangerous that drastic preventive actions might be justified, as they were with the invasive mussel and seaweed species.

Another strategy for control of introduced or exotic species is genetic control – the genetic engineering of species that are purposely introduced to alter the environmental tolerances, reproduction or other processes in the undesirable species. The issues surrounding this type of control strategy are similar in many ways to those associated with biological control – concerns about the possible negative impacts of introducing a non-indigenous organism to an area. There are numerous examples where genetic approaches have been used successfully in terrestrial agriculture, such as the engineering of plant crops so that they are capable of producing their own insecticides. Similar genetic manipulations might be used on marine pests such as HABs. It might be possible, for example, to engineer a HAB species so that it no longer produced toxin. Likewise, one can envision genetic manipulations which might make a particular bacterial strain more pathogenic, or more specific in its activity towards HAB cells. However, society's concerns loom large for these types of strategies, and one can expect that it will be exceedingly difficult to obtain approval for such approaches in the near future. Nevertheless, we should not rule out these strategies on the basis of "gut feelings" or speculation, but rather should pursue the research and testing needed to obtain the data on which to base such decisions.

The last of the five control strategies is environmental manipulation – physical or chemical modifications of the environment so that either the target species is affected and/or a natural or introduced biocontrolled species is enhanced. For HABs, this might involve the large-scale manipulation of nutrient levels in coastal waters through pollution control policies. The affects of these policies will likely take years or even decades to become apparent, but are likely to lead to changes in the coastal phytoplankton community in heavily polluted areas, and potentially in a reduction in HABs. On shorter time scales, environmental manipulation becomes more difficult to envision but might include efforts to alter water circulation or residence time such as through dredging or opening of channels. Another approach might be aeration or other

methods to disrupt stratification, again leading to changes in the phytoplankton community composition.

SUMMARY

The topic of prevention, control and mitigation of HABs is a broad one that encompasses many different approaches and strategies. Some are well established, at least in the laboratory, and others are only at the theoretical or conceptual stage. All require considerable research and testing before they can be fully evaluated. With appropriate research progress will be made and our ability to manage HABs will greatly improve.

ACKNOWLEDGEMENTS

This work was funded by EPA Grant CR827090, the Cove Point Foundation, the Sholley Foundation, Florida Institute of Phosphate Research Grant 99-03-138, and NOAA Cooperative Agreement NA17RJ1223. This is contribution number 10726 from the Woods Hole Oceanographic Institution.

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Harmful Algae Management and Mitigation. 2004.
Hall, S., Etheridge, S., Anderson, D., Kleindinst, J., Zhu, M. and Zou, Y. (Eds.)
Asia-Pacific Economic Coooperation (Singapore): APEC Publication #204-MR-04.2