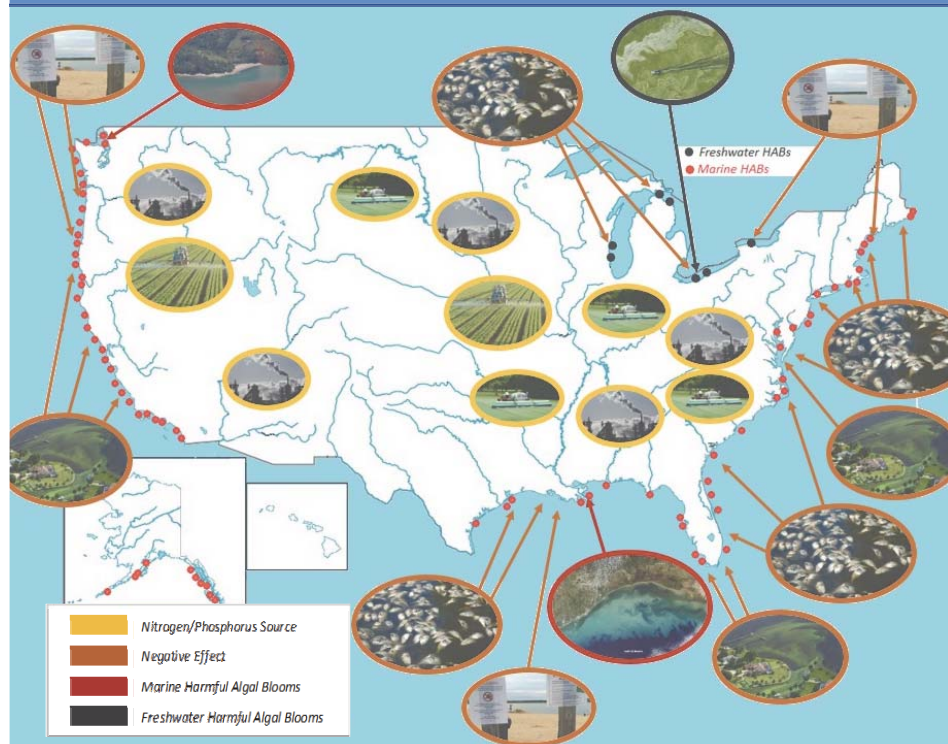


# The Harmful Algal Blooms and Hypoxia Research and Control Amendments Act of 2017

*A Comprehensive Scientific Analysis*



Columbia University, School of International and Public Affairs  
Master of Public Administration in Environmental Science and Policy  
Workshop in Applied Earth Systems Management, Summer 2018



The Harmful Algal Bloom and Hypoxia Research and Control Amendments Act of 2017



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MPA in Environmental Science and Policy – Summer 2018  
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## EXECUTIVE SUMMARY



Few environmental issues have the tangible economic risks and scientific consensus to unite decision-makers in the U.S. Congress, but harmful algal blooms have done just that. After high-profile seasonal blooms in the Gulf of Mexico vaulted the issue into public consciousness in the 1990s, the Harmful Algal Bloom and Hypoxia Research and Control Act of 1998 passed with unanimous support (105th Congress, 1998). The Environmental Protection Agency (EPA) and National Oceanographic and Atmospheric Administration (NOAA) have studied harmful algal blooms and their negative environmental impacts since 1980 (Hoagland et. al., 2006), but the 1998 Act instituted requirements for an Inter-Agency Task Force to consolidate scientific research and determine possible mitigation efforts against harmful algal blooms (U.S. Code, 1998). The 1998 Act is the predecessor to the proposed Harmful Algal Bloom and Hypoxia Research and Control Amendments Act of 2017, which is the focus of this report.

A bipartisan cross-section of legislators sponsored the Amendments Act of 2017 (S.1057; H.R.4417) against a backdrop of increasingly severe and frequent harmful algal blooms in their respective states. On Lake Erie, the number of algal blooms NOAA classifies as severe has increased by 114% since 2016; global cases of hypoxia have doubled each decade since the 1960s; and recent, migratory blooms in the Chesapeake Bay, Florida, and California coast have led to broad economic and public health concerns (NOAA, 2018b; Diaz, 2008; USGS, 2018). Certain algal strains release toxins that poison humans, harm marine mammals, and pollute public air and water (Liew, 2000). Other strains of microalgae simply bloom in large numbers, coating water surfaces with an opaque and malodorous film (Gilbert et. Al., 2006). When these algae die, they decompose and deplete dissolved oxygen levels in the lower layers of their waterways; at high algal densities, such as those in excess of the World Health Organization's standard of 10 parts per billion, this can create "hypoxic" zones where oxygen-dependent species cannot survive (U.S. EPA, n.d.; Anderson, 2017). The complex ecological and economic impacts of these issues are cause to continue and expand the study of these phenomena.

