Global Perspectives on Harmful Algal Blooms: Impacts and Responses

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Abstract

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Harmful algal blooms (HABs) can have devastating effects on aquatic ecosystems, economies, and communities. In general, their effects are also likely to worsen and become more frequent because of climate change. This paper will examine contemporary attempts to predict, prevent, monitor, control, and adapt to HABs.

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Dedication

To my family, my late grandparents Lester and Jean Brown and my late sixth grade teacher Maureen Ouellette.

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Foreword

Over the summer of 2020, I interned remotely for The Climate Change Law Observatory for Chile (*El Observatorio de la Ley de Cambio Climático para Chile*), an initiative co-run by The Center for Climate and Resilience Research ((CR)2) (*El Centro de la Ciencia del Clima y la Resiliencia*), a Chilean organization (in collaboration with *El Centro de Derecho Ambiental, de la Universidad de Chile*, the University of Chile's Center for Environmental Law). After the internship ended, I returned to Clark University for my second and final year in the school's International Development and Social Change Master's program. I was required to write a final paper for the program and asked my supervisor for the internship, Cecilia Ibarra, if there were any subjects I could write about that could potentially benefit (CR)2. She suggested harmful algal blooms (HABs).

HABs refer to the excessive growth of phytoplankton which can hurt humans and aquatic species (and in certain cases, cause "red tides") (Sanseverino et al., 2016). Chile has a large aquaculture sector (Organization for Economic Co-operation and Development [OECD], 2020), that HABs threaten, and experienced a massive HAB in 2016, killing off 12% of the country's salmon production and leading to an economic loss of over $800 million (León-Muñoz et al., 2018). However, Chile is not unique in being vulnerable to HABs. As this paper will touch on, HABs have affected countries as different as China, Ecuador, Saudi Arabia, and the US (Alias Gokul et al., 2020; Borbor-Córdova et al., 2018; D'Anglada et al., 2018; Marraro et al., 2016; Tian & Huang, 2019; Webster & Pavolvich, 2019). HABs can even occur in inland bodies of water, meaning that different communities in places like Michigan, Florida, and California are all vulnerable to HABs (Anderson et al., 2019; Hoagland et al., 2020; Webster & Pavolvich, 2019), albeit in different ways. That vulnerability to HABs is so widespread globally speaks to the pressing need for policy-makers to enact policies that can stop HABs from happening and monitor and control them if they do.

Introduction

Harmful algal blooms (HABs) are growths of phytoplankton which can produce nocive toxins and deplete oxygen in waterbodies, threatening ecosystems and human health (Sanseverino et al., 2016). They can partially or entirely kill off populations of other plants and animals near them, causing serious problems for biodiversity and for people who depend on aquatic resources for their livelihoods (Sanseverino et al., 2016). The toxins they produce can reach humans in a range of ways, including through direct physical contact (e.g. when someone is swimming) or through consumption of water or seafood that has been affected by HAB toxins, potentially leading to illness or even death (Sanseverino et al., 2016). They can harm organisms as diverse as sea birds, marine mammals, fish, sea grasses, invertebrates (Griffith & Gobler, 2020), and, of course, humans (Sanseverino et al., 2016).

HABs are not a rare or minor problem. Their direct costs have been estimated conservatively to be about $100 billion per year - and that is not including healthcare costs (Bernard et al., 2014; Trainer & Yoshida, 2014, as cited in Borja et al., 2020). Single HABs can be especially devastating, such as the aforementioned 2016 HAB which killed off 12% of Chile’s salmon production (León-Muñoz et al., 2018), a 2014 HAB in Lake Erie that cost a drinking water plant in Toledo, Ohio roughly $4 million and the economy about $65 million (Bingham et al., 2015, as cited in Gaskill et al., 2020), or a HAB in the North Pacific Ocean that produced record-breaking concentrations of the neurotoxin domoic acid in 2015 (Moore et al., 2020). Additionally, certain HAB species may be producing faster-growing and longer-lasting HABs (Griffith and Gobler 2020). The faster growing and longer lasting HABs become, the more important it will be to understand them and their impacts and to think about ways to prevent and minimize them.

This paper seeks to provide an overview at a global scale of how HABs are changing and what those changes mean for ecosystems and communities. It also seeks to describe many of the most common and several of the more recent approaches to addressing HABs. Additionally, it aims to provide different kinds of readers (e.g. policy-makers, researchers) with insights to inform their work (Table 1).

Table 1.

Reader	This Paper May Give…
Policy-makers (at various administrative levels: municipal, state or province, national)	• A general overview of what HABs are and related policy responses. • Ideas of certain networks and organizations that government bodies could work with. • A sense of how policies (e.g. those related to climate change and greenhouse gas emissions) have unintended consequences related to HABs.
NGOs	• Ideas of certain actors to collaborate with to address HABs. • Inspiration for types of HAB response projects to implement or ways to improve existing projects.
Members of the Fishing Industry	• More insight into how others in the field work with researchers and government officials to prepare for and adapt to HABs.
Potential Volunteers	• A sense of what HAB-focused citizen science initiatives are like. • An understanding of current HAB-related technological devices, programs, and networks.
Researchers	• A review of the broader context for the research project(s) they are working on. For researchers working in related fields, this paper may serve as a brief guide to the science behind HABs and responses to them. • For HAB researchers, many of the concepts may seem familiar, but it may offer new information (and maybe even new perspectives).

This paper first describes the methods used for this research. It then provides some basic information about HABs: what they are; how different human activities can drive their growth;

their negative impacts; community perceptions of and responses to them; HABs, justice, and equity; and efforts to address them. This paper goes on to examine four central aspects of responding to HABs: prediction, prevention, monitoring, and control and, then, to make recommendations related to research, responses to HABs, and HABs' effects on communities.

Methods

In order to conduct a systematic review of existing literature, two search engines were used to find the academic articles for this paper: Google Scholar and the Goddard Library's "Discovery at Clark Libraries" search function. Those search engines were used to look for peer-reviewed articles in either English or Spanish. For the Clark/Goddard search engine, these keywords were used: "Harmful algal blooms", "climate change", "Chile", "mitigation", "community responses", "local knowledge", "food systems", and "Floraciones de algas nocivas". For the Google Scholar search engine, these keywords were used: "Harmful algal blooms", "Chile", "Africa", "China", "Korea", "Australia", "Latin America", "Caribbean", "Europe", "monitoring", "mitigating", "solutions", "algae", "Floraciones de algas nocivas", "FAN", and "Chile".

The National Centers for Coastal Ocean Science's (NCCOS) (part of the US National Oceanic and Atmospheric Administration (NOAA)) website provided additional materials. These were mostly government reports and other technical publications, as opposed to academic journal articles. One report (Sanseverino et al., 2016) was found by searching "harmful algal report" in Google. The RAMOGE report (n.d.a), as well as a page on RAMOGE's website (n.d.b), was found by searching "RAMOGE" in Google after reading about RAMOGE in Borja et al. (2020). The name of every journal was checked in Bealls' List, a website that identifies predatory journals. Any journal that Beall's List identified as predatory was eliminated from the study.

Background

HAB-producing species (referred to in this paper as HAB species) are phytoplankton, including dinoflagellates, diatoms, and cyanobacteria (Sanseverino et al., 2016). Among those three, dinoflagellates are most often responsible for HABs. They are also responsible for what are commonly referred to as “red tides”. Dinoflagellates are microalgae that propel themselves using two tail-like appendages. When they reproduce, they form dormant cells called cysts that can persist for several years at the bottom of a waterbody before germinating to produce HABs. The toxins dinoflagellates produce can lead to a range of illnesses in humans, including Diarrhetic Shellfish Poisoning (DSP), Neurotoxic Shellfish Poisoning (NPS), Paralytic Shellfish Poisoning (PSP), and Ciguatera Fish Poisoning (CFP) (Sanseverino et al., 2016).

Diatoms are unicellular organisms that often have spines that can clog and damage fish gills, killing the fish (Sanseverino et al., 2016). Diatoms in the *Pseudo-nitzschia* genus produce domoic acid, which causes Amnesic Fish Poisoning (Sanseverino et al., 2016). Cyanobacteria, also known as blue green algae, are bacteria that have been known to release cyanotoxins into drinking and recreational water, causing serious public health problems (Sanseverino et al., 2016). Those blooms that dinoflagellates, diatoms, or cyanobacteria form that hurt other species (in some cases, humans) are considered HABs.

Human activities have been and are driving the dramatic expansion of HABs (into both fresh and marine waters) and increasing the frequency and the duration of HAB species (Glibert, 2020).

Drivers of Harmful Algal Blooms

Although HABs occur naturally, human behavior can unintentionally drive the growth of HABs in a number of ways. A major way is by adding nutrients that benefit HAB species into waterbodies, such as nitrogen (N) and phosphorus (P), also known as nutrient loading. For example, nutrient loading, combined with a range of other factors, including rising temperatures and extreme climatic conditions, will likely enable cyanobacteria to dominate in many aquatic ecosystems (Paerl et al., 2019). Nutrient loading is related to a process called eutrophication, during which the amount of nutrients in a waterbody far exceeds typical levels for that waterbody, excessively fueling the growth of algae, including HAB species (Young et al., 2015). As a result, the algae depletes much of the oxygen in the waterbody (Young et al., 2015).

Several human activities that cause nutrient loading, including agricultural intensification, development on previously undeveloped land, and energy consumption, increase as the human population grows (Marraro et al., 2016). Synthetic fertilizer application, a major driver of nutrient loading, is projected to increase dramatically in many regions of the world (Anderson, 2012). Weakening sanitation infrastructure can also play a part, since aging sewage and storm water systems can leak nutrients into surrounding soils and surface water (Marraro et al., 2016). However, projections of nutrient pollution globally are less certain than climate projections because nutrient pollution is decreasing in some regions (i.e. Europe) and stabilizing in others (i.e. North America and Australia) (Glibert, 2020).

In addition to nutrient loading, humans have been altering and degrading aquatic habitats in other ways, including overfishing, sedimentation, and harbor construction (Wells et al., 2020). The resulting changes in these habitats can often favor the expansion of harmful algae (Wells et al., 2020). The northwestern Gulf of Mexico provides a striking example of how human changes to aquatic habitats can substantially encourage the growth of HAB species. The area's benthic habitat does not offer optimal conditions for the2 growth of benthic dinoflagellates (Durán-Riveroll et al., 2019). However, the thousands of oil platforms that humans have constructed in the area provide substrates on which benthic dinoflagellates can attach and reproduce (Durán-Riveroll et al., 2019) (That is not to say that oil platforms are the prime cause of HABs in the region, but they can contribute to the expansion of HAB species.). Other human activities, such as destroying mangroves and deforestation more generally, lead to a range of changes, including nutrient loading and coastal erosion, that have consequences for the number and biogeography of benthic HAB species (Durán-Riveroll et al., 2019). The introduction of exotic species, including fish and shellfish, is another human-led driver of changes in HAB biogeography, intensity, and frequency (Cuellar-Martinez et al., 2018).

