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Approaches to monitoring, control and management of harmful algal blooms (HABs)

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ABSTRACT

Virtually every coastal country in the world is affected by harmful algal blooms (HABs, commonly called "red tides"). These phenomena are caused by blooms of microscopic algae. Some of these algae are toxic, and can lead to illness and death in humans, fish, seabirds, marine mammals, and other oceanic life, typically as a result of the transfer of toxins through the food web. Sometimes the direct release of toxic compounds can be lethal to marine animals. Non-toxic HABs cause damage to ecosystems, fisheries resources, and recreational facilities, often due to the sheer biomass of the accumulated algae. The term "HAB" also applies to non-toxic blooms of macroalgae (seaweeds), which can cause major ecological impacts such as the displacement of indigenous species, habitat alteration and oxygen depletion in bottom waters.

Globally, the nature of the HAB problem has changed considerably over the last several decades. The number of toxic blooms, the resulting economic losses, the types of resources affected, and the number of toxins and toxic species have all increased dramatically. Some of this expansion has been attributed to storms, currents and other natural phenomena, but human activities are also frequently implicated. Humans have contributed by transporting toxic species in ballast water, and by adding massive and increasing quantities of industrial, agricultural and sewage effluents to coastal waters. In many urbanized coastal regions, these inputs have altered the size and composition of the nutrient pool which has, in turn, created a more favorable nutrient environment for certain HAB species. The steady expansion in the use of fertilizers for agricultural production represents a large and worrisome source of nutrients in coastal waters that promote some HABs.

The diversity in HAB species and their impacts presents a significant challenge to those responsible for the management of coastal resources. Furthermore, HABs are complex oceanographic phenomena that require multidisciplinary study ranging from molecular and cell biology to large-scale field surveys, numerical modelling, and remote sensing from space. Our understanding of these phenomena is increasing dramatically, and with this understanding comes technologies and management tools that can reduce HAB incidence and impact. Here I summarize the global HAB problem, its trends and causes, and new technologies and approaches to monitoring, control and management, highlighting molecular probes for cell detection, rapid and sensitive toxin assays, remote sensing detection and tracking of blooms, bloom control and mitigation strategies, and the use of large-scale physical/biological models to analyze past blooms and forecast future ones.

1. Introduction

Over the last several decades, countries throughout the world have experienced an escalating and worrisome trend in the incidence of problems termed "harmful algal blooms" (HABs). The term "harmful algal bloom" is very broad and covers blooms of many types, but HABs all have one unique feature in common—they cause harm, either due to their production of toxins or to the manner in which the cells' physical structure or accumulated biomass affects co-occurring organisms and alters food-web dynamics. HAB events are characterized by the proliferation and occasional dominance of particular species of toxic or harmful algae. In some cases, these microscopic cells increase in abundance until their pigments discolor the water—hence the common use of the term "red tide". There are, however, "blooms" of species which

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do not have high cell concentrations and which do not discolor the water, but which still cause harm, typically because of the potent toxins produced by those algae.

Several decades ago, relatively few countries were affected by HABs, but now most coastal countries are threatened, in many cases over large geographic areas and by more than one harmful or toxic species [1,2]. The causes behind this expansion are debated, with possible explanations ranging from natural mechanisms of species dispersal and enhancement (e.g., climate change) to a host of human-related phenomena such as pollution-related nutrient enrichment, climatic shifts, or transport of algal species via ship ballast water [1–3]. Whatever the reasons, coastal regions throughout the world are now subject to an unprecedented variety and frequency of HAB events. Many countries are faced with a bewildering array of toxic or harmful species and impacts, as well as disturbing trends of increasing bloom incidence, larger areas affected, more fisheries resources impacted, and higher economic losses.

2. HAB impacts

When toxic phytoplankton are filtered from the water as food by shellfish, their toxins accumulate in those shellfish to levels that can be lethal to humans or other consumers. The poisoning syndromes have been given the names paralytic, diarrhetic, neurotoxic, amnesic, and azaspiracid shellfish poisoning (PSP, DSP, NSP, ASP, and AZP respectively). Except for ASP, all are caused by biotoxins synthesized by a class of marine algae called dinoflagellates. The ASP toxin, domoic acid, is produced by diatoms that until recently were thought to be free of toxins. A sixth human illness, ciguatera fish poisoning (CFP) is caused by toxins produced by dinoflagellates that live on surfaces in many coral reef communities. Ciguatoxins are transferred through the food chain from herbivorous reef fishes to larger carnivorous, often commercially valuable finfish.