It is impossible to adopt one universal roadmap for effective mitigation of more than 300 unique strains of algae that cause harmful algae blooms (UNESCO, 2007). Consequently, ongoing Federal research about harmful algal blooms is critical. Diverse algae strains do have something in common, however, in that anthropogenic influences are making them worse (Carpenter, 2005). Human nutrient pollution into both fresh and salt water bodies feeds algal blooms, and there are clear links from increased industrial agricultural and urbanization to more frequent and severe U.S. harmful algal events (Li, 2015). Climate change, fishery overuse, and wetlands removal all create positive feedback loops that increase the inputs algae need to bloom rapidly and decrease their natural buffers (U.S. EPA Office of Water, 2013).

The following analysis will first establish the scientific principles informing the Amendments Act of 2017. Section II will define harmful algae, thresholds for hypoxia, and common impacts on human and non-human systems. Sections III through V will enumerate the goals of the proposed policy, detail markers of increasing severity that prompt Federal intervention, and analyze the efficacy of the bill in devoting adequate resources for research and mitigation. Establishing this background is critical, as impacts are not distributed evenly nationwide (WHOI, 2016c). Finally, the report will conclude with techniques to predict, prevent, and remediate harmful algal blooms and hypoxia and the stakeholders that Federal policymakers must engage to successfully undertake such efforts



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## I. INTRODUCTION

Algae are dynamic, photosynthetic organisms that naturally occur in fresh and salt water bodies. Like other photosynthetic organisms (i.e. plants), these organisms require nutrients, sunlight, and water to survive, grow, and reproduce (USGS, 2017). While algae occur naturally, when they bloom, or reproduce rapidly, they can become harmful (Lopez, 2008). Microalgae that contain chlorophyll and propagate as single-celled phytoplankton or cyanobacteria can bloom at an unsustainable rate. Examples of microalgae include cyanobacterial algae in freshwater and dinoflagellates and diatoms in marine environments. These large-scale blooms block sunlight from reaching deeper into the water bodies on which the blooms occur. The blocked sunlight is required by other marine plant and macro-algae species, such as kelp, living below the surface on which marine animal life depends. Furthermore, when the surface blooms die, they sink into the middle and lower depths of their host waterbodies, and use up the water's dissolved oxygen as they biodegrade. As algal decomposition consumes oxygen, it creates hypoxic zones ("dead zones") where marine life does not have enough oxygen to breathe (U.S. EPA, n.d.). Some algal species also produce toxins that are hazardous to marine and human life. As discussed later in this report, thresholds for hypoxic conditions, habitat impact, and toxin production ultimately determine the harm that can be incurred by algal blooms (Li, 2015).

The following analysis focuses on the scientific and policy context, within the United States, for the Harmful Algal Bloom and Hypoxia Research and Control Amendments Act of 2017, which seeks to amend the Harmful Algal Bloom and Hypoxia Research and Control Act of 1998. The 1998 Act was proposed and passed with unanimous, bipartisan support at a time when both freshwater and saltwater harmful algal blooms emerged as a critical and impactful issue on the national stage (105th Congress of the United States, 1998). The 2017 Amendment, H.R.4417, aims to undertake the following four actions:

- 1. Add the Army Corp of Engineers to the established Inter-Agency Task Force.**  
The Army Corps of Engineers manages waterways and restores wetlands across the United States, and its inclusion will allow the Task Force to model engineering solutions.
- 2. Define harmful algal blooms of "national significance" based on relative size, location, and potential economic impact.**  
This provision sets standards for determining appropriate Federal allocation of funds to study and manage localized outbreaks, and provides a mechanism for stakeholders to request relief.
- 3. Create a publicly accessible website as a resource for scientists, policymakers, and other stakeholders to share information.**  
A website will provide an outlet for public, private, and academic dialogue, bringing more resources together against the complex and evolving issue of harmful algal blooms.
- 4. Extend funding of \$22 million per year for research and mitigation through 2023, with allowance for additional private donations to support Task Force activities.**  
\$110 million in funding over this five-year span will promote remediate and preventative actions against blooms; private donations will provide an alternate source of funding for the program to



assist states and localities affected by major harmful algal blooms and/or hypoxic events (Congress, 2017).

The list of detrimental impacts from harmful algal blooms and hypoxia is extensive, ranging from economic damage to public health risks to ecological disruption, and the costs of these harms are detailed throughout this report. The events themselves are concentrated locally, typically in coastal regions with dense, human settlement, and also temporally, as algae bloom seasonally and tend to migrate through waterways, as happens with Florida's infamous "red tide" that originates 10 to 40 miles off the state's Gulf coast (Florida Fish and Wildlife Conservation Commission, 2018). Policymakers in Washington recognize the need for Federal intervention in events of "national significance" to reduce highly localized costs from harmful algal blooms that are now impacting every U.S. state (U.S. EPA, 105th Congress, 1998).

A critical component of the harmful algal bloom issue, and an important nuance of any effective legislation to address it, is the immense variability and complexity of algae biology and physiology. Among thousands of species of algae, there are at least 75 varieties that are innately toxic and as many as 300 that contribute to harmful algal blooms, each of which prefers different nutrients, water conditions, and temperatures (UNESCO, 2007). Toxic algae is harmful even in small doses, while other harmful algal strains are damaging in large quantities when they promulgate rapidly and lead to hypoxia (Gilbert et. Al., 2006). When discussing the science behind harmful algal blooms and possible scientific and policy tools for prevention and remediation, there are no panaceas or ubiquitous answers, and ongoing research is imperative for identifying solutions specific to each algae strain and its necessary environment.

Harmful algal bloom events have also been increasing in severity, size, distribution, and frequency over the last three decades; one of the most potent harmful algal blooms, comprised of cyanobacteria, increased from 13 to 23 yearly cases from the 1990s to 2000s alone (Li, 2015). The growing prominence of these events spurred Federal action in 1998, but the past two decades of heavy investment in research -- in many ways supported by the 1998 Act and subsequent 2004 and 2014 amendments to it -- have only revealed the ways in which anthropogenic nutrient loading and climate change continue to accelerate this environmental and economic threat (U.S. EPA Office of Water, 2013; Li, 2015).

The following section will elaborate on this scientific background before examining the tactical role of United States Federal intervention in local research and remediation as outlined in the Act. The analysis will be conducted through the lens of several prominent case studies, or events of "national significance," such as the Gulf of Mexico Lake Erie, and nationally-prominent Florida red tide, but the same principles apply to other harmful algal blooms and hypoxia that impact every U.S. state and major waterway (WHOI, 2016b; Ritzel, 2014; Florida Fish and Wildlife Conservation Commission, 2018; NOAA, 2018b).



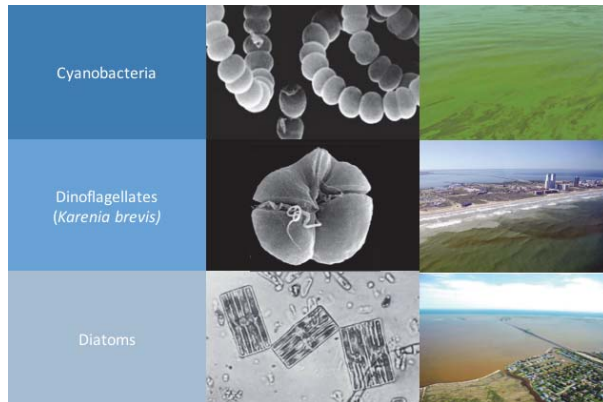
## II. THE SCIENCE OF HARMFUL ALGAL BLOOMS



- Algal blooms may occur naturally and are not always harmful when they propagate.
- Scientists must define and understand the causes and impacts of harmful algal blooms.
- The number of algal blooms are increasing each year: The 2018 forecast for Lake Erie calls for Harmful Algal Blooms that will be 114 times more likely to be more severe than those in 2016, and 6% more likely to be more severe than those in 2017 (NOAA, 2018b).
- The EPA considers nitrogen and phosphorus pollution to be the most pervasive and critical water quality issue in the country (U.S. EPA, 2015).
- The Harmful Algal Bloom and Hypoxia Research and Control Amendments Act of 2017 seeks to acknowledge the growing propensity of algal blooms becoming harmful and promote scientific research that can inform mitigation. In this section, we review existing scientific consensus on harmful algal blooms and the sources that feed their occurrence (Congress, 2017).

### A. DEFINING HARMFUL ALGAL BLOOMS

Like perturbations of other natural systems, harmful algal blooms are a product of complex, scientific interactions that lead to devastating environmental consequences and may have negative effects on human welfare. The conditions that feed harmful algal blooms originate from many sources, including nutrient deposition from agricultural or industrial runoff, atmospheric pollution, intrusion of offshore waters, upwelling in coastal ecosystems, waterbody stratification, and extreme weather (Hazen et al., 2015). From 1980 to the present, the United States Environmental Protection Agency (EPA) and NOAA undertook scientific research into harmful algal blooms and their negative effects on the environments in which they propagate (Heisler et. Al, 2008; Hoagland et. Al., 2006).



*Cyanobacteria, commonly referred to as “blue-green algae” can cause green, slimy blooms. Dinoflagellate species, such as Karenia brevis, can cause harmful conditions, such as those in the Gulf of Mexico seasonal blooms. Diatom microorganisms come in many shapes and sizes and often cause brown tides. (WHOI, n.d.; NOAA, 2013a; Huisman et al. 2018; Smithsonian Institution, 2011; Carmichael, 1994; Round et al. 1990).*

Scientists have identified the possibility for between 30,000 and more than 1,000,000 different species of algae to be in existence (Guiry, M., 2012). Harmful algal blooms are caused by about 300 different species of microalgae that form mass occurrences on top of warm-water bodies. Within the 300 different species of microalgae, about 75 produce toxins. In other words, in the lexicon of all algal species, about 1% are directly toxic (UNESCO, 2007). These species produce and emit toxins that are either harmful to other organisms, including humans, or they become harmful by bioaccumulating through the food chain (Creekmore, 1999). While all microalgae contribute to the physical effects of Harmful Algal Blooms (coating surfaces of waterways, blocking sunlight from deeper waters, and creating hypoxic zones during decomposition), toxic microalgae, such as cyanobacteria, dinoflagellates, and diatoms, directly poison the ecosystem of the waters on which they propagate (U.S. EPA, 2018).

## B. FEEDING BLOOMS

Scientific research has already uncovered that nitrogen and phosphorus feed naturally occurring algal blooms that propagate in warm, shallow surface waters in rivers and their fresh and salt water basins, such as the Mississippi River and Gulf of Mexico (Sellner et. Al., 2003).

**Eutrophication** can be caused by different sources and yield different results in unique watersheds, but the process of excess nutrients feeds harmful algal strains in the same fundamental ways. Areas with increased nutrient loading are more likely to develop harmful algal blooms than similar areas without added nutrients (Glibert and Burkholder,

**DEFINITION: Eutrophication is the growth of algae due to nutrient loading into water bodies where they propagate.**

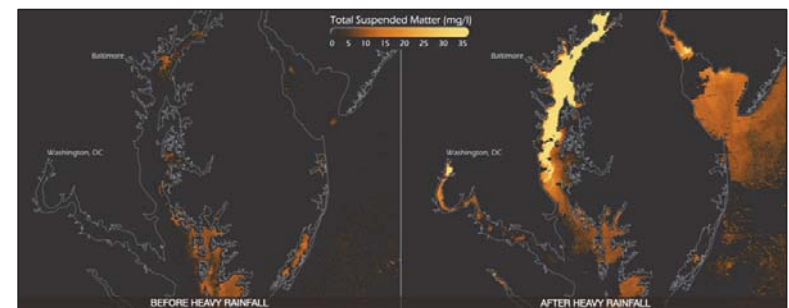
**DEFINITION: Water Stratification is the process by which warmer water sits on top of colder water, and the layers do not mix or cycle into each other.**



2006). The types of nutrients (nitrogen or phosphorus), the water temperature, **water stratification**, and other factors will favor certain algal strains over others (U.S. EPA Office of Water, 2013). Depending on the type of algae that thrives in a particular water body, environmental harm may occur because the algae itself is toxic and/or because the growth of the algae is depleting the water of nutrients or oxygen.

Nutrients can enter watersheds via a variety of methods, including:

- Synthetic or manure fertilizer on farms, lawns, and recreational areas can be picked up by precipitation, washing them through natural channels and streams into river tributaries and into the rivers themselves.
- Fossil fuel burning releases nitrates and nitrous oxide into the atmosphere that returns to the ground through acidified precipitation (rain and snow) and particle deposition as nitrogen oxides, nitric acid vapor, gaseous ammonia, particulate nitrate, ammonium compounds, and organic nitrogen (Anderson et. Al., 2002).
- Wastewater leaks or seepage directly enter into rivers and their tributaries (Dodds et. Al., 2016).
- Excess aquaculture feed deposits nutrients in the water, despite efforts to establish segregated aquaculture farms (Anderson, 2012).
- Excess feed in livestock farms results in nitrogenous waste on farms, which can runoff into water bodies (Pitcairn, C. et. Al., 1998).



*Runoff from precipitation, particularly extreme weather events, moves nutrient-rich sediments into waterways. This map shows suspended sediment in Chesapeake Bay – a harmful algal bloom hot spot – before and after heavy rainfall, 2011 (NOAA, 2018d).*

The EPA and NOAA identified nitrogenous fertilizers as the main source of nutrient loading that is increasing eutrophication and feeding algal blooms in salt water bodies (U.S. EPA, 2018). The use of fertilizers by farmers and other large-scale agriculturalists is leading to increased algal bloom frequency globally (Biello, 2014). Coasts of North America, Asia, and Europe are all areas with high use of nitrogen based fertilizers, and this correlates with simultaneously large amounts of particular algal strains, such





as those responsible for causing paralytic shellfish poisoning (Gilbert, A. et. Al., 2006). The number of recorded incidents of harmful algal blooms worldwide has increased from 1970 to today to include regions where they were never previously documented. Records of paralytic shellfish poisoning (PSP) are considered the most comprehensive record of harmful algal bloom impact, as nearly every coastal community worldwide holds some dependency on shellfish as either part of their diet or part of their economy. Until 1970, PSP-producing blooms were recorded only in Europe, North America, and Japan. By 1990, the range of PSP-producing blooms expanded to include the Southern Hemisphere, including South Africa, India, Australia, Thailand, Brunei, Malaysia, the Philippines, and Papua New Guinea. Similarly, the number of harmful algal bloom species recorded also increased. Furthermore, in the southern hemisphere, Australia has records of its coastal water quality dating back to the 1970s. Under these circumstances, it is possible to infer that the number of algal bloom events has been increasing and spreading geographically despite the possibility of increased sophistication in monitoring techniques accounting for some of the increase in documentation by 1990 and beyond (Hallegraff, 1993).

In the United States, farm fertilizer in runoff accounts for 65% of the contribution of nitrogenous material into U.S. waters (McCrackin, M. et. Al., 2017). NOAA and EPA also identified phosphoric runoff as the main source of algal feed in fresh water bodies (NOAA, 2018b). While these systems were initially studied as isolated incidents, research showing links between harmful algal bloom events led to the 2017 proposal to expand the scope of waterbody research to include interactions between rivers and their outlets (Congress, 2017). **Farmers**, for this reason, are critical stakeholders regarding the sources of harmful algal blooms. It is notable that, while every U.S. state has experienced harmful algal blooms, some communities, like coastal areas or regions with heavy farming industries upstream, bear disproportionate costs from harmful algal blooms (WHOI, 2016b). Furthermore, it is important to note inefficiencies in nutrient loading systems. Nutrient loading often occurs past a point at which fertilization is fruitful. Adding fertilizers to arable land can improve yields, but fertilizers are often continuously loaded, even after soil nutrient saturation has been exceeded. Above this point, fertilizer sits on top of soil without absorption, readily available for being picked up by water on land and runoff into nearby waterways, promoting algal blooms (Dodds, W. et. al., 2009).

Like farmers, aquaculturists comprise another group that is responsible for adding nutrient rich substances to US waterways. Nutrients are added to the waterways via fish food and fish excrement. Fish food is enriched with nutrients to promote fish growth, and fish excrement is high in both phosphorus and ammonium ( $\text{NH}_4$ ), a nitrogenous compound (Yeo et. al., 2004; Kibria et al. 1997).

**STAKEHOLDER SPOTLIGHT: Farmers rely heavily on water for irrigation and the development of their livelihood. They add nutrients to farm soils in form of nitrogenous fertilizers. These fertilizers accumulate on the soil surface when too much is used contributing to nitrogenous runoff into rivers systems. The farm community is a key upstream stakeholder.**



Farmers and fishermen are not the only sources responsible for nutrient dumping, as other recreational users of fertilizers and other nutrient rich substances, such as golf courses, also play a role. Fertilizers are added to **residential lawns, golf courses, and recreational areas**. Excess fertilizer can runoff into nearby

**STAKEHOLDER SPOTLIGHