Harmful Algal Blooms in Asia: an insidious and escalating water pollution phenomenon with effects on ecological and human health

Patricia M. Glibert

Abstract: Harmful Algal Blooms (HABs), those proliferations of algae that cause environmental, economic, or human health problems, are increasing in frequency, duration, and geographic extent due to nutrient pollution. The scale of the HAB problem in Asia has escalated in recent decades in parallel with the increase in use of agricultural fertilizer, the development of aquaculture, and a growing population. Three examples, all from China but illustrative of the diversity of events and their ecological, economic, and human health effects throughout Asia, are highlighted here. These examples include inland (Lake Tai or Taihu) as well as offshore (East China Sea and Yellow Sea) waters. The future outlook for controlling these blooms is bleak. The effects of advancing industrialized agriculture and a continually growing population will continue to result in more nutrient pollution and more HABs——and more effects - in the foreseeable future.

Keywords water pollution; nutrient pollution; eutrophication; red tide; Lake Taihu; East China Sea; Yellow Sea

Massive population. Manufacturing epicenter. Rapid economic growth. These are our images of China. Here's another: pollution powerhouse. As stated by Kahn and Yardley[1], "...just as the speed and scale of China's rise as an economic power have no clear parallel in history, so too its pollution problem has shattered all precedents. Environmental degradation is now so severe, with such stark domestic and international repercussions, that pollution poses not only a major long-term burden on the Chinese public but also an acute political challenge..." The temporal and spatial scale of the massive economic expansion of polluting industries is unprecedented. This expansion has been at a huge environmental cost with ramifications that include human and ecological health, as well as enormous economic costs.

Although pollution is occurring on land, in the air, and in water, the challenge of water pollution is particularly great. The scale of the water pollution problems in China almost defies description. A few stark statistics highlight the magnitude of this issue. In 2007, official estimates of the extent of water pollution were doubled due to previously unreported agricultural waste.[2,3] In 2010, over 40% of all state-monitored rivers were considered "Grade 4," meaning unsuitable for human contact.[4] Hundreds of millions of Chinese lack access to safe drinking water due to pollution.[5]

Typically one associates water pollution with chemical discharges from industrial processes. Yet these types of pollutants are only one of the types of pollutants that affect water. Increased infectious bacteria or other water-borne diseases, such as cholera, in areas receiving raw sewage are another.[6] Still another is the increased proliferation of toxic or harmful algal blooms (HABs). Harmful algae are those proliferations of algae that can cause ecological harm to food webs when they accumulate in massive quantities, and they can cause both

Patricia M. Glibert is a Professor with the University of Maryland Center for Environmental Science. Named one of the top 25 professors in Maryland, she is aquatic ecologist with over 30 years of experience working on issues related to nutrient loading, eutrophication, and harmful algae. In addition to her work in Chesapeake Bay, she has recently completed studies in East China Sea, Hong Kong coastal waters, Kuwait Bay, and the Gulf of Oman.

ecological and human health impacts when these cells produce toxic or other bioactive compounds.[7]

Harmful algae can grow in all waters, from rivers and lakes to reservoirs and oceans, and in all these waters the events can cause significant impacts. The frequency, duration, and geographic extent of harmful and toxic algae are increasing throughout Asia, and throughout much of the world (Fig. 1).[8,9,10] While China is experiencing some of the largest impacts

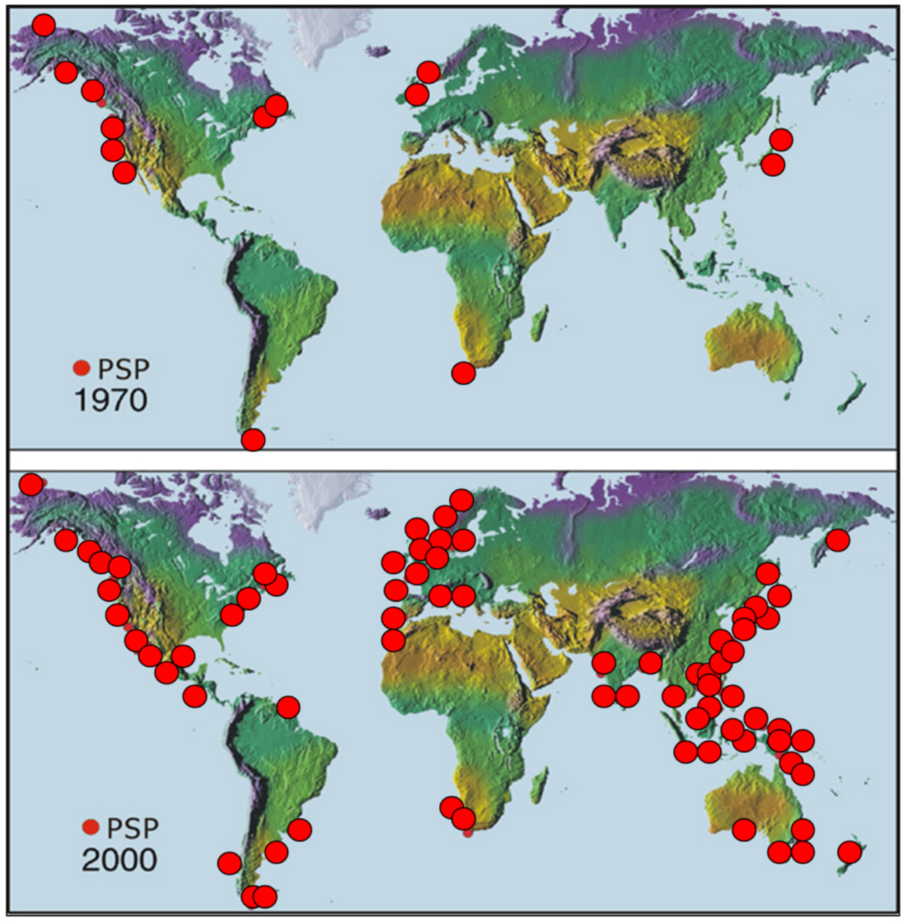

Figure 1: The change in global distribution from 1970 to 2000 of the harmful algae that cause paralytic shellfish poisoning (PSP). The upper panel shows the recorded occurrences of PSP by 1970, while the lower map shows the recorded occurrences of this syndrome through the year 2000. The expansion has been particularly large throughout southeast Asia, Europe and South America. Paralytic shellfish poisoning is but one syndrome caused by HABs and results in diarrhea, nausea, vomiting, and respiratory paralysis when shellfish which have consumed the toxic algae are eaten by humans. Map reproduced from Glibert et al. (2005) with permission of the Oceanography Society.

from HABs in Asia, other areas in Asia with particular concern over increasing HABs are the Philippines, Malaysia, Hong Kong, Japan, and Korea.[11] The countries of West Asia are also not immune to such problems, and numerous new HAB events and associated ecological and economic effects have been reported in this region over the past decade.[12,13,14] It has been estimated that direct human poisoning events in Asia from toxic algae number in the thousands annually.[15] One of the most common environmental effects of HABs is fish kills, including fish grown in the expanding aquaculture industry. Damages to the aquaculture industry have been estimated in the tens to hundreds of millions of dollars for blooms that have occurred in Korea, Japan, and the Philippines. Single HAB fish-kill events in Korea have been estimated to have cost from $1-100 million in lost fish, while in Japan such events have been estimated to have resulted in losses of fish worth more than $300 million.[16]

The increasing frequency of HABs, their relationship to population and economic development and the increasing use of industrialized fertilizers, and their economic and human health consequences are the subjects of this paper. This brief synopsis is not meant as a review of the ecology or the dynamics of algal blooms, but rather as an introduction to the kinds of environmental, economic, and human health impacts that can occur. This paper begins with a brief, general description of algal blooms, the diversity of organisms producing HABs, and the general ecological and human health consequences of such phenomena. Then, an overview of increasing nutrient enrichment is provided and the linkage drawn between population growth, agricultural and economic development, and the nutrients that fuel the proliferation of such blooms. Several examples of HAB events and their impacts are then highlighted. While these examples do not illustrate all possible HAB event types, they do serve to illustrate the diversity of these problems and the fact that such events occur from freshwater to marine waters and that the causative organisms are also diverse. The examples chosen are all from China but, as noted above, throughout Asia, similar examples involving the species described here as well as numerous other HAB species can be found.

The Harmful Algal Bloom Phenomenon

Algae are a normal part of the aquatic ecosystem; they form the base of the aquatic food web. Most are microscopic in size, but some are macroscopic. Most algae are not harmful. Algae only can become "harmful" when they either accumulate in massive amounts or when the composition of the algal community shifts to species that make compounds (including toxins) that disrupt the normal food web or that can harm human consumers.[17] Much has been written about the ecological and biological complexity of HABs and the conditions associated with their formation.[e.g. 18,19,20]

Some HABs are technically not "algae" at all, but rather small animal-like microbes that obtain their nutrition by grazing (on other small algae or bacteria); they either do not photosynthesize at all or only do so in conjunction with grazing.[e.g. 21,22,23] Other HABs are more bacteria-like. These are the cyanobacteria (CyanoHABs), some of which have the ability to "fix" nitrogen from the atmosphere as their nitrogen source. Thus, the term "HAB" is an operational term, not a technical one.[24] Some HABs are planktonic, living in the water column, while others live in or near the sediment or attached to surfaces for some or all of their life cycle.

By definition, all HABs cause harm - either ecological, economic, or human health. Not all HABs make toxins; some are harmful in other ways. Among those that do make toxins, there are many types of toxins, with new toxins ones being discovered frequently.[25] Making the task of understanding these phenomena all the more complex, not all species are toxic under all conditions, and it is not completely understood when and why different species may become toxic.[26]

There are many species of HABs, and they have a vast array of environmental and human health impacts[27] (Fig. 2, Table 1). Some algal toxins kill fish directly. Others do not have direct effects on the organisms that feed on them, such as fish or filter-feeding shellfish, but the toxin can accumulate in the shellfish and then cause harm to the humans who consume them. In other cases, the toxins are released into the water column where they can get into the water supply and affect human consumers through their drinking water.

The effects of HAB toxins on humans are many; the species that make these sorts of toxins are diverse,[28] as are the pathways of exposure (Table 1). One important pathway by which people are exposed to toxin, as mentioned above, is through consumption of seafood that had previously been exposed to HABs or their toxins. For example, when shellfish are eaten that have consumed (through their filter feeding) the HAB diatom *Pseudo-nitzschia* spp. the most common symptoms are cramps and vomiting, but neurological disorders, such as short-term memory loss, can also occur.[29] (Note that the use of the term "spp.", denotes multiple species of an organism). Because of this latter effect, this syndrome is

Figure 2: Images of a "red tide" in East China Sea (upper left; photo by J. Li), a freshwater "green tide" (upper right; photo by T. Archer), a fish kill from toxic algae (lower left; photo by P. Glibert), and microscopic views of a common toxic red tide microorganism (lower right; photos by Y. Fukuyo).

termed Amnesic Shellfish Poisoning (ASP).[30] Exposure to this HAB type is now being linked to seizure and memory loss in laboratory animals, and to premature births and strandings in animals such as sea lions.[31,32,33] As another example, when mussels or other shellfish are consumed that have previously ingested the HAB dinoflagellate *Alexandrium* spp., effects can range from numbness around lips and mouth to respiratory paralysis and, with high doses, death.[34] This HAB syndrome is termed Paralytic Shellfish Poisoning (PSP). Another common HAB dinoflagellate species in Asia that causes PSP toxicity is *Pyrodinium bahamense* (var. *compressum*); this species has been particularly problematic in the Philippines, Indonesia, and Malaysia, where many human fatalities have been reported over the past several decades.[35] ASP and PSP are just a few of the effects of HAB toxins (Table 1).

Table 1. The general types of poisoning that occur from toxic algae, their vectors, and the symptoms or disease expression. Reproduced from Glibert (2008).

ILLNESS	TOXIN AND CAUSATIVE SPECIES	SYMPTOMS
Amnesic Shellfish poisoning (ASP)	**Domoic acid from the diatom _Pseudo-nitzschia_ spp. in shellfish**	**Short-term memory loss, vomiting, cramps**
Diarrheic shellfish poisoning (DSP)	**Okadaic acid from the dinoflagellate _Dinophysis_ spp. in shellfish**	**Diarrhea, vomiting, cramping**
Neurotoxic shellfish poisoning (NSP)	**Brevetoxin from the dinoflagellate _Karenia_ spp. in shellfish, aerosolized toxins**	**Nausea, diarrhea, eye irritation, respiratory distress, death**
Paralytic shellfish poisoning (PSP)	**Saxitoxin from the dinoflagellate _Alexandrium_ spp. and other species in shellfish**	**Numbness around lips and mouth, extremities; respiratory paralysis, death**
Cyanotoxin poisoning	**Microcystins and other toxins from cyanobacteria in water**	**Skin irritation, respiratory irritation, tumor-promotion, liver cancer, failure; neurological diseases such as Parkinson's, ALS, and dementia**

Other important pathways by which humans are exposed to HAB toxins are direct contact with water (swimming, drinking) and indirect contact via aerosols. One of the most common HAB types in freshwater, and one exemplifying the effect of both direct and indirect contact, is the CyanoHAB, *Microcystis* spp. Exposure to water with this HAB or its toxin can cause skin or respiratory irritation, but prolonged, repeated, or intensive exposure to the HAB toxin has been associated with tumor promotion, especially liver cancer.[36] As this toxin and other related toxins can affect the nervous system, it has been suggested that some neurological diseases such as Parkinson's Disease or dementia may also be related to some of the toxic and bioreactive compounds originating from this HAB group.[37] In yet other cases, toxins carried by sea spray and breathed by human consumers may cause respiratory distress.[38]

In addition to direct effects from toxins, some HABs are harmful to the ecosystem through their sheer biomass accumulation.[39] It is these visible accumulations that gave these events their common term, "red tides". Such biomass accumulation can lead to a multitude of negative consequences. For one, their accumulation can reduce the light penetration in the water column, thereby reducing habitat suitability for the growth of submersed grasses. Exceedingly high biomass can also cause fish gills to clog, leading to suffocation.[40] High biomass blooms can also lead to the development of "dead zones."[41] Dead zones are formed when the algae begin to die and their decomposition depletes the water of oxygen. Dead zones do not support (aerobic) aquatic life, and are responsible for losses of millions of dollars worth of fish annually.[42]

Fertilized to Death

The term for the enrichment of waters with excess nutrients leading to algal proliferation and a cascade of ecosystem consequences is eutrophication.[e.g.43,44] The nutrients which fuel eutrophication, nitrogen and phosphorus, make their way into waterways from two main anthropogenic sources - their use in agriculture and from sewage discharge, although industrial sources of these nutrients are not insignificant in some places. In agriculture, nitrogen and phosphorus-based fertilizers are used to enhance crop yield and food production. While there are natural sources of nitrogen and phosphorus, the use of chemical fertilizers is responsible for the "Green Revolution," which supports the ever-increasing human population.[45] The rate of use of industrial fertilizers has escalated in the past several decades.[46,47,48] China has increased its use of nitrogen fertilizer fourfold since the 1970s and together with the other countries of southeast Asia uses half of the world's nitrogen supply.[49]

The transfer of fertilizer nutrients through agriculture to food is extremely inefficient, however, leading to large amounts of nutrients being exported to the environment. About 14% of fertilizer nitrogen is consumed in food when vegetables are eaten, but only 4% is consumed in food when meat is eaten.[50] Those chemical fertilizers not taken up directly by the farm crops and harvested find their way into the environment in several ways. They can run off from farm fields directly into streams and rivers. They can percolate into the groundwater. In some instances, especially in the case of nitrogen, some of the fertilizer volatilizes into the atmosphere and can be transported and later deposited on land or sea by wet or dry deposition.[51]

In addition to fertilizer use, animal agriculture is expanding to meet the dietary demands of the population, and increasingly animal production is concentrated in large industrial feeding operations (concentrated animal operations, CAFOs). China has tens of thousands of such operations, which are estimated to produce more than 40 times the nitrogen pollution of industrial factories.[52] Moreover, animal waste is not treated and thus is an important source of nitrogen pollution in local waterways. Aquaculture is another type of concentrated animal operation, and the export of nitrogen from these expanding industries is substantial.[53,54] Of course, both animals and people consume these nutrients in their food and, in return, generate nitrogen and phosphorus in their waste. Although most industrialized parts of the world treat human sewage, this treatment typically does not actually remove nitrogen.

Although there are thousands of species of algae, not all of them respond equally to nutrient enrichment. Algal *blooms* occur when there is a rapid increase in their growth rate and biomass. Algal blooms can be promoted when these nutrients from agriculture, aquaculture, or sewage are discharged into water, and when other physical, chemical, or biological conditions are favorable for growth of these microbes.[55,56] Nutrients - particularly nitrogen and phosphorus - are essential for the growth of algae. These chemicals are necessary for the organisms to build new biomass (amino acids, proteins, DNA, lipids), and for energy (ATP) for metabolism.[57] Just like plants on land, different species of algae have preferences for different nutrients, different forms of those nutrients, and different proportions of nutrients. For example, some species preferentially use ammonium or urea for their nitrogen; others use nitrate.[58,59,60] Some species have also been shown to increase their toxicity levels in the presence of excess nitrogen relative to phosphorus, a critical concern when HABs proliferate in reservoirs, as the toxins can get into the water supply.[61,62] That China, as well as many other Asian countries, have escalated their use of nitrogen fertilizers relative to phosphorus fertilizers may be relevant in this regard.[63] Understanding which species preferentially use which forms of nutrients and in which proportions relative to knowledge of source and amounts of nutrient loads and the pathways by which nutrients are cycled in the environment provides important clues to understanding which species may proliferate under which conditions.

The examples below highlight three cases of HABs in China. These case studies are meant to illustrate that HABs have effects from freshwater to marine waters and that there is a diversity of HAB types and effects, but that all have several things in common. All of these cases resulted from excessive nutrient pollution; all caused harm to the environment and had resulting economic consequences; some were associated with human health impacts. Finally, the examples serve to highlight that the options for reducing the frequency or magnitude of such events are few. The ecology and dynamics of these blooms are complex and fascinating in their own right; the emphasis placed here is on the changing frequency or magnitude of these events and their effects.

TAIHU

Lake Tai (Taihu), the third largest lake in China, is located in the watershed of the Chiangjiang (Yangtze) River, the most industrialized area of China. This lake serves as a drinking water reservoir for over 2 million people.[64] Long known as a scenic area and tourist destination, Taihu is now choked annually with blooms of the toxic CyanoHAB species, *Microcystis aeruginosa*. This species makes several toxic or bioactive compounds, the most toxic of which is microcystin.[65]

The impact of these blooms is staggering. Blooms have been of such magnitude that as recently as a few years ago, the water supply intake had to be closed, leaving millions of people without potable water for several weeks.[66,67] In 2007 alone, over 6,000 tons of algae were removed from Taihu and from the drinking water pipes.[68] Tons of algal-killing chemicals were added to treat the water. City managers and leaders demanded that 1,000 factories be closed to reduce industrial and atmospheric sources of nitrogen and phosphorus to the lake.[69]

A recent analysis of the change in bloom frequency and duration shows that prior to

1997, blooms occurred, but only lasted about a month.[70] Since then, bloom duration has increased to be almost year-round (Fig. 3A).[71] Additionally, the initial date when blooms first occur during the year has become earlier and earlier.[72] Similarly, the spatial extent of these blooms has changed. In the early to mid 1990s, when blooms occurred they were

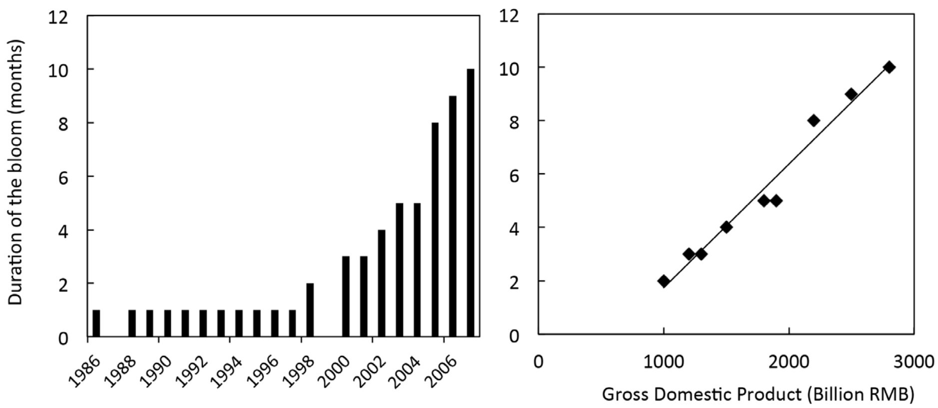

Figure 3: A - left panel - Annual duration (number of months) of the *Microcystis* sp. blooms in Lake Taihu, and B - right panel - annual duration of the bloom in relation to the annual gross domestic product. Figure replotted from Duan et al. (2009).

limited in extent, but in the most recent years blooms are covering virtually all of the lake.[73] This change in frequency and magnitude is related to the rapid development of the region and the corresponding increase in levels of nitrogen and phosphorus. Strong and significant relationships have been found between changes in nutrient loads and biomass of these bloom-forming microbes.[74,75] The relationship between nutrient pollution and the extent of these blooms is illustrated by the strongly significant correlation between gross domestic product and the initial date of bloom formation as well as duration (Fig. 3B).[76] Gross domestic product here is a proxy variable for population growth and the rapidly expanding anthropogenic footprint in the watershed, and to distinguish these pollution effects from those due to global warming (which would not be related to gross domestic product).[77] Both population growth and growth of agriculture are significant sources of nutrient pollution to the lake. Waste from CAFOs alone is estimated to contribute 35% of the nutrient pollution to Taihu.[78] Fertilizer use in the Taihu watershed is estimated to be >40% higher than the national average.[79] Further evidence that nutrient pollution is related to these blooms is the fact that 3 million tons of sewage enter the lake daily, with only about half of that receiving any treatment.[80]

The human health concerns related to these algal blooms are many. It has been reported that the increase in liver cancer in this eastern region of China is related to the toxins found in drinking water.[81,82] These toxins, among which are those derived from the *M. aeruginosa* and related CyanoHAB blooms, are also consumed when people eat fish or duck from the lake that have consumed these toxins. While no statistics are available with regard to the toxin effects of the most recent blooms in Taihu, it has been reported that toxin levels from *M. aeruginosa* in Taihu have soared in the past few years and are now many, many-fold higher than the "safe" levels established by the World Health Organization.[83] A recent study of children exposed to microcystin from another lake had very high rates of liver cancer.[84] Chinese officials now formally recognize the existence of "cancer villages," where unusually high rates of cancer are reported as a result of water, as well as other, pollutants.[85]

Investments of hundreds of millions of dollars are now being made in sewage upgrades in the Taihu region,[86] which should help to lessen bloom frequency and/or intensity, but pressures from agricultural discharge are likely to continue. Other control measures have, or are being taken. For example, water diversions from the Changjiang River have been undertaken with the goal of reducing the nutrient levels, but such measures are only effective for subregions of the lake or have been other unintended consequences, such as potentially elevated nutrient loads from the river diversions themselves.[87,88]

EAST CHINA SEA

The second example of algal blooms and their effects is taken from the coastal waters of the East China Sea. Coastal blooms do not always have the public's attention to the extent that freshwater blooms do, as they are away from view of most citizens. However, their effects can be just as significant from human health, ecosystem health, and economic points of view. Blooms in the East China Sea have been increasing, just as those of Taihu, and their occurrence tracks the increases in nutrient fertilizer use over the past several decades, as well as the increase in intensity of aquaculture development (Fig. 4).[89,90,91] In this case, the causative nutrients originate in the upper reaches of the Changjiang River and are transported offshore with the flow of the river.

One particularly massive bloom occurred in 2005 in this region.[92] The causative species were several, but the main one that led to ecosystem damage was *Karenia mikimotoi*, a dinoflagellate. The total area affected by this bloom was ultimately estimated to be over 15,000 km,[2,93] resulting in a massive fish kill in the coastal aquaculture areas.[94] The East China Sea has intensive aquaculture production.[95] The production of high market-value fish-cage aquaculture in this area has increased more than twofold from the early 1990s to the early 2000s.[96] Red drum, croaker, grouper, and sea bream, worth about $2.5 million, were lost due to this bloom.[97]

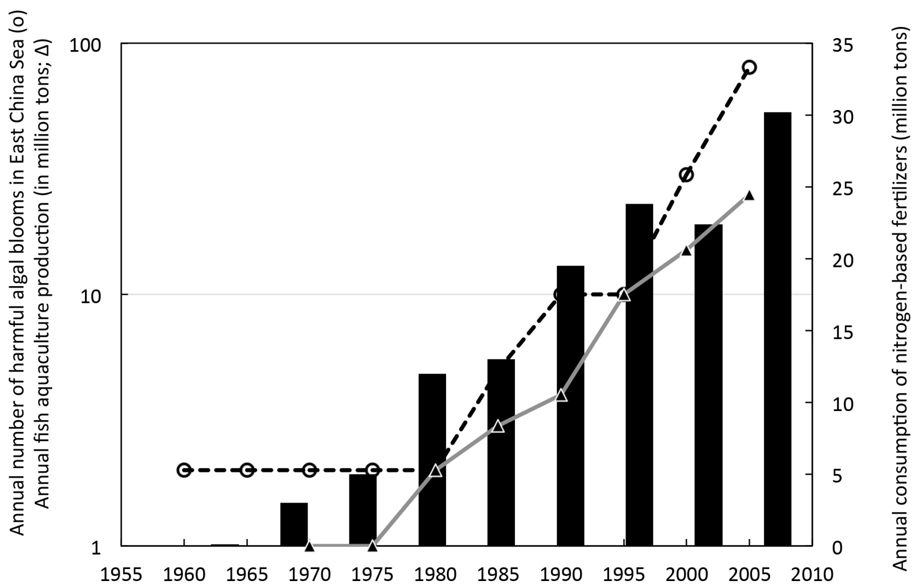

Figure 4: Comparison of the number of harmful algal bloom events in the East China Sea over time (o) in relation to the expansion in finfish aquaculture in the East China Sea (Δ) and the overall consumption of nitrogen-based fertilizer by China (bars). Note the use of the log scale on the primary X-axis. Data on numbers of harmful algal blooms and aquaculture development are derived from Furuya et al. (2010) and the nitrogen fertilizer data are from the Food and Agriculture Organization of the United Nations (*FAO*).

Karenia spp. makes a toxin, a polyether compound called brevetoxin, that affects the nervous system.[98] Brevetoxin kills fish directly. Shellfish are unaffected by this toxin (they have no nervous system), but fish and all mammals are affected.[99] Shellfish can, however, accumulate this toxin. The most common source of exposure for people is through consumption of shellfish, but in many Asian countries, fish are also an important vector. In Asia, it is common to consume whole fish, rather than fillets, exposing consumers to the liver and stomachs, where the fish would have the highest level of toxins.[100] Some of the symptoms associated with toxin poisoning from *Karenia*-affected seafood include, "nausea, vomiting, diarrhea... numbness and tingling in the lips, mouth and face, as well as numbness and tingling in the extremities… [Moreover,]... overall loss of coordination, and partial limb paralysis may also occur... [as well as] slurred speech, headache, pupil dilation, and overall fatigue... and more severe clinical progression that often involves paralysis, respiratory distress and death if undiagnosed and untreated."[101] Because many of these symptoms are common to many intestinal or neurological illnesses, the effects of *Karenia*-toxin poisoning are typically underreported and misdiagnosed not only in Asia but in other regions of the world where this species also occurs.[102] Effects of brevetoxin may remain in the ecosystem even after the bloom itself has passed.[103] Human impacts of the 2005 bloom in the East China Sea were minimized due to the fact that the bloom was located offshore and due to the unfortunate fact that the bloom killed the aquaculture fish, making them unsuitable for market and therefore human consumption.

Few direct countermeasures are being undertaken to control these blooms. However, extensive research is being undertaken to understand - and ultimately predict - when such outbreaks may occur. [e.g.104] Such knowledge may allow aquaculturists to take measures to protect their investment.

Yellow Sea

The third example of the increasing impacts of harmful algae in China comes from the Yellow Sea. This example is one that received widespread international coverage. In 2008, a bloom of the macroalgal species *Enteromorpha prolifera* (also called *Ulva prolifera* or sea lettuce) occurred at the venue of the Olympic Games sailing competition, almost blanketing the water with filamentous scum.[105] Blooms of this magnitude in this region had not previously been observed. One of the features of this species and its blooms is that it tends to float, making detection from remote sensing (satellite imaging) feasible. It is from such approaches that the scale of these blooms and their change over time can be estimated.[106] A 10-year record of images of the region shows that prior to 2007, the area covered by *E. prolifera* was <21 km^2. In 2008 the scale of the bloom was >1900 km^2, and in 2009 it was 1600 km^2.[107]

The Yellow Sea has long had massive nutrient loading, especially nitrogen.[108] Interestingly, there is no evidence that the quantity of nutrient loading changed dramatically in 2008 when the magnitude of these blooms began to escalate (the increase in nutrient load-

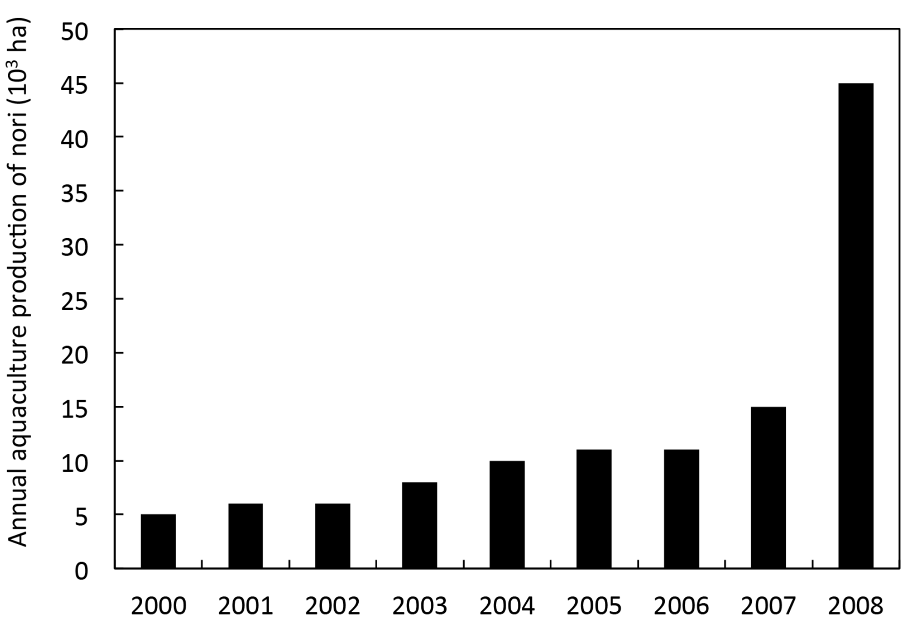

Figure 5: Annual production of nori in the Yellow Sea. Note the extent of the change between 2007 and 2008. Data replotted from Hu et al. (2010).

ing has been more steady over the past decades). One change that did occur between 2007 and 2008 was the scale of aquaculture production of the seaweed *Porphyra yezoensis* (or nori). Nori are the thin sheets of seaweed used in cooking, typically in sushi. The scale of production of nori increased from ~600 Ha in 1999 to >40,000 Ha in 2008 (Fig. 5).[109] Nori are cultured on rafts and ropes, the same physical substrate to which *E. prolifera* attaches. Culturing nori without *E. prolifera* "contaminants" is difficult. When nori are harvested, *E. prolifera* detaches and begins to float away. When the winds and currents are favorable, the *E. prolifera* algae are then transported into the Yellow Sea, where they can continue to access nutrients and grow. Under the "right" conditions (including favorable winds), they can accumulate in bloom proportion along the shore near Qingdao. This is the scenario that occurred in 2008, leading to the massive and costly blooms at that time. The bloom reoccurred, albeit at various magnitudes, in the same region in 2009 and 2010. The aquaculture production of nori thus provides the conditions for the *initiation* of growth of *E. prolifera*, but its *biomass* accumulates when the bloom is transported to the nutrient-rich Yellow Sea, where its prolific growth and accumulation exemplifies its name, *prolifera*.

The 2008 Olympic games were severely impacted by this bloom event (Fig. 6). Approximately 1 million tons of algae were removed from the waters before the sailing regatta, requiring about 15,000 members of the Army to assist in the removal effort.[110] It has been estimated that the cost associated with the management of the *E. prolifera* event in 2008

Figure 6: The 2008 bloom that blanketed the venue for the Olympic Sailing Regatta in Qingdao was caused by Enteromorpha prolifera (upper left panel- photo by M.J. Zhou; upper right panel- photo by G.W. Saunders, www.unb.ca/cemar), causing a massive area of the region to be covered by algae (lower left panel- reproduced from Furuya et al., 2010; lower right panel- photo by V. Kovalenko, yachtpals.com).

was greater than $100 million. In addition to the immediate costs of clean up, the bloom also caused massive damage to the abalone and sea cucumber industries, both important cultured species in the Qingdao region. When these losses are calculated along with the immediate management costs, the total economic loss due to the 2008 *E. prolifera* bloom is closer to $200 million.[111] This figure overshadows the estimate of the profit of the nori industry in 2007, which was roughly $50 million.[112] Qingdao, when not an international destination for sailors, is a local tourist and holiday region for Chinese. Thus, the economic losses associated with blooms of this magnitude are enormous.

Enteromorpha prolifera is a species that occurs worldwide, often associated with regions of high nutrient input, including near sewage outfalls.[113] This case study highlights the complexity of the interactions that may be required for a bloom to affect a particular region. As shown here for the Yellow Sea, nutrient enrichment is a necessary condition for this quantity of biomass of algae to be formed - but in order for the bloom to be initiated, the nori industry and the availability of physical substrate were also required.

In small amounts, this species is not generally considered to be toxic to wildlife or to humans. However, in large quanitites toxic compounds form which can have devastating impacts. When large quantities of *Enteromorpha* spp. begin to decompose, ammonia and hydrogen sulfide are given off.[114] These can be at levels that are acutely toxic to fish.[115] Low levels of hydrogen sulfide can also cause human illnesses. At low doses, eye irritation or sore throat may occur, while at higher levels symptoms may range from dizziness to breathing difficulty to memory loss. New data also suggests that *Enteromorpha* spp. make the compound dopamine which inhibits other animals as a chemical defense against grazing.[116] Neither the levels of dopamine from the 2008 Qingdao bloom, nor its potential effects on wildlife or humans who came in contact with it are known. Prolonged exposure to such chemicals *in general* is associated with neurological disorders such as depression, schizophrenia and attention deficit disorder.[117]

The phenomena of these blooms in the Yellow Sea is still comparatively young and much is yet to be learned about their causes, impacts, and potential controls. What is apparent is the need for the economic costs of these events to be balanced against the economics of the growing aquaculture industry.

OUTLOOK

This brief review has highlighted just a few examples of the types, impacts, and economic costs associated with the expanding HAB problem in China. The examples discussed here are not unique to China but represent some of the types of HAB events that occur throughout Asia. The increased use of nitrogen and phosphorus-based fertilizers has expanded in recent decades, with the positive outcome of increased food supplies and reduced malnutrition. Global fertilizer use is projected to double by the year 2080.[118] World population is expected to reach 9 billion within the next few decades, and diets are becoming more meat-based with economic development, leading to increasing concentration of meat production in CAFOs.[119] The growth of aquaculture throughout Asia is also occurring at an astounding pace.[120] Energy consumption is rising (Fig. 7).[121] Population, agriculture, aquaculture, and energy consumption are all associated with increasing nutrient pollution, especially nitrogen.[e.g.122,123] Most of these increases are on track to occur in parts of Asia that are already saturated with nitrogen and poorly prepared to deal with the resulting environmental and human health effects of nutrient pollution. Pressures for increasing development are at odds with the pressures for reducing nutrient loads. Costs for building new sewage treatment facilities or developing more efficient agriculture are still often considered to be too great an investment to yield an immediate payback. The consequences of development and the excessive use of nutrients are increased eutrophication, changes in ecology and biodiversity, more HABs, and more algal toxins.[124]

While China was highlighted here, the types of algal blooms described are expanding throughout Asia and the world. There are many more types of toxic algal blooms than described here, with equally challenging human health and economic consequences. Although the science of understanding how and why these events occur has been rapidly advancing, the prospects of reducing these events or their impacts are, unfortunately, not very bright. When climate change and rising temperatures are also considered, the outlook is even more bleak. The growth of many of the species that form these blooms increases under warmer conditions.[125] Some CyanoHAB species, including *M. aeruginosa*, have been found to become more toxic at higher temperatures.[126] Indirect effects of warming must

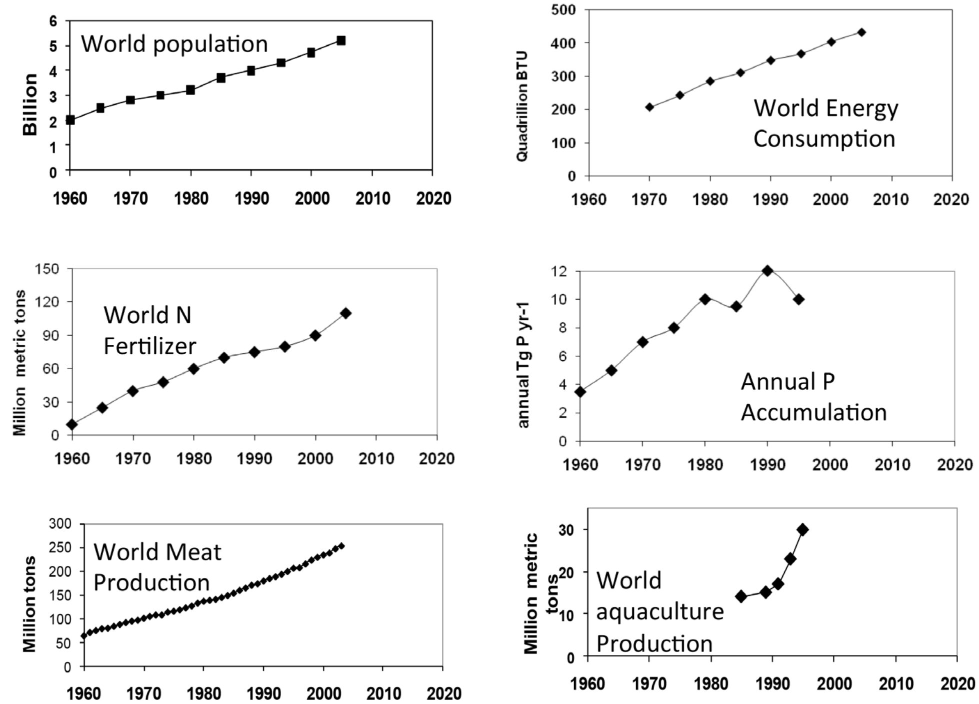

Figure 7: General trends in population, energy consumption, fertilizer use, and accumulation, and meat and aquaculture production from 1960 to present. Data compiled from www.census.gov/ipc/www/img/worldpop.gif, Global Fertilizer Industry, www.fertilizer.org, and the Food and Agriculture Organization (FAO) of the United Nations (2007). Reproduced from Glibert et al. (2010) with permission of the *Journal of Marine Systems*.

also be considered. As temperatures warm, precipitation patterns will continue to change. Higher precipitation rates, projected for some parts of the world, will lead to greater runoff and greater water pollution.[127] Warmer temperatures will also increase the rate at which nitrogen gaseous compounds (for example, ammonium) are volatilized to the atmosphere. The problems are thus enormous and immeasurably complex, and the challenges associated with reversing these events in the short term are more than daunting.

To address these needs, the community of biologists and chemists studying these events will need to interface closely with a wide array of peers in other fields: public health officials (to further understand human health effects); fisheries biologists and fishermen (to further understand impacts on ecosystems); climate scientists (to assess climate change scenarios); watershed modelers and hydrologists (to estimate future changes in the land derived inputs); and social scientists, managers, and policy makers (to define future land use scenarios and to interpret results in a policy context).[128] There is progress along these lines and cross-regional Asian studies on HABs are underway.[129] Predictive models are advancing to provide early warning for aquaculturists. Monitoring of water and seafood is underway in many areas to protect human health. Massive sums are being invested to upgrade sewage treatment in many areas. At the current scale, however, these efforts are far too little to stem the effects of advancing industrialized agriculture (and aquaculture) and a growing human population. Unfortunately, ecosystems and human health will likely continue to be affected by HABs in Asia and worldwide at an escalating pace until the economic scale of lost ecosystem services and human health impacts outpaces economic and population growth. Nutrient loads must be reduced, but the challenge is great.

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