Climate change may be driving the speed and extending the duration of certain HABs (Griffith & Gobler, 2020)., another reason why serious reductions in GHGs are desperately needed. HABs are happening more often, lasting longer, and occurring in new places – both in fresh and marine waters (Glibert, 2020). In correlation, climatic changes and other anthropogenic impacts are occurring with increased regularity in marine and freshwater systems (Sanseverino et al., 2016).

Of course, one of the most direct ways climate change may affect aquatic ecosystems is through changes in temperature. For example, warming can accelerate the growth of cyanobacteria (Griffith & Gobler, 2020). However, the relationships between how toxic a HAB is and temperature may be non-linear and may vary from strain to strain (Griffith & Gobler, 2020). Toxic cyanobacteria have growth rates that increase with warming temperatures up to an optimal temperature that is higher than it is for other kinds of phytoplankton (Griffith & Gobler, 2020), which they may compete with. Additionally, by absorbing light at the surface of a body of water, cyanobacterial blooms can increase local temperatures, causing a vicious cycle where the bloom warms the water and the warmer water drives the bloom's growth, leading, in turn, to warmer water (Griffith & Gobler, 2020). Although cyanobacteria may thrive in higher temperatures, other classes of phytoplankton including diatoms and dinoflagellates decay when temperatures get too high (Sanseverino et al., 2016). If cyanobacteria are competing with diatoms and/or dinoflagellates in a particular habitat, increased local temperatures caused by climate change could favor the dominance of cyanobacteria.

HABs may expand into new areas. For example, a study conducted in the north-west European shelf attempted to predict the distribution of HAB species (Townhill et al., 2019). The study predicted that the majority of species will expand north during this century and that the central and northern North Sea will become more suitable for HAB species (Townhill et al., 2019), potentially affecting Norway and the UK. Changes in precipitation patterns (e.g. increases in the frequency of droughts and storms in different regions) could make factors, like freshwater flows and water residence times, more conducive to the growth of HABs (Glibert, 2020).

Temporal limits on HABs, like geographic ones, may also shift. Another study found that *Alexandrium* (dinoflagellates) blooms in the Puget Sound could start up to two months earlier and end up to a month later by the end of the 21st century (Moore et al., 2011, as cited in Townhill et al., 2019, p. 1890).

Climate change could drive HAB growth through ocean acidification. As ocean acidification kills off coral reefs, they sometimes turn into systems dominated by macroalga and provide habitats for benthic HAB species (Berdalet et al., 2017). For example, researchers working in the Red Sea observed high mortalities among corals on inshore reefs; those dead coral surfaces could favor the expansion of HABs (Alias Gokul et al., 2020).

As humans continue to spur the growth of HABs through the activities described in this sub-section, HABs' effects on people and the environment may become much worse.

HABs' Health, Economic, and Environmental Effects

Changes in HAB distribution, frequency, size, and toxicity will have serious implications for public health. Marine HABs, for example, can indirectly poison people in a number of ways (including through infected seafood) leading to illnesses, such as Amnesic Shellfish Poisoning (ASP), Neurotoxic Shellfish Poisoning (NSP), Paralytic Shellfish Poisoning (PSP), and Ciguatera Fish Poisoning (CFP) (Sanseverino et al., 2016). Globally, CFP is one of the most dangerous poisoning syndromes that HABs cause in humans (Anderson, 2012). Estimates put the number of cases of CFP that occur around the world each year at somewhere between 50,000 and 100,000 (Anderson et al., 2019). However, those estimates may even cover as little as 20% of actual cases because CFP is often misdiagnosed or underreported (Anderson et al., 2019; Berdalet et al., 2017). One implication of these observations is that HABs may be having a much larger impact on public health than one might think, especially since food consumption is just one of the ways HABs can make people sick. For example, certain toxins can become aerosolized, get picked up by winds, and get into the lungs of people nearby, causing respiratory problems (Griffith & Gobler, 2020). There is a lot of uncertainty about: when toxins enter the air in the form of airborne droplets, how much the toxins actually make it through the transition, and of the human health effects of breathing in aerosolized toxins (Hu et al. 2020).

Of course, the illnesses HABs cause bring financial costs with them, which contribute to the HABs' overall costs to economies. Misleading symptoms that can accompany exposure to a

HAB can make it very difficult to accurately assess the financial health costs of HABs because of misdiagnosis (Kouakou & Poder, 2019). Regardless, the health effects of HABs can be very costly. Estimated total costs of medical treatments from long-lasting, large HABs can be in the millions of dollars (Hoagland et al., 2020). Those costs could rise to tens of millions if those kinds of HABs were to become commonplace (Hoagland et al., 2020). Breathing difficulty and gastroenteritis are among the most severe HAB-related illnesses in terms of their impact on human health (Kouakou & Poder, 2019).

HABs also pose significant risks for economies, businesses, and individuals' livelihoods. As mentioned earlier, globally, a conservative estimate has placed the direct cost of HABs at about $100 billion per year, not including healthcare costs (Bernard et al., 2014; Trainer and Yoshida, 2014, as cited in Borja et al., 2020). However, estimating the total costs of HABs impacts can be very complex (Borja et al., 2020).The rise in the size and frequency of HABs may increase their economic costs. How people undertake certain economic activities in the future, of course, will also affect the levels of risk HABs pose. For instance, since the number of desalination plants are growing, it is "inevitable" that desalination plants will cross paths with HABs (Anderson, 2012). HABs could prevent desalination plants from providing freshwater to communities who need it because the algae themselves could pass through many of a plant's pretreatment tools, such as filters (Anderson, 2012).

HABs are serious threats to aquatic ecosystems. Fish that are near HABs, which deplete oxygen in the water, can experience oxidative stress and die (Sanseverino et al., 2016). The toxins that HABs produce can travel through the food chain as organisms consume other organisms infected by the toxins (Sanseverino et al., 2016). HAB species can harm many organisms at different levels of the water column. Harmful dinoflagellates sometimes migrate to the benthic zone at the bottom of the water column at night and to the surface of the water column by day (Griffith & Gobler, 2020). Certain algae can form dense mats that smother any aquatic organisms in a water body (D'Anglada et al., 2018). These are just a few of HABs' impacts on aquatic systems.

Community Perceptions of and Responses to HABs

Several of the academic articles examined how communities (and individuals within those communities) perceive and respond to HABs. One study (Moore et al., 2020) looked at how 16 fishery-dependent communities in the northwestern United States adapted to fishery harvest closures in 2015. Those closures were the result of a gigantic HAB of *Pseudo-nitzschia* in the Pacific Ocean. Perhaps unsurprisingly, income diversification was an effective strategy for many whose livelihood the HAB had affected. However, income diversification sometimes came with additional costs, such as the need to buy new gear and permits for different fisheries. Regulatory restrictions could keep some fishers from switching to new fisheries. Even when they could switch to new fisheries, fishers might lack specific knowledge about the new fisheries and/or the best vessels for accessing them.

Other researchers (Webster & Pavolvich, 2019) sought to model how different groups of agents (e.g. farmers, coastal business owners, policy-makers) in the Lake Erie watershed perceive HABs and whether and how they respond to them. A key aspect of the model was whether or not policy-makers implemented policies in response to HABs. They found that agents in the model tended to have relatively short memories. After a HAB occurred, these agents generally did not remain concerned for a long time. People in the model may also become desensitized to HABs as they continue to occur. However, certain interest groups (e.g. local farmers) continued to be concerned for a lot longer.

Of course, their paper is based on a model (albeit a model based on the watershed's history) and is specific to one particular part of the world. It would be risky to assume that members of any community would definitely behave like the agents in this model. However, their article does offer some insight into how individuals may behave. The possibility of different members of the public losing interest in and concern for HABs is worth keeping in mind when implementing HAB-related policies and programs because it could undermine support for those policies and programs.

Another study shows the value of collaborating with interest groups. The study looked at efforts aimed at spreading information about Ciguatera Fish Poisoning (CFP) in three coastal fishing communities in Cuba (Morrison et al. 2008, as cited in Durán-Riveroll et al., 2019, p. 17). Where the fishing community was well organized, information about CFP was shared effectively and the number of CFP cases was low (Morrison et al. 2008, as cited in Durán-Riveroll et al., 2019, p. 17). In a less organized community, the information barely made it to the fishers and CFP cases remained high (Morrison et al. 2008, as cited in Durán-Riveroll et al., 2019, p. 17). The study shows why it is important to establish strong networks of information exchange among seafood producers, regulatory authorities, and public health personnel and to promote local education in areas where ciguatera is common (Morrison et al. 2008, as cited in Durán-Riveroll et al., 2019, p. 17).

Researchers for a different study examined how coastal authorities, fishers, and restaurant owners in coastal Ecuador perceived and reacted to HABs – in this case, "red tide" events (Borbor-Córdova et al., 2018). In general, the respondents tended to have a low risk perception of HABs' impacts on human health. There was more of a concern for how the "red tides" would affect the beaches aesthetically and the local tourism sector. Someone's livelihood or profession and education level were significant determinants of that person's risk perceptions of HABs. A lack of education often coincided with a low risk perception. However, most fishers who had lived along the coast for 30 years or more were highly aware of the existence of red tides and the authors concluded that they tended to have a high risk perception of HABs' impacts on livelihoods, but a low risk perception of their impacts on human health. People with higher levels of education often identified nutrient inputs and climate change as drivers of HABs.

Other factors contributed to the overall low risk perception. For instance, there was a misconception among certain respondents that cooking an infected shellfish would eliminate the toxins (Borbor-Córdova et al., 2018). Another factor was adaptation itself: fishers who had developed strategies for adapting to the HABs were more likely to have a lower risk perception. That outcome points to a potential unanticipated consequence of supporting adaptation efforts.

Another way that community members respond to HABs is through citizen science, engaging in efforts to prevent and minimize the HABs affecting their communities. Later parts of this section will talk about different citizen science projects.

HABs, Justice, and Equity

HABs are deeply, thematically linked with questions of environmental justice and equity. Those who did little to contribute to the growth of HABs may, in many cases, be highly affected by them. As with other natural disasters, communities with high levels of social, political, and financial capital may be better able to withstand HABs than less advantaged communities (Moore, 2020).[1] Communities where highly polluting businesses have established themselves may bear the brunt of the pollution's effects on HABs. For example, the community of Mariel,

[1] The same argument could be applied to some companies, including companies whose practices drive HAB growth.

Cuba, which experienced high levels of industrial pollution has had the highest rate of ciguatera fish poisoning in the country (Morrison, 2008).

HABs can also undermine long-standing cultural and livelihood practices, potentially affecting the physical and emotional health of people involved in those practices (Moore, 2020). For example, many Alaskan Native American communities have traditionally harvested and consumed shellfish (Harley, 2020). However, concerns over paralytic shellfish toxins linked to HABs from *Alexandrium* species have led to a decline in shellfish consumption in some communities (Harley, 2020).

HAB-Focused Programs

This section will briefly discuss several major organizations that implement programs to address HABs. This section is by no means meant to be an exhaustive list of all the organizations that do so. At the international, national, and regional level, many organizations and networks have been formed to address HABs. There is a database of global marine HABs called the Harmful Algal Events Dataset (HAEDAT) (Sanseverino et al., 2016), that is part of UNESCO's (United Nations Educational, Scientific and Cultural Organization) Intergovernmental Oceanographic Commission (IOC) (Harmful Algal Events Dataset [HAEDAT], 2018). The IOC and UNESCO's Scientific Committee on Oceanic Research (SCOR) and the sponsored two international programs GEOHAB (2000-2013) and GlobalHAB (2016 - set to end in 2025) (Anderson et al., 2019). Both programs helped define goals, objectives, and action plans that guide HAB management and research efforts at regional and local levels (Anderson et al., 2019). Both have collaborated with other international efforts, including the Group on Earth Observations Biodiversity Observation Network (GEO BON), the Marine Biodiversity Observation Network (MBON), and the Global Ocean Observing System (GOOS) (Anderson et al., 2019). GEO BON, a collaboration of roughly 100 governmental, non-governmental, and inter-governmental organizations focused on improving practices related to data on biological diversity, is just one of the Group on Earth Observations' programs (Group on Earth Observations [GEO], n.d.). Another one of its programs, the GEO Biodiversity and Ecosystem Sustainability community is working on an early warning system for HABs (GEO, n.d.).[2]

In Asia, several regional coordinating groups exist, such as The Northwest Pacific Action Plan (NOWPAP) (an initiative of the United Nations Environment Programme's Regional Seas Programme), the Targeted HAB Species in the East Asia Waters (EASTHAB) program, the Inter-governmental Oceanographic Commission's Sub-Commission for the Western Pacific-HAB (IOC/WESTPAC-HAB), and the HABs section of the North Pacific Marine Science Organization (PICES) (Anderson et al., 2019). In 1995, South Korea established a national monitoring program, that works with over 30 local offices, through the National Fisheries Research and Development Institute (NFRDI) (Anderson et al., 2019). China and the Philippines have similar initiatives called Chinese Ecology and Oceanography of Harmful Algal Blooms (CEOHAB) and Ecology and Oceanography of Harmful Algal Blooms in the Philippines (PhilHABS), respectively (Anderson et al., 2019).

The EU has funded a range of HAB research projects, including ASIMUTH (Applied Simulations and Integrated Modeling for the Understanding of Toxic and Harmful Algal Blooms) (Anderson et al., 2019). Led by Ireland, in partnership with Scotland, France, and Spain, the project aimed to improve the ability of warning systems to forecast HABs, especially in and around the North-Eastern Atlantic European shelf (Anderson et al., 2019). Other EU

[2] For policy-makers looking to scale up or improve HAB monitoring efforts, UNESCO's SCOR and IOC and GEO BON, MBON, and GOOS may be the most important organizations to try to collaborate with (of those described in this sub-section) simply because of their international scale. Of course, it may also make sense to consider collaborating with regional and national organizations in one's region.

research projects include: Co-development of Climate services for adaptation to changing Marine Ecosystems (CoCliME) and the Atlantic Area network for introduction of innovative toxicity alert systems for safer seafood products (Alertox-Net) ((Anderson et al., 2019).

In Latin America, the International Atomic Energy Agency has supported a network of Latin American and Caribbean (LAC) countries, including Brazil, Chile, and Mexico (Cuellar-Martinez et al., 2018). The network acts as an early warning system for both HABs and biotoxins in seafood (Cuellar-Martinez et al., 2018). It has two regional reference centers: one in El Salvador and the other in Cuba (Cuellar-Martinez et al., 2018).

In the US, the National Oceanic and Atmospheric Administration (NOAA) and the National Aeronautics and Space Administration (NASA), and several federal agencies fund programs within regions of the US (Anderson et al., 2019). The latter, in turn, support HAB monitoring programs and form part of a network for monitoring the oceans (Anderson et al., 2019).

Responding to HABs

This section will look at HAB-response strategies that can fall into one or more of the following categories: prediction (of a HAB), prevention (of a HAB in the first place), monitoring (an existing HAB), and control (limiting the extent and impacts of a HAB after it has happened). In many cases, a combination of strategies from several or all of these categories is needed. HABs are likely to be a problem humans will be grappling with for a long time. Governments and nongovernmental organizations should coordinate to scale up response strategies, which means sharing lessons learned from past responses, such as the responses this section highlights.

Prediction

HAB prediction enables control and monitoring responses to be better informed and prepared. It can also help to evaluate how effective prevention methods are. This section will describe several individual US-based prediction projects, before describing a prediction system in Shenzhen City, China, a prediction approach using deep learning in South Korea, and the potential of studying HAB cysts.

The Prevention, Control, and Mitigation of Harmful Algal Blooms Program (PCMHAB) managed by NOAA's National Centers for Coastal Ocean Science (NCCOS), has led to different scientific projects that could aid HAB prediction and monitoring initiatives. For example, one project was aimed at developing tools to predict blooms of *Karenia brevis*, a HAB species, in the Gulf of Mexico West Florida Shelf in order to inform management agencies (National Centers for Coastal Ocean Science [NCCOS], n.d.a). The researchers' hypothesis was that upwelling is needed for *K. brevis* blooms to form, but if there is too much upwelling, a diatom bloom will occur instead (NCCOS, n.d.a). Based on this hypothesis and the conceptual model they developed, they were able to explain why there was no *K. brevis* HAB in 2010 and to predict (months in advance) that there would be no major bloom in 2013, but that one would occur in 2014 (NCCOS, n.d.a). Another PCMHAB project focused on *K. brevis* involved the development of a portable hand-held sensor that uses nucleic acid sequence-based amplification to detect *K. brevis* (NCCOS, n.d.b).

K. brevis is not the only HAB species that has been the target of a PCMHAB program. For example, a PCMHAB initiative sought to understand and model what causes blooms of *Alexandrium fundyense*, a HAB species, in the Gulf of Maine (NCCOS, n.d.c). The researchers analyzed annual cyst maps to find out the minimum number of sampling stations they would need in order to make accurate predictions about *A. fundyense* (NCCOS, n.d.c). Through various experiments and through analyzing field data, they studied how *A. fundyense* cysts sink to the ocean bottom and how water flows move sediments and cysts up from the bottom and around the region (NCCOS, n.d.c). All of this information was then incorporated into a pre-existing model that is geared towards predicting *Alexandrium* blooms (NCCOS, n.d.c).

Off the coast of Shenzhen City in China, researchers have developed a method that combines on-the-ground and satellite observations with a hydrodynamic and water quality model and a web-based Geographic Information System (Tian & Huang, 2019). The on-the-ground observations come from a series of buoys and tide, hydrologic, and meteorological observation stations (Tian & Huang, 2019). Users who go onto the web portal can view real-time maps, on-the-ground observations, early warning information and forecasts (Tian & Huang, 2019). The program has been used to predict HABs up to five days in advance. Its models for estimating chlorophyll-a distributions rely on deep learning algorithms (Tian & Huang, 2019).

Researchers in South Korea used a deep learning model to predict algal blooms in four of the country's major rivers (Lee & Lee, 2018). Deep learning is a sub-method of machine learning, where a machine analyzes a large amount of data and identifies patterns from it. The data came from 16 dammed pools on the rivers and included variables, such as temperature, number of cyanobacteria cells, and chlorophyll-a concentrations. The researchers were interested in finding out which of three deep learning methods (multilayer perceptron (MLP), long short-term memory (LSTM), and recurrent neural network (RNN)) could most effectively predict chlorophyll-a concentrations a week in advance. They compared the results with an ordinary least square regression analysis (or OLS, which the authors identify as a commonly used model) and the data itself that was based on a measure called the root mean square error. Overall, the

LSTM model was the most effective at making predictions. For most of the dammed pools, the deep learning models turned out to be more accurate than the OLS.

A research approach worth highlighting because it could inform prediction strategies is studying HAB cysts. *Alexandrium* cysts can remain preserved in sediments for centuries (Feifel et al., 2012, as cited in Hennon & Dyhrman, 2020). Researchers could possibly revive *Alexandrium* cysts for physiological studies in order to understand how *Alexandrium* species have historically responded to periods of ocean warming (Ribeiro et al. 2013, As cited in Hennon & Dyhrman, 2020[3]). How they have responded in the past may be very indicative of how they would behave in future periods of ocean warming.

<u>Prevention</u>

A multi-pronged approach to HABs would benefit from prevention and prediction measures because prevention could limit the number and size of HABs and prediction could help to evaluate how effective the prevention measures were. Of course, preventing a HAB from happening in the first place saves governments, NGOs, and other organizations the costs and challenges involved with controlling that HAB and/or mitigating its impacts (e.g. closing beaches or temporarily banning fishing in an area).

This section will primarily discuss nutrient reduction strategies (i.e. reducing the amount of fuel humans unintentionally provide algae). It will also discuss other prevention strategies, including dredging, using chemical treatments, changing the rate and flow of water into a waterbody, and managing the release of ballast waters from ships.

The US has had a long history of nutrient reduction strategies. For example, in the 1960s and 1970s, the rising socioeconomic costs of more frequent HABs in Lake Erie led the

[3] Technically, Hennon & Dyhrman made a suggestion that is inspired by Ribeiro et al.'s work reviving and studying the resting cysts of *Pentapharsodinium dalei* found in a Swedish fjord.

government to implement policies to improve sewage treatment and point-source controls (Webster & Pavolvich, 2019). As a result, nutrient pollution and HAB frequency decreased in the 1980s (Webster & Pavolvich, 2019). However, in the 1990s, agricultural expansion and the increased use of highly soluble chemical fertilizers created a large amount of non-point source pollution (Webster & Pavolvich, 2019). The US and Canada signed the Great Lakes Water Quality Protocol in 2012 (which amended the Agreement Between Canada and the United States of America on Great Lakes Water Quality), further outlining how the two countries would collaboratively manage and restore the Great Lakes (International Joint Commission [IJC], 2012; Marraro et al., 2016). Annex 4 of the protocol is an action plan for how both countries intend to reduce nutrient inputs in order to prevent HABs (Marraro et al., 2016). Since many countries share bodies of water with their neighbors, it may be important to form similar agreements to ensure that none of the countries are putting too many nutrients into the system. Doing so, could go a long way in preventing HABs.

In the United States, the Interagency Working Group on Harmful Algal Bloom and Hypoxia Research and Control Act (IWG-HABHRCA) has led the US part of the agreement (D'Anglada et al., 2018). IWG-HABHRCA has also guided other efforts to reduce nutrient inputs, including management practices like the use of reactive or filter mats to absorb P that would otherwise come into waterways through run-off (D'Anglada et al., 2018)[4]. They also created a Demonstration Farm Network in Ohio where they assessed what effects certain farming

[4] The water moves through the mats, which are made up of a material that lets the water through, but traps the phosphorus. For example, a U.S. Geological Survey team has developed a filter made of a discarded mining byproduct called mine drainage ochre (U.S. Geological Survey [USGS], 2017).

practices had on nutrient inputs and demonstrated practices that could reduce those inputs (USGS, 2017)[5].

Another way that IWG-HABHRCA has been trying to reduce nutrient inputs is through conservation and restoration. In 2016, they started implementing the three-year Western Lake Erie Basin Initiative conservation effort (D'Anglada et al., 2018)[6], through the United States Department of Agriculture's Natural Resources Conservation Service (USDA-NRCS) (Lee et al., 2017). Through the effort, the USDA-NRCS offered financial assistance to support conservation on private agricultural land, prioritizing areas with vulnerable soils (Lee et al., 2017). Not only can conservation bring a host of social and environmental benefits, it can reduce the amount of nutrients that go into the soil of a given area by ensuring that part of that area is not used for farmland, thereby reducing the potential for HABs.

Restoring wetlands, reforesting or creating prairie filter strips in watersheds can help provide buffers between farmlands and waterways (Lee et al., 2017). The plants in those buffers filter out much of the nutrient inputs that the farms produce before they reach the waterway (Lee et al., 2017),.[7] Additionally, restored wetlands can also limit the amount of runoff that comes into waterways and the rate that the runoff moves (Lee et al., 2017), limiting any inputs of nutrients the water might bring with it. Around 2016, the USDA Forest Service reforested areas along streams to limit the amount of nutrient inputs that enter into them (Marraro et al. 2016). All of these actions could prevent or limit the growth of HABs.

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[5] On a side note, it can be a lot harder for governments to change agricultural policy – particularly policies related to nutrient inputs – in the middle of the growing season (Webster & Pavolvich, 2019). That is a challenge policy-makers should be aware of when planning nutrient reduction policies that are focused on agriculture.

[6] Around when the report was published in 2018, the conservation effort had a budget of $41 million (D'Anglada et al., 2018).

[7] Prairie filter strips involve planting prairie vegetation (United States Department of Agriculture [USDA], 2013).

Other strategies for reducing inputs of nutrients into the soil that came up in a report on Lake Erie include: no-till farming; keeping septic tanks in good condition[8]; implementing policies that reduce the amount N and/or P available in fertilizers; and using GPS and precision soil mapping to target agricultural soils for nutrient application or conservation[9] (Lee et al., 2017).

The U.S. Geological Survey (USGS) has been involved with monitoring the levels of nutrients (as well as other water characteristics) in waterways, particularly through the National Water Quality Network (D'Anglada et al., 2018). It partners with other states and Federal agencies to track nitrate levels using optical-sensor technology in various streams and rivers across the country (Marraro et al., 2016).[10] The optical-sensors provide updates on an hourly basis (Marraro et al., 2016). USGS has also helped lead the Mississippi River Basin Monitoring Collaborative which aims to evaluate progress made by nutrient reduction projects in the Mississippi River basin area (Young et al., 2015).

Additionally, recycling wastes from a farm's animal operations can create a "closed loop" that provides additional fertilizer for farmers and keeps nutrients out of water systems (Paerl et al., 2018). The use of flashboard risers in drainage ditches is a way to increase water residence time, which allows for more N to be processed and, therefore, kept from moving downstream (Paerl et al., 2018).

Lake Taihu in China[11], the country's third largest freshwater lake, has been the focus of a lot of HAB-related research because it has recently been experiencing recurring cyanobacterial

[8] Septic tanks in poor condition can leak nutrients.
[9] a practice that can also improve efficiency.
[10] Nitrate is a form of N (Bernhard, 2010).
[11] As a side note, China has grown to have one of the highest numbers of HAB researchers and managers in the world (Anderson, 2012).

HABs (CyanoHABs) (Paerl et al., 2015). Reducing inputs of nitrogen (N) and phosphorus (P) into Lake Taihu is probably the most effective way to reduce the risks of blooms (Paerl et al., 2015). Importantly, even with a nutrient management strategy in place, it may take years or decades for nutrients in a waterbody to substantially diminish because quantities of N and P from previous inputs are still in the water column and surrounding sediments (Paerl et al., 2015). Anyone planning to implement a nutrient reduction program should be aware that nutrients that predate the program may remain in the local environment even after the program is up and running.

Two ways to reduce the risks posed by residual P in sediments[12] include: to remove the sediments or to use chemical treatments (Paerl et al., 2019). Sediment removal, which often involves dredging, can be expensive, detrimental to aquatic habitats, and can accidentally release stored nutrients (Paerl et al., 2019). There are chemical treatments, such as Phoslock (CSIRO, Australia), that precipitate P and keep it bound to the sediments (Paerl et al., 2019). This approach can be less destructive than dredging (Paerl et al., 2019).

Lake Trummen in Sweden had been experiencing cyanobacterial HABs that were driven by domestic sewage and industrial nutrient inputs (Paerl et al., 2018). To solve the problem, over two years, the upper half meter of the lake's bottom sediment was removed using suction dredging (Paerl et al., 2018). It worked. However, the project's success was partly due to the lake's small size (~1 km^2 with a mean depth of 1.6 m) and simultaneous nutrient reduction initiatives in the watershed (Paerl et al., 2018).

[12] Even after successful nutrient reduction efforts, there are sometimes still large amounts of remaining P in soils, the bottom of creeks, and wetlands which can still enter into the water column (Paerl et al., 2019).

In Saudi Arabia, developing and managing mangrove plantations has been identified as a way to help mitigate the effects of nutrient loading (Alias Gokul et al., 2020). This approach is worth mentioning because of how common mangroves are in aquatic systems in many parts of the world, meaning that the strategy could be adapted to other world areas.

It is important to note that N can also be emitted into the airshed (through burning fossil fuels (National Science Foundation [NSF], 2010)) and precipitation can cause N compounds to fall from the air (Marraro et al., 2016), eventually joining waterbodies where they can contribute to the growth of HABs. In other words, reducing the emissions of N into the air is another nutrient management strategy (Marraro et al., 2016).

An analysis of water level changes and their effects on chlorophyll-a concentrations in China's Xiangxi Bay found that raising water levels could reduce HAB proliferation (Liu et al., 2017, as cited in Lee & Lee, 2018, p. 3). The reason why is that the added water could help to blend the water column, minimizing the time the algae spent at the surface and dispersing nutrients (Liu et al., 2017, as cited in Lee & Lee, 2018, p. 3).

Nutrient loading pollution can take the form of point source pollution (i.e. where pollution enters a waterway from a discernable, specific space) or non-point source pollution (USEPA, 2020). This section has focused mostly on non-point source pollution. However, it is important to limit the amount of nutrients released from point sources. For example, there has been a strong correlation between increasing aquaculture productivity in the Saudi Arabian city of Al Lith (home to a major aquaculture facility) and a widening spatial coverage of local HABs and rising levels of chlorophyll-a concentrations (Alias Gokul et al., 2020).

In addition to nutrient loading, another way that humans can drive the expansion of HAB species is by unintentionally transporting HAB organisms in the ballasts of ships (López-Cortés et al., 2019). There are international regulations that aim to prevent ballast waters from being released in marine areas that are particularly sensitive (Anderson et al., 2019).

Monitoring

Monitoring is crucial to understanding how best to respond to HABs[13]. Monitoring can help answer questions like: "What beaches should be closed?" and "Where is it safe to fish?". This section will first discuss various HAB monitoring systems, it will then turn to an example of a multilateral marine management project with a large HAB monitoring component. Next, it will describe several citizen science initiatives. Finally, it will talk about several scientific advances related to monitoring.

Within different states and regions of the US, there are many HAB monitoring programs. One such program is the Southeast Alaska Tribal Ocean Research (SEATOR) partnership, a collaboration of tribal governments and communities (Harley et al., 2020). SEATOR partners make observations of phytoplankton and of conditions that could contribute to HABs, such as sea surface temperature (SST) and salinity (Harley et al., 2020). They make all of their data publicly available both on their own website and on the AHAB network site that the Alaska Ocean Observing System (AOOS) hosts (Anderson et al., 2019). SEATOR also issues advisories about whether they think it is safe to collect and consume marine products (given their possible exposure to HABs), which Native American tribal communities and partners can take into consideration (Harley et al., 2020).

In the Great Lakes Region, the Center for Operational Oceanographic Products and Services (CO-OPS) (part of the National Oceanic and Atmospheric Administration (NOAA)), the National Centers for Coastal Ocean Science (NCCOS) (also part of NOAA), and the Great

[13] There is overlap between many of the prediction and monitoring approaches this paper describes. In general, the monitoring approaches described in this paper involve both anticipating future HABs and studying present ones.

Lakes Environmental Research Laboratory (GLERL) create HAB forecast bulletins based on a five-day outlook for Lake Erie (Anderson et al., 2019). The bulletins draw from observations (that remote sensing equipment and buoys within the lake collect hourly) of factors like wind, waves, and the levels of chlorophyll and nutrients (Anderson et al., 2019). On a weekly basis, a hyperspectral imaging sensor is flown over drinking water intakes (Anderson et al., 2019). Since those flyovers take place below the cloud layer, the sensors are able to gather information that the clouds often block the satellites from obtaining (Anderson et al., 2019). Many of these observations are available in the Great Lakes Observing System (GLOS) HAB Data Portal (Anderson et al., 2019). This information can help guide the management of drinking water treatment and coastal recreation (Anderson et al., 2019) (e.g. deciding when to open and close public beaches).

The California Harmful Algal Bloom Monitoring and Alert Program (Cal-HABMAP) has a weekly monitoring program that is focused on major piers and harbors (Anderson et al., 2019). They look in particular for eight HAB taxa (e.g. *Alexandrium* spp.) using light microscopy (Anderson et al., 2019). Prioritizing major piers and harbors may make sense because HAB species can sometimes be found in ships' ballast water and disturbances to aquatic habitats caused by constructing harbors can increase the likelihood of HABs (López-Cortés et al., 2019; Wells et al., 2020). From a public health perspective, since harbors often are near large population centers, they are places where a HAB occurrence could be particularly harmful. Immediate results from the weekly program are sent via an email listserv to managers and stakeholders and a steering committee (made up of state and federal government officials and academic partners) provides guidance (Anderson et al., 2019). The data is later made available on the Southern California Coastal Ocean Observing System's (SCCOOS) public archive. It is worth mentioning that Cal-HABMAP also works with the Central and Northern California Ocean Observing System (CeNCOOS) (Anderson et al., 2019).

In 2005, the Water Center for the Humid Tropics of Latin America and the Caribbean (CATHALAC, an international organization based in Panama: http://www.cathalac.int) collaborated with SERVIR, a joint initiative between NASA and USAID, to assist El Salvador's National Red Tide Commission (CONAMAR) (United States Agency for International Development [USAID], n.d.). They created a map of chlorophyll concentrations in ocean waters (as indicators of HAB likelihood) near Central America's coast, which they update daily and have made publicly accessible online (USAID, n.d.). CONAMAR uses information gathered from this project to determine whether to implement bans on harvesting and selling different seafood species based on toxicity levels (USAID, n.d). Since 2006, there have been no recorded human deaths because of shellfish toxins (USAID, n.d).[14] As with other projects, part of what makes the project effective is that the map is updated very regularly and that it is publicly accessible. If a ban is not in place, a fisher might still decide to avoid harvesting from certain areas because of their chlorophyll levels.

In addition to social and environmental benefits, effective monitoring can also bring economic ones. An early warning system for domoic acid contamination in razor clams in the State of Washington provided accurate and timely information about where exactly harmful algae and/or their toxins were, which informed which beaches were opened and closed (Marraro et al., 2016). This system saved the state's coastal fisheries at least $3 million per year (Marraro et al., 2016).

[14] Although, since the report does not list the year it was published, I do not know whether that is still true up to the present.

In Europe, France, Monaco, and Italy are part of the Accord RAMOGE, through which they coordinate efforts to monitor blooms of *Ostreopsis ovata*, a benthic dinoflagellate that can cause respiratory problems for humans (Spain also collaborates with *O. ovata* monitoring efforts.) (Borja et al., 2020). The Accord could be a source of inspiration for policy-makers who are considering developing collaborative, environmental management agreements, either with other countries or with other state or municipal governments within the same country. The accord is made up of a Commission with seven representatives from each country, a Technical Committee with five representatives from each country, Working Groups, and a Permanent Secretariat (RAMOGE, n.d.a). The Commission has published guides and organized meetings (with a range of actors) on how to limit society's negative impacts on the marine environment (RAMOGE, n.d.a). For example, in 2014, it compiled a bibliography of studies on *Ostreopsis* that policy-makers and researchers could use (RAMOGE, n.d.b). The Commission has also worked with local diving clubs to encourage divers to gather information about different HAB species (RAMOGE, n.d.a).

An important aspect of many monitoring programs are citizen science initiatives. On Florida's west coast, lifeguards and park rangers use their smartphones to file daily reports that may interest beach goers (e.g. rip currents, wind speeds, HABs) (Anderson et al., 2019). Another initiative called SoundToxins brings together a diverse range of stakeholders in the Puget Sound from shellfish and fish farmers, to members of Native American tribes, to volunteers who are just interested in helping (Anderson et al., 2019). SoundToxins' participants are trained and given equipment to collect water samples in order to identify certain HAB species such as species in the genera of *Alexandrium, Pseudo-nitzschia*, and *Heterosigma* (Anderson et al., 2019). The information they gather goes into a central database that lets the Washington State

Department of Health know which areas to prioritize for additional shellfish toxin analyses (Anderson et al., 2019). Interestingly, SEATOR's weekly or biweekly phytoplankton monitoring approach in southeast Alaska is based on methods developed for the SoundToxins project (Harley et al., 2020).

There are at least two citizen science programs that inform the Gulf of Mexico Coastal Ocean Observing System (GCOOS) (Anderson et al., 2019). In one, the Nucleic Acid Sequence Based Amplification (NASBA) program, volunteers are trained to use a hand-held, battery-operated sensor to detect and measure *K. brevis* RNA (Anderson et al., 2019). The data is then uploaded to a portal at the GCOOS (Anderson et al., 2019). In another project, volunteers are trained to use a microscope attached to their smartphone that can process water samples (Anderson et al., 2019). The volunteers take a video of the sample, rather than counting phytoplankton, and that video is uploaded to a separate GCOOS portal that uses deep learning software to estimate a cell count from the video (Anderson et al., 2019)[15].

An EU-funded program called Seas, Oceans, & Public Health in Europe (SOPHIE) launched a citizen science initiative called "Mapping *Ostreopsis* spp." (Borja et al., 2020). In the initiative, tourism operators who are members of the WILDSEA Europe ecotourism network (and who live and work by the ocean year-round) monitor the subspecies locally (Borja et al., 2020).

A study demonstrated the use of a method for identifying different phytoplankton types in bloom concentrations from space: Probabilistic Phytoplankton Community Classification (PPCC) (Smith & Bernard, 2020). Their study area was the Southern Benguela, which is off of

[15] The government is significantly involved in several of these citizen science initiatives. The SoundToxins project was initially driven by government funding, through NOAA (SoundToxins, n.d.). NOAA is a partner of GCOOS (GCOOS, n.d.).

the west coast of South Africa (Smith & Bernard, 2020). This method could be used to help determine site selection for industries that HABs may directly affect, such as aquaculture and desalinization (Smith & Bernard, 2020). *In situ* and *in vitro* techniques for identifying phytoplankton at the species level substantially outweigh remote sensing techniques for doing so and ocean color remote sensing works best when it is paired with information gathered *in situ* about phytoplankton (Smith & Bernard, 2020).

In another project, researchers used chlorophyll concentrations as a way to gauge the likelihood of HABs (Alias Gokul et al., 2020). They used satellite observations of chlorophyll-a concentrations gathered through the European Space Agency (ESA)'s Ocean Colour Climate Change Initiative (OC-CCI)(Alias Gokul et al., 2020). They also used aquaculture production data from the Sea Around Us project, which aims to create a database for annual reported aquaculture production in all coastal countries from 1950 to 2010 (Alias Gokul et al., 2020). This data, as well as data from other sources, was used to create a map of HAB events in the Red Sea (Alias Gokul et al., 2020). They also used the data to examine the area near the Saudi Arabian city of Al-Lith, home to the Red Sea's biggest aquaculture facility, to see if there was a correlation between aquaculture activities and HAB events between 2002 and 2010 (Alias Gokul et al., 2020).

An unconventional approach to monitoring HABs that shows potential is the use of drones in Japan's Nagasaki Prefecture.[16] This project aimed to minimize the effects of HABs on local aquaculture by quickly informing local fish farmers, who in turn can move fish cages and stop feeding (Kimura et al., 2019). First, a drone flies over the waterbody in question and takes photos. The color conditions captured in the photos are compared with a color reference sample

[16] South Korea has been using unmanned aerial vehicles to monitor HABs (Anderson et al., 2019).

to identify areas that are at a significant risk for HABs. Flying the drone generally takes less time than collecting data by boat. If areas in the waterbody are identified as at risk, a second drone is sent to those areas to collect seawater samples. After the samples have been tested, emails are sent out to a list-serve, which includes local fish farmers. The emails include the alert level (normal, caution, and alert), the location, date and time of the water sampling, the results of the sample (including number of harmful plankton in each sample), and a URL for the program's web application. The web application features a map of the waterbody that is color-coded based on risk levels. The user can click on different parts of the map and get more detailed information on the samples that were taken in that part of the waterbody. The system was able to identify harmful plankton with more than 90% accuracy. This system can cut down the amount of time it typically takes to identify a HAB from six hours (under what they call the conventional approach) to 15 minutes. Of course, generally, the sooner fish farmers can respond to a HAB, the more likely they will be to save some of their fish.

Control

Control techniques should be seen as a last resort, after prevention measures have been taken. Control techniques vary substantially from the use of chemicals to the use of living species. Budgets, timing, and ecological concerns can be some of the major determining factors for picking one technique over another. This section will focus first on some of the non-living materials that are used to control HABs, before discussing the use of living organisms.

A few examples of control methods include the use of coagulants (specifically for high-biomass HABs), electrolysis, acoustic disruption, and ozonation (Anderson et al., 2019).[17] In a similar vein to ozonation, the United States Army Corps of Engineers' Aquatic Plant Control

[17] Ozonation refers to treating a substance or compound with ozone (Merriam-Webster, 2020).

Research Program has been researching how pumping bubbles into waterbodies could potentially break up CyanoHABs (D'Anglada et al., 2018). Mechanical aeration and mixing the water column are ways to make conditions in small inland lakes less favorable to cyanobacteria (Lee et al., 2017).

Clay has been used in waterbodies to form ionic bonds with algal cell membranes, moving those cells out of the water column in a process referred to as clay flocculation (Paerl et al., 2018). Although clay flocculation is more commonly known for its use in dispersing marine dinoflagellates, it works as well in freshwater habitats (Paerl et al., 2018). Other authors also note that the method has proven effective (Anderson et al., 2019).

Hydrogen peroxide has been found to effectively reduce cyanobacterial HABs without causing long-term pollution (Paerl et al., 2018). Copper is also used as an algaecide but it is toxic to many plant and animal species and it leaves a residue in sediments that is a legacy pollutant (Paerl et al., 2018). Since applying algaecide treatments is often costly and can face many challenges, doing so is usually limited to small impoundments (Paerl et al., 2018).

Changing the amount of light that enters an aquatic system may also have potential as a HAB control technique (Gaskill et al., 2020). Artificial dye products have been used to block incoming light, and research shows the approach has had no effect on fish, crayfish or tadpoles, but has been known to reduce zooplankton diversity (Gaskill et al., 2020). The authors focus their paper on another light reduction technique: the use of glacial rock flour (GRF) (the naturally-occurring mix of small particles caused by a glacier moving over bedrock) (Gaskill et al., 2020). They put GRF in tanks dominated by cyanobacteria. After just nine days, the cyanobacteria in different tanks had declined by 49.4% to 77.6% (Gaskill et al., 2020). Despite how quickly the approach worked in the lab, there are some concerns about it (Gaskill et al., 2020). One is that, since it would involve adding inorganic particles to waterbodies, it could mean reducing those waterbodies' storage capacity for water (Gaskill et al., 2020). Another concern is that, at least at first, the approach would need to be reapplied more frequently than other geoengineering techniques (Gaskill et al., 2020).

Another approach is the use of algicides. NOAA, for example, has been researching the effects of bacteria-produced algicides, both on HABs and other species in the target habitats (D'Anglada et al., 2018). Barley straw, which releases a chemical that prevents new algal growth, has been used in small inland lake's (Lee et al., 2017). Barley straw has been found to be effective at targeting cyanobacteria in field tests (Pal et al., 2020). It is listed among a range of different materials that have also been successful in field tests against bacteria, including leachates of the root of *Ephedra equisetina* (a shrub species), the biocide Sea Kleen, L-lysine, and anthraquinone-59 (Pal et al., 2020).

Bacteria may also offer potential for eliminating some of the toxins caused by HABs. Some cyanobacteria can produce cyanotoxins that affect municipal water supplies (NCCOS, n.d.d). A PCMHAB research project has been looking at the potential of using a local bacteria to destroy cyanotoxins (NCCOS, n.d.d). This bacteria could be used in a biological filter that water treatment facilities could use to get rid of cyanotoxins (NCCOS, n.d.d). One of the benefits of the uses of natural algicides to treat HABs and/or their toxins is that they avoid the risks posed by adding any chemicals into local habitats. However, even if an algicide project involves no chemical inputs, it will still be very important to make sure that the project does not introduce anything (e.g. a non-native species) to an ecological system that would significantly alter its balance.

Various efforts have been made in China and other countries to use filter-feeding fish to reduce cyanobacterial HABs and these efforts have sometimes been effective (Pal et al., 2020). The fish that have been studied include Bighead Carp (*Aristichthys nobilis),* Silver Carp (*Hypophthalmichthys molitrix*), Nile Tilapia (*Oreochromis niloticus*), as well as a freshwater mussel, the Triangle Shell Mussel (*Hyriopsis cumingii*) (Pal et al., 2020). Zooplankton, such as cyclopoids, copepods, and calanoids, have the potential to lower cyanobacterial densities without contaminating the ecosystem and at a low cost (Pal et al., 2020).

HAB control techniques may have unintended consequences. For example, different methods for controlling *Karenia brevis* blooms, whether they be physical, chemical, or biological, may have side effects on different features of the environment (Hoagland et al., 2020). It is also not entirely certain how they would affect the blooms themselves (Hoagland et al., 2020).

Perhaps it is because of that concern for unintended consequences that some researchers argue for an approach focused on informing the public, rather than using chemical, physical, or biological control techniques, to address *K. brevis* in southwest Florida (Hoagland et al., 2020). Their approach heavily emphasizes continuing to research and monitor HABs and to regularly educate and notify the public about them, as opposed to emphasizing control measures (Hoagland et al., 2020).

Recommendations

This section will discuss some key recommendations for addressing HABs, starting with recommendations related to research before turning to recommendations related to government policies and finally discussing recommendations related to how communities cope with HABs.

One key point worth mentioning, which is especially relevant to policy-makers, is that investing in addressing HABs (through prediction, prevention, monitoring and/or control) may, in many cases, be well worth it.[18] As the HABs Health, Economic, and Environmental Effects sub-section of the Background section describes, HABs can take major tolls on economies. They can also be costly for public utilities: for example, such as the aforementioned drinking water plant in Toledo, Ohio that lost $4 million because of a 2014 HAB in Lake Erie (Bingham et al., 2015, as cited in Gaskill et al., 2020).

<u>Research</u>

It is important to consistently fund HAB research (Hoagland et al., 2020). In the US, funding for HAB research has generally only increased temporarily following significant HABs (Hoagland et al., 2020). A lack of consistent funding can make it harder for researchers to implement important, long-term projects.

There are certain areas where more research is needed. For example, there has been little research into the toxicokinetics of HAB toxins (in other words, their distribution, reactivity, and stability) in environments that have been altered by climate change (Griffith & Gobler, 2020). There has also been little research into how aquatic ecosystems change when HABs occur in tandem with acidification and/or deoxygenation (Griffith & Gobler, 2020). Researchers could study how HABs react to current variations to try to better understand how they will react in future climate change scenarios (Anderson, 2012). Finally, there is a need to study the costs of the long-term effects of chronic exposure to harmful algae (Kouakou & Poder, 2019). It will be important to learn more about how temperature changes alter bloom toxicity for specific

[18] That is not to say that specific HAB responses are always worth the investment. It will be important to evaluate which responses are most worth the investment and have little to no negative environmental or social side effects.

cyanobacteria strains in order to better predict and prepare for periods of high toxicity (Griffith & Gobler, 2020).

To spur research, there have been a number of funding competitions for HAB research and related projects. The products and techniques that competition participants strive to create vary significantly. They include affordable, real-time P and N sensors (as part of "The Nutrient Water Sensor Challenge" that the Alliance for Coastal Technologies launched and that NOAA and the USEPA sponsored) and ways to extract excess P from freshwater bodies while creating valuable byproducts (as part of "The George Barley Water Prize" that the Everglades Foundation sponsors) (Lee et al., 2017). Research competitions can be an effective way for policy-makers and the staff of NGOs, such as foundations, to build up momentum towards solving a particular research project.

Preventive Measures and Responses to HABs

Since climate change has been found to contribute to the expansion and increased frequency of certain HABs (Griffith & Gobler, 2020), policies that increase or decrease greenhouse gas emissions have effects on HABs. One substantial way to address HABs is to reduce the amount of greenhouse gases that enter the atmosphere. If people working to mitigate climate change were to collaborate with people working to address HABs, they may find that they are better able to bring government and public attention to their respective main areas of concern. They could also benefit from sharing their knowledge (e.g. about those areas of concern, best practices for working with governments or educating the public).

Construction projects, such as the development of harbors and offshore oil platforms, can alter habitats in favor of HABs (Durán-Riveroll et al., 2019, Wells et al., 2020). Other changes humans make to aquatic habitats, such as over-fishing and projects that lead to excessive sedimentation, can also favor HABs (Wells et al., 2020). Any activity with implications for aquatic systems, from construction planning to issuing fishing permits, should involve a careful assessment of what that activity means for HABs. That assessment should consider the combined impact of other past and current activities in and near that aquatic system, as well as those pending approval. If the activity increases the likelihood, size and/or toxicity of HABs, it may be better not to go through with it.

Since watersheds are interconnected systems, it is important to learn how upstream activities affect downstream conditions (Paerl et al., 2018). With that in mind, nutrient management strategies should be focused on the entire basin, rather than considering each individual waterbody as independent (Paerl et al., 2018). Although inputs of just N or just P in one part of a watershed might not contribute to HAB growth in that part, they might flow into another part of a watershed where they would (Paerl et al., 2018). Since many watersheds cross political borders, reducing nutrient inputs throughout the watershed may involve collaborations between authorities in different jurisdictions or between countries, such as the US-Canada collaboration: the Great Lakes Water Quality Protocol (Marraro et al., 2016). Transnational collaboration is especially important because the shared use of waterbodies (by both individuals and governments) can lead to a tragedy of the commons, in which some actors drive the growth of HABs with little incentive to stop despite the effects on other actors.

One way to reduce nutrient inputs is to improve and repair aging sewage and water systems because they have been known to leak nutrients (Marraro et al., 2016), as have old septic tanks (Lee et al., 2017). Additionally, ecological conservation and restoration practices, such as reforestation and planting native vegetation in buffer zones, can significantly reduce nutrient inputs (Alias Gokul et al., 2020; D'Anglada et al., 2018; Lee et al., 2017; Marraro et al. 2016;

United States Department of Agriculture [USDA], 2013). Considering that they may often come with many other social and ecological benefits, policy-makers may want to consider prioritizing them as HAB prevention strategies.

The “Responding to HABs” section describes various approaches that are worth considering. These include: the use of drones for monitoring (Kimura et al., 2019); and the use of biological algicides, such as bacteria and barley straw (D’Anglada et al., 2018; Lee et al., 2017; Pal et al., 2020). Manipulating light to reduce algae populations may also have a lot of potential (Gaskill et al., 2020).

HABs and Communities

When fishery-dependent communities adapt to the economic impacts of a HAB, adaptation often faces different barriers and challenges, such as stress and limited access to other fishing areas or to other job opportunities (Moore et al., 2020). Fishers who are prevented from returning to their previous fishing areas because of a HAB sometimes lack the fishing gear needed to access other fishing areas or the job skills needed for certain other kinds of work. Increased advertising may lead to increased sales of seafood unaffected by HABs that could partially or entirely offset the loss of the affected seafood. People working in hospitality also sometimes used advertising their services and/or took on other work as an adaptation strategy (Moore et al., 2020). Policy-makers interested in helping fishery-dependent communities to be better able to adapt to HABs should be aware of these challenges (Moore et al., 2020). Policy-makers could implement programs that make it easier for fishers to acquire new fishing gear, to develop the skills needed for other kinds of work, to get connected to new work opportunities, and to improve their ability to advertise. Those programs could also be tailored to other affected community members, such as people working in hospitality.

Educating the public about HABs is an important part of enhancing communities' adaptive capacity. In the Ecuadorian study on community perceptions of HABs, the authors recommended implementing educational programs about HABs for community groups, public health practitioners, and coastal managers (Borbor-Córdova et al., 2018).

For publicly-available webpages that provide current HAB-related information about waterbodies (e.g. maps of chlorophyll concentrations), it can be beneficial to allow opportunities for the public to review and comment on the webpage (Hoagland et al., 2020). It can also be beneficial to have regular sessions where professionals in fields related to HABs review the data and the website itself (Hoagland et al., 2020).

Conclusion

HABs pose a whole range of serious threats to ecosystems, public health, economies, and livelihoods. This paper has described some of the ways that humans drive the growth of HABs and various ways that they respond to them: particularly with respect to prediction, prevention, monitoring, and mitigation. It has also looked at community-level perceptions of and responses to HABs. Although HABs are a naturally occurring phenomenon, we as a species are dramatically driving their growth in a range of ways, including by putting nutrients into ecosystems, building in aquatic habitats, and emitting greenhouse gases (Durán-Riveroll et al., 2019, Paerl et al., 2019, Wells et al., 2020).

To face HABs, we will need to: use a range of techniques (such as those described in this paper); curtail practices that are harmful to ecosystem health (which means prioritizing nutrient reduction and climate change mitigation efforts); and coordinate across national boundaries to scale up responses as much as possible.

Table 2. Selected Initiatives

Initiative	Country(ies)	Author(s)	More Information
Harmful Algal Events Dataset (HAEDAT)	International	Sanseverino et al., 2016, Harmful Algal Events Dataset [HAEDAT], 2018.	Database of marine HABs around the world. It is part of UNESCO's (United Nations Educational, Scientific and Cultural Organization) Intergovernmental Oceanographic Commission (IOC).
GEOHAB (2000-2013) and GlobalHAB (2016 - set to end in 2025)	International	Anderson et al., 2019	HAB programs sponsored by IOC and UNESCO's Scientific Committee on Oceanic Research (SCOR) that set goals, objectives, and action plans to guide HAB management and research efforts at regional and local levels.
Responding to HABs in Lake Taihu	China	Paerl et al., 2015	Reducing inputs of N and P have been identified as probably the most effective ways to reduce the risk of future CyanoHABs in the lake.
Phoslock (from CSIRO)	Australia	Paerl et al., 2019	A chemical treatment that keeps P bound to sediments.
Monitoring system in Shenzhen City	China	Tian & Huang, 2019	It combines *in situ* and satellite observations, a hydrodynamic and water quality model, and a web-based Geographic Information System. It provides real-time maps with information about local HAB risks.
Applied Simulations and Integrated Modeling for the Understanding of Toxic and Harmful Algal Blooms (ASIMUTH)	EU, Ireland, France, Spain, and Scotland	Anderson et al., 2019	EU-funded project that Ireland led (in collaboration with France, Spain, and Scotland) to improve early warning systems for HABs, particularly around the North-Eastern Atlantic European shelf.
Dredging in Lake Trummen	Sweden	Paerl et al., 2018	The uppermost half meter of the lake's bottom sediment was removed by suction dredging over two years, successfully addressing the CyanoHABs in it.
Accord RAMOGE	France, Monaco, Italy, and Spain	Borja et al., 2020, RAMOGE (n.d.a), RAMOGE (n.d.b)	The accord between France, Monaco, and Italy (that is aimed at protecting the marine environment they share) has a program focused on researching and monitoring *Ostreopsis ovata*. Spain is also involved in this monitoring effort.

Network of LAC countries	Latin America	Cuellar-Martinez et al., 2018	The International Atomic Energy Agency has supported a network of Latin American and Caribbean countries that work as an early warning system for HABs. The network has a regional reference center in El Salvador and another in Cuba.
SERVIR/ CATHALAC collaboration in El Salvador	El Salvador	United States Agency for International Development [USAID], n.d.	The Water Center for the Humid Tropics of Latin America and the Caribbean and SERVIR collaborated with the El Salvadorian government to create a publicly-available map of chlorophyll concentrations in the region's ocean that is updated daily.
Western Lake Erie Basin Initiative conservation effort	US	D'Anglada et al., 2018, Lee et al., 2017	In 2016, the three-year Western Lake Erie Basin Initiative conservation effort began. The program offered financial assistance to encourage conservation of private agricultural land, with a priority given to areas with very vulnerable soils.
Citizen science in Florida	US	Anderson et al., 2019	On Florida's west coast, lifeguards and park rangers file daily reports on their smartphones that include information (e.g. rip currents, wind speeds) that may interest anyone planning on going to the beach.
Probabilistic Phytoplankton Community Classification (PPCC)	South Africa	Smith & Bernard, 2020	A study demonstrated the use of a method for identifying different phytoplankton types in bloom concentrations using satellites: the Probabilistic Phytoplankton Community Classification (PPCC).
Creating a HAB atlas of the Red Sea	Saudi Arabia	Alias Gokul et al., 2020	Researchers used satellite observations of chlorophyll concentrations and aquaculture production data to create an atlas of HABs in the Red Sea and to study the connections between HABs and aquaculture in the region.
Drones	Japan	Kimura et al., 2019	Researchers used drones to efficiently predict marine HABs in Japan's Nagasaki Prefecture. The information the drones collect is used to inform an email alert system and a publicly-available map that helps fish farmers know where it is safe to operate.

Deep learning	South Korea	Lee & Lee, 2018	Researchers in South Korea used a deep learning model to predict algal blooms in four of the country's major rivers.
Use of glacial rock flour	US	Gaskill et al., 2020	Researchers used glacial rock flour (a mix of particles caused by a glacier moving over bedrock) to effectively reduce cyanobacteria in tanks.

Figure 1. Selected Responses to HABs in Africa and the Middle East

Created by author using Visme.

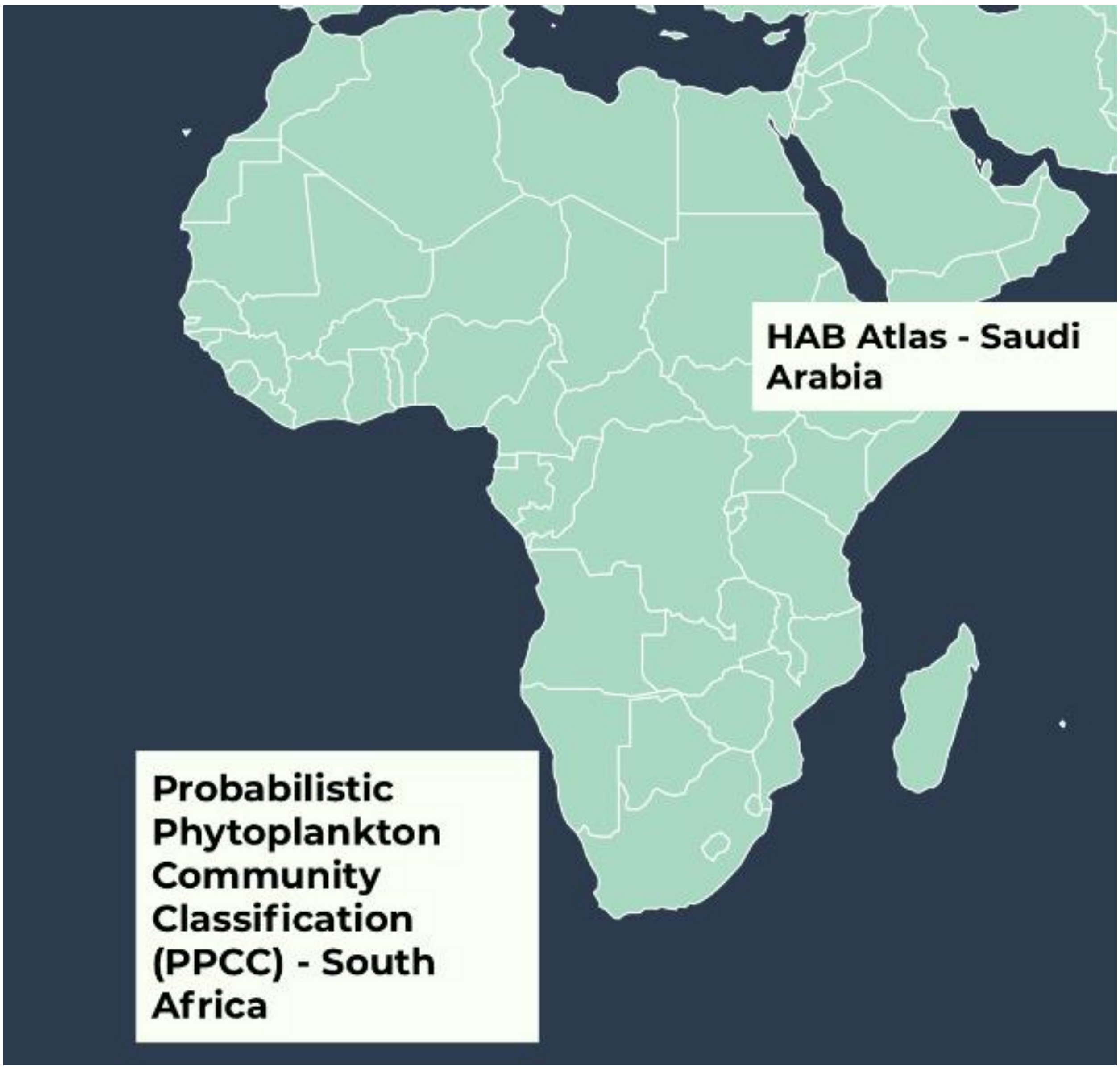


Figure 2. Selected Responses to HABs in Asia

Created by author using Visme.

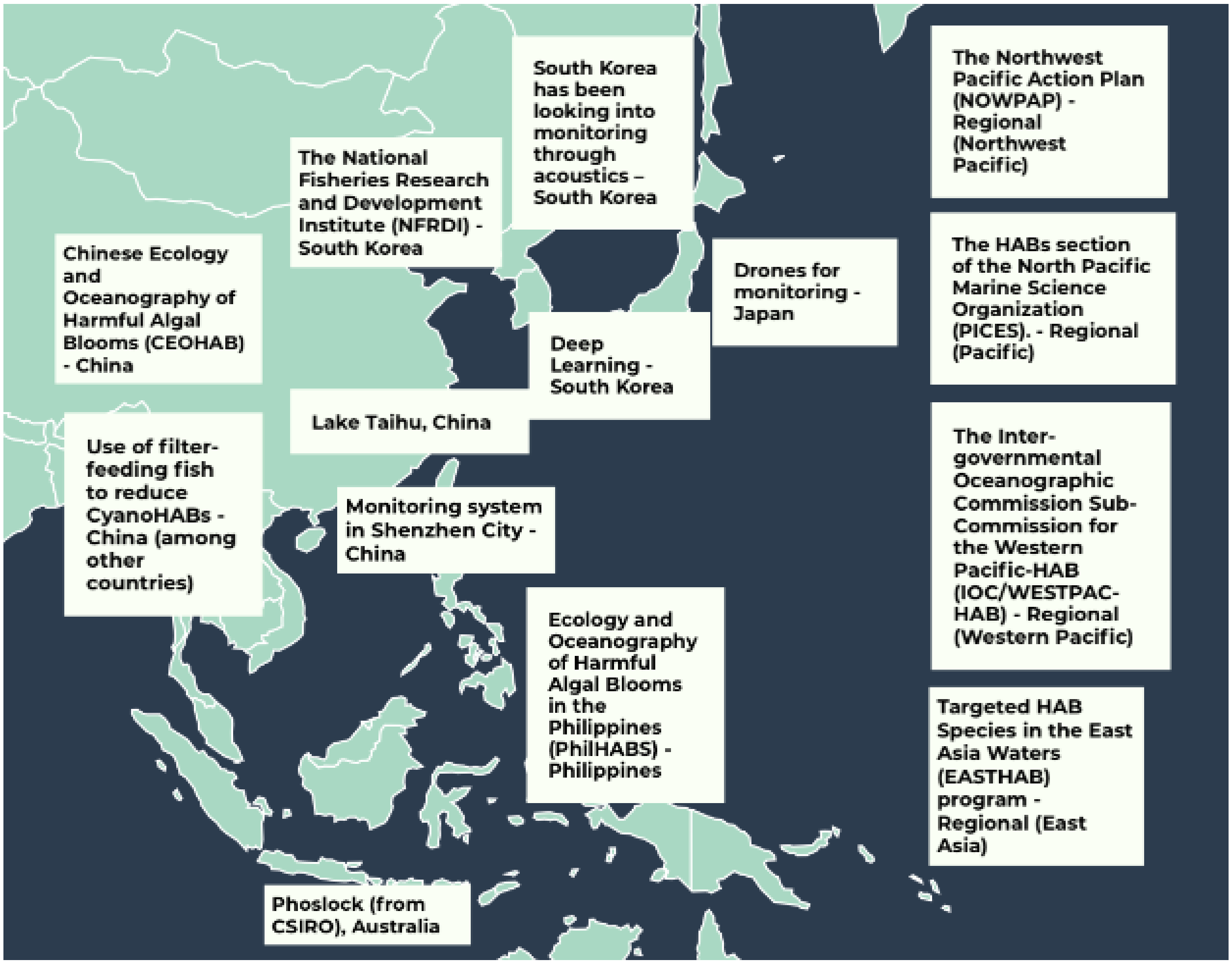


Figure 3. Selected Responses to HABs in Europe

Created by author using Visme.

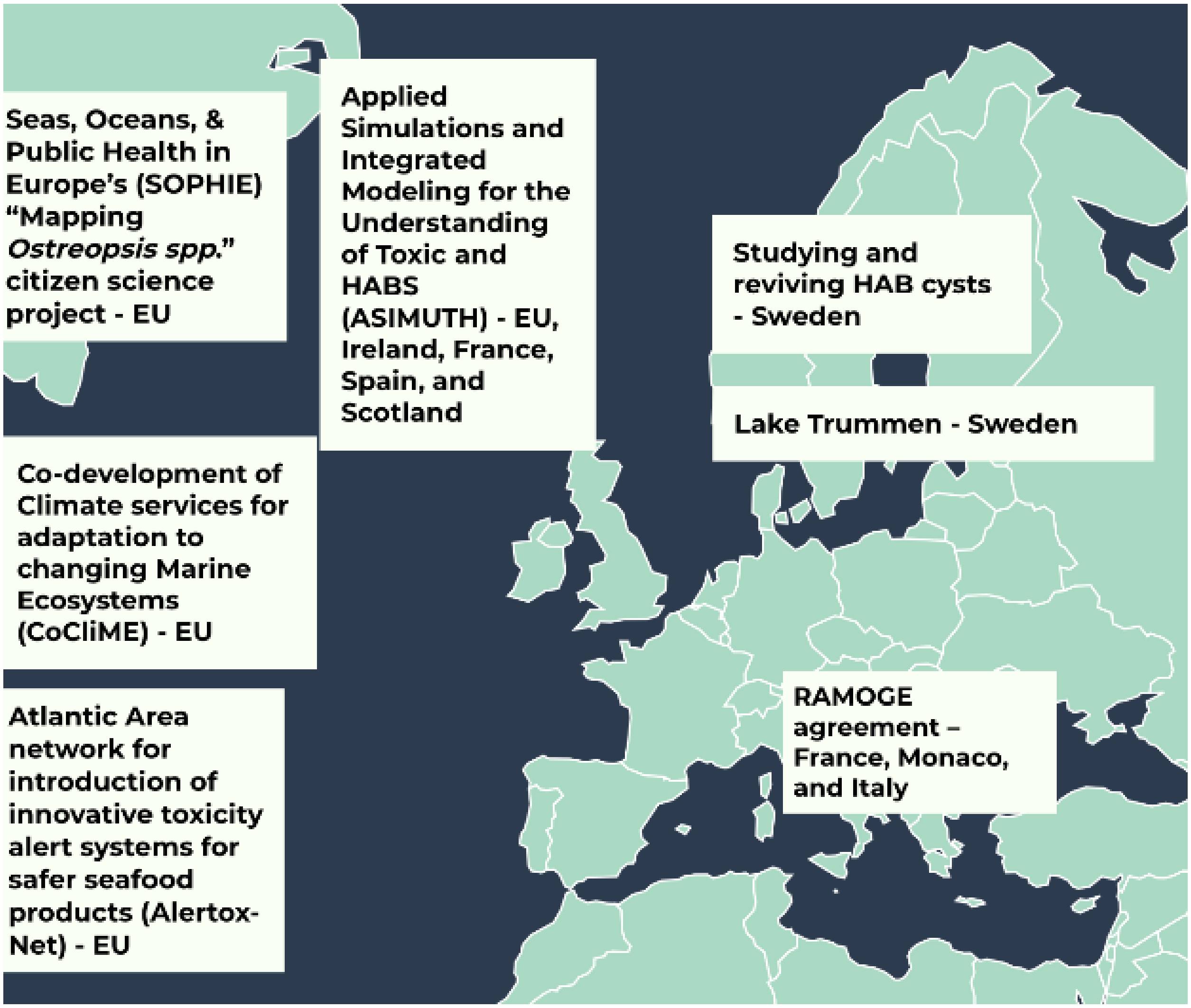
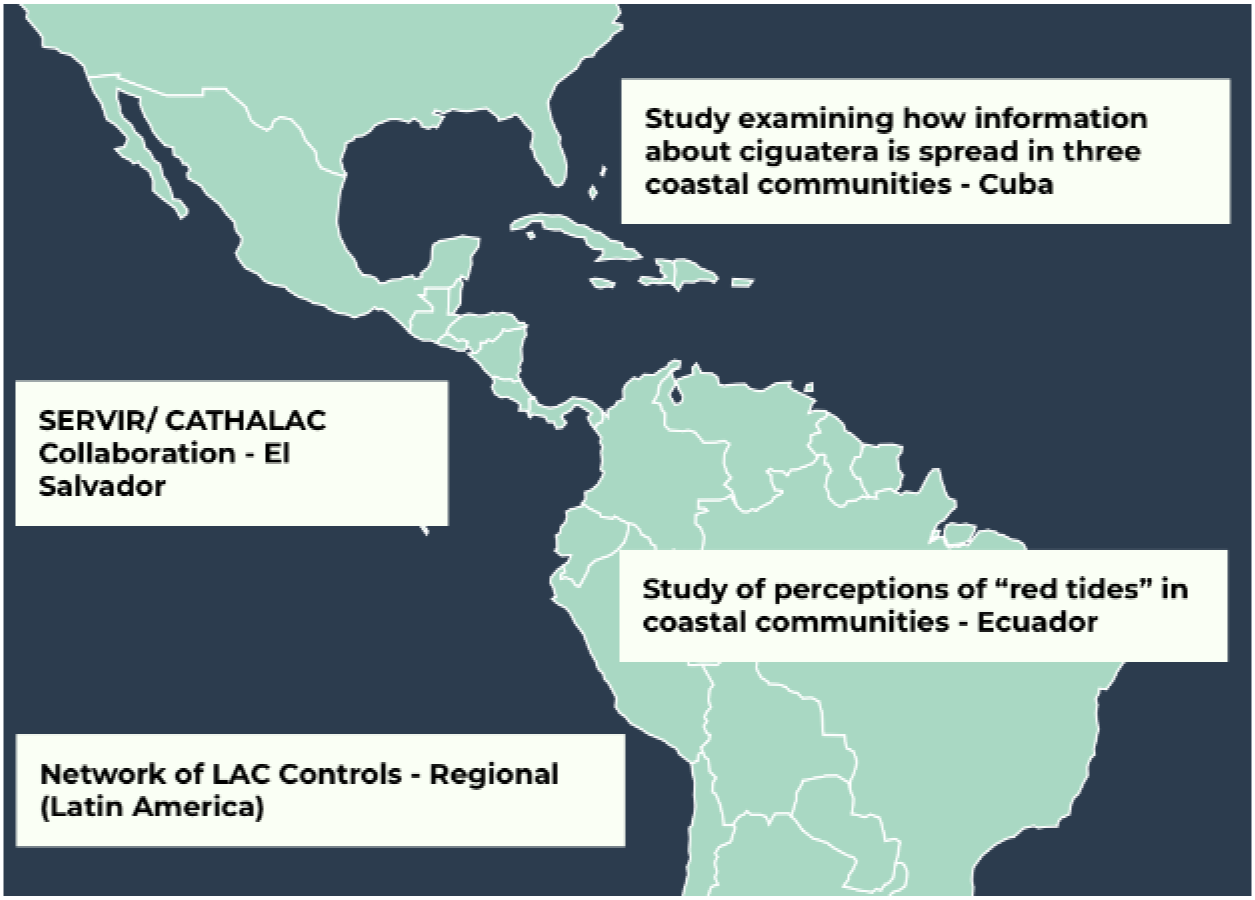


Figure 4. Selected Responses to HABs in North America

Created by author using Visme.

Figure 5. Selected Responses to HABs in Latin America

Created by author using Visme.



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