Another type of HAB impact occurs when marine fauna are killed by algal species that release toxins and other compounds into the water. Fish and shrimp mortalities from these types of HABs have increased considerably at aquaculture sites in recent years. HABs also cause mortalities of wild fish, seabirds, whales, dolphins, and other marine animals, typically as a result of the transfer of toxins through the food web [2].

Non-toxic blooms of algae can cause harm in a variety of ways. One prominent mechanism relates to the high biomass that some blooms achieve. When this biomass decays as the bloom terminates, oxygen is consumed, leading to widespread mortalities of plants and animals in the affected area. Large, prolonged blooms of non-toxic algal species can reduce light penetration to the bottom, decreasing densities of submerged aquatic vegetation that can have dramatic impacts on coastal ecosystems, as these grass beds serve as nurseries for the food and the young of commercially important fish and shellfish. These "high biomass" blooms are sometimes linked to excessive pollution inputs, but can also occur in pristine waters.

Macroalgae (seaweeds) can also cause problems. Over the past several decades, blooms of macroalgae have been increasing along many of the world's coastlines. Macroalgal blooms often occur in nutrient-enriched estuaries and nearshore areas that are shallow enough for light to penetrate to the sea floor. These blooms have a broad range of ecological effects, and often last longer than "typical" phytoplankton HABs. Once established, macroalgal blooms can remain in an environment for years unless the nutrient supply decreases. They can be particularly harmful to coral reefs. Under high nutrient conditions, opportunistic macroalgal species out-compete, overgrow and replace the coral.

HABs have an array of economic impacts, including the costs of conducting monitoring programs for shellfish and other affected resources, short- and long-term closure of harvestable shellfish and fish stocks, reductions in seafood sales (including the avoidance of "safe" seafood as a result of over-reaction to health advisories), mortalities of wild and farmed fish, shellfish, and coral reefs, impacts on tourism and tourism-related businesses, and medical treatment of exposed populations. Estimates of actual impacts are few, in part because these economic losses are difficult to quantify. A conservative estimate of the average annual economic impact resulting from HABs in the US is approximately US$75 million over the period 1987–2000 [4]. The impact from individual blooms, however, can exceed this annual average, as had occurred for example in 1976 when a massive bloom of the dinoflagellate *Ceratium tripos* led to extensive oxygen depletion in the New York Bight, affecting surf clams, ocean quahogs, scallops, finfish and lobster. The total lost sales in all sectors combined were estimated to be US$1.33 billion in year 2000 dollars [5].

Losses have been significant in other countries as well [6]. In Japan, for example, fish mortalities due to red tides in the Seto Inland Sea cost fishermen tens of millions of dollars per year, especially during the early 1970s. Even now, after extensive pollution control efforts have decreased bloom incidence, blooms of raphidophytes and dinoflagellates still kill cultured finfish and shellfish [11]. In China, a widespread red tide in 1989 along the coast of Hebei Province affected 15,000 ha of shrimp ponds, resulting in a loss valued at US$40 million [7]. These are but a few of many major HAB events with significant economic costs.

3. Recent trends

The nature of the HAB problem has changed considerably over the last three decades throughout the world. Fig. 1 shows the cumulative global increase in the recorded distribution of the causative organisms and the confirmed appearance of PSP toxins in shellfish. Clearly, a dramatic expansion in the areas affected by PSP toxins has occurred in recent years. A similar pattern applies to many of the other HAB types. Few would argue 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 throughout the world [1–3]. Disagreement only arises with respect to the reasons for this expansion.

The first thought of many is that pollution or other human activities are involved, and this is indeed a factor in some areas [3,8]. Many HAB species can thrive on the nitrogen and phosphorous commonly found in agricultural, sewage, and industrial discharges. On close inspection, however, some of the "new" or expanded HAB problems have occurred in waters where pollution is not an obvious factor. The organisms responsible for HABs have been on earth for thousands or even millions of years, during which time they had ample opportunities to disperse, assisted by changing climate, movement of tectonic plates, and other global changes. Some new bloom events may thus reflect indigenous populations that are discovered because of better detection methods and more observers.

It is also clear that man has contributed to the global HAB expansion by transporting toxic species in ship ballast water [9]. Another factor underlying the global expansion in HABs is the dramatic increase in aquaculture activities in many countries. This leads to increased monitoring of product quality and safety, revealing indigenous toxic algae that were probably always there [1]. In addition, construction of aquaculture facilities has placed fish and shellfish resources in areas where toxic algal species occur but were previously unknown, leading to mortality events or toxicity outbreaks that would not have been noticed had the aquaculture facility not been placed there.

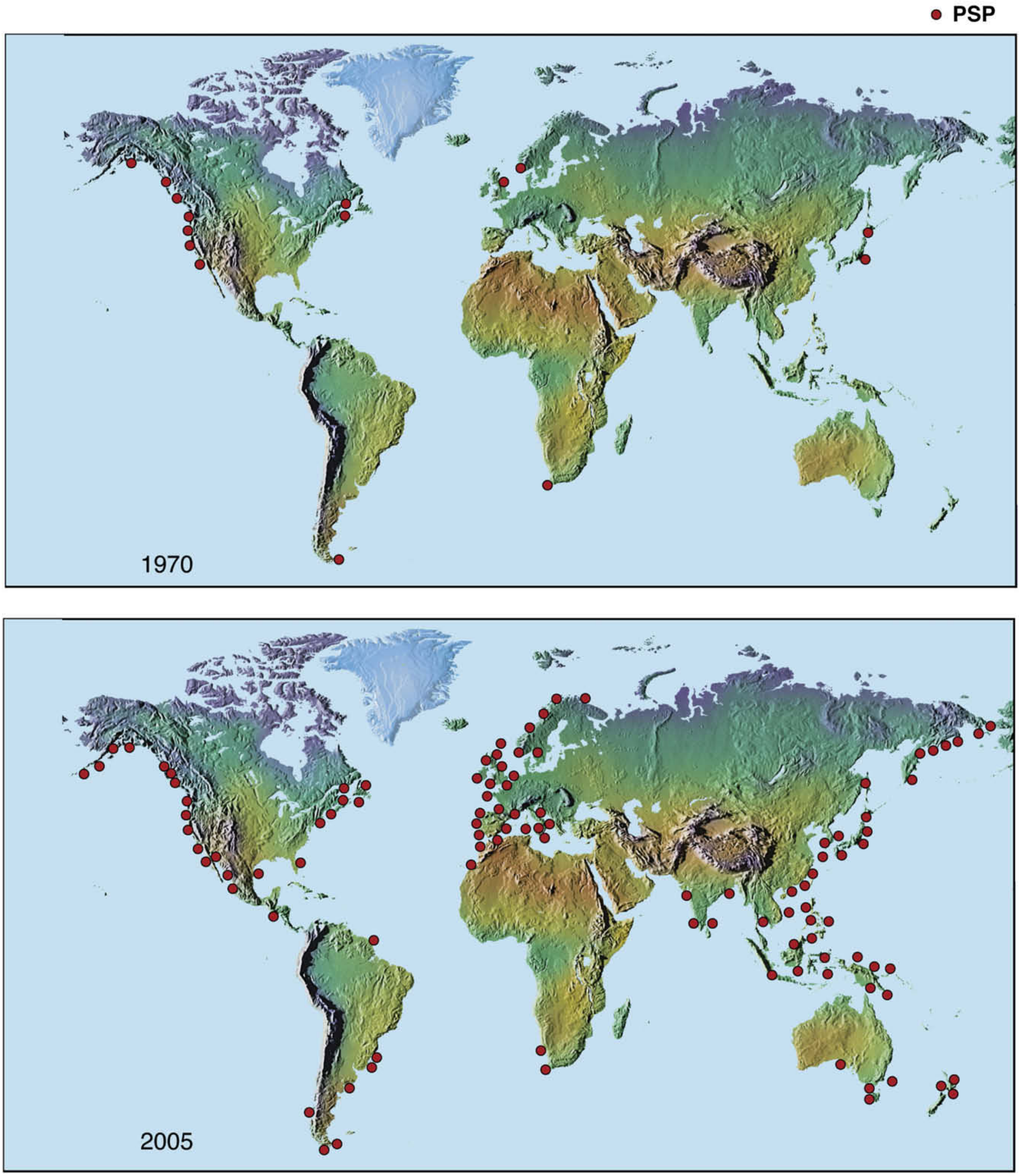

Fig. 1. The global expansion in the distribution of PSP toxins – 1970 versus 2005. (Credit: US National Office for Harmful Algal Blooms, Woods Hole Oceanographic Institution, Woods Hole, MA.)

It is now clear that the global expansion of HAB phenomena is in part a reflection of our ability to better define the boundaries of the problem—the nature and extent of toxic or harmful species and their impacts. Those boundaries are, however, also expanding due to natural dispersal via storms or currents, as well as to enhanced growth as a result of pollution or other anthropogenic influences. The fact that part of the expansion is simply because of increased scientific awareness and detection capabilities should not temper our concern. The global problem of HABs is serious and large—much larger than we thought.

4. Management issues

This diversity in blooms and their impacts presents a significant challenge to those responsible for the management of coastal resources threatened by 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 [10] highlights the many different strategies adopted by countries and commercial enterprises worldwide to monitor and manage HABs in coastal waters. A few example strategies are briefly introduced below.

4.1. 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 are the routine monitoring programs for toxins in shellfish, as currently conducted in more than 50 countries [10]. The detection of dangerous levels of HAB toxins in shellfish will lead to harvesting restrictions to keep the contaminated product off the market. Another common mitigation strategy is the towing of fish net pens away from the sites of intense HABs [10].

4.2. 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 don't have all of the knowledge we need about why HABs occur in many areas, so it is obviously difficult to regulate or control the critical factors. This argues for substantial and sustained research on all aspects of HABs, including their ecology, physiology and oceanography. 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 [3,8]. The legislative or policy changes implemented in the Seto Inland Sea and other locations demonstrate that control of sewage or waste discharges has the potential to prevent certain types of HABs [11]. Many countries are implementing sewage reduction strategies, and this trend should be encouraged.

4.3. Control

Bloom control is 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 [12].

There are five general categories or strategies that can be used to combat or suppress an invasive or harmful species. These include: mechanical, biological, chemical, genetic and environmental control. Several of these have been applied to HAB species. For example, one form of mechanical control is the removal of HAB cells from the water by dispersing clay over the water surface [13–15]. The clay particles aggregate with each other and with HAB cells, removing those cells through sedimentation. In countries such as Korea, where a fish-farming industry worth hundreds of millions of dollars is threatened by HABs, this control strategy makes sense, economically and socially, and so work has progressed (Fig. 2; [13]). In other areas, the cost/benefit rationale is not as clear, and considerable effort will be required to bring research to direct application. For example, research on clay mitigation has proceeded quite far in countries such as the US [14–16] but a significant barrier exists with respect to the ability to obtain permits, environmental clearances and funds to employ this strategy on more than an experimental scale.

Fig. 2. Clay dispersal as a bloom suppression strategy during a fish-killing HAB outbreak in South Korea. (Photo credit: H. Kim.)

There are a variety of organisms that could theoretically be used to control HABs, but biological control has many logistical problems and is far from the application stage. Biocontrol is used extensively in agriculture, such as in the release of sterile males or the use of pheromones to control insect pests [17], but there is still considerable opposition to the concept of releasing one organism to control another in the ocean. 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 [18]), there are many cases where the approach has been both effective and environmentally benign on land [17,19]. The concept deserves some consideration in marine systems.

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 using copper sulfate delivered with crop dusting airplanes [20]. Chemical control has not been actively pursued by the HAB community, presumably because of the general feeling 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 the other organisms.

Another strategy for the 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 produces toxin. Likewise, one can envision genetic manipulations that might make a particular bacterial strain more pathogenic 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 hypothetical impacts, but rather should pursue the research and testing needed to obtain the data on which to base such decisions. Indeed, as the HAB problem continues to worsen in certain areas of the world, the pressure for, and the acceptance of bloom control or suppression strategies are likely to increase.

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 bio-controlled species is enhanced. For HABs, this might involve the large-scale manipulation of nutrient levels in coastal waters through pollution control policies. 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.

5. Emerging technologies

The HAB problem has been a significant research focus throughout the world, and as a result, many new technologies are emerging that can help considerably with the management challenges we face.

Of paramount importance in this regard are methods to detect and quantify toxins, where progress has been rapid. Sophisticated analytical techniques combining chromatographic and mass spectrometry techniques (e.g., LC-MS) have been developed for all major HAB toxins, and are now taking the place of many older methods, including the widely used, but socially undesirable mouse bioassays. At the other extreme, simple test kits have been developed that are analogous to home pregnancy kits (Fig. 3). These allow inexpensive, rapid testing for toxins, and show great promise for use in screening samples, avoiding costly analysis for the many samples that are negative in monitoring programs. These kits also show promise to allow remote areas (such as offshore shellfish beds) to be harvested, as fishermen are more likely to harvest in an area if they can know with reasonable certainty that the product they bring to shore will not contain toxins above regulatory limits.

Another important management need is bloom detection and tracking. Here again, there has been progress on both ends of the spatial spectrum. At the largest scale, satellite remote sensing is now used operationally to detect HABs in the Gulf of Mexico, and with simple transport models, forecasts are now issued of impending landfall or exposure [21]. That capability is not easily transferred to other HABs, as the blooms being detected are very dense and mono-specific, and thus have a chlorophyll signature that reveals their presence. For other HABs, remote sensing applications rely on detecting the water masses in which the cells reside—using sea surface temperature for example [22].

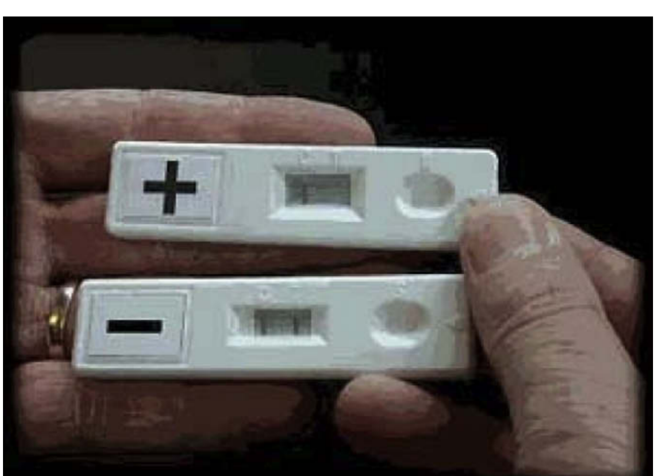

Fig. 3. Jellett MIST test strip for rapid and simple PSP toxin detection.

At the smallest scale, "molecular probes" have been developed for many HAB species that allow them to be detected and counted more easily and faster than has been possible with traditional microscopy [23]. These probes are often either antibodies or short segments of DNA that are specific for the HAB species of interest. They are then used in a variety of formats, some of which are amenable to remote, automated operation, and thus can be deployed in moored instruments that can become the sentinels for HABs. There is a clear need for technologies of this type in the emerging global ocean observing system.

Observations and measurements like those given above are important, but they need to be augmented with numerical models, which are also under rapid development. The most advanced of these are coupled physical–biological models that resolve a region's circulation, and include biological components that simulate a HAB species' bloom dynamics, and in the near future, the uptake of toxin as those organisms are consumed by shellfish [24,25]. These models are used predominantly in hindcast mode at present (i.e., in simulating past observations), but are advancing rapidly towards operational use for short-term forecasts similar to those used for the weather. These models will require observations of oceanographic parameters and HAB abundance and distribution that can be assimilated into the models to improve forecasts, exactly as is done with weather forecasts. Again, this is a role that ocean observing systems can and should play.

6. Summary

The problems and impacts of HABs are diverse, as are the causes and underlying mechanisms controlling the blooms. Pollution and other human activities in the coastal zone have increased the abundance of algae, including harmful and toxic forms. We cannot blame all new outbreaks and new problems on these actions, however, as HABs in some locations are natural phenomena that occurred long before humans exerted their influence on the ocean. As the growing world population increases its use of the coastal zone and demands more fisheries and recreational resources, there is a clear need to understand HAB phenomena and to develop scientifically sound management and mitigation policies. Research advances are significant and promising in this regard, spurred on by international cooperation and coordination. Scientifically based management of fisheries and other resources threatened by HABs is a reality in many countries, and this capability will rapidly expand to those nations that presently do not recognize their HAB problems, or who are struggling to deal with them.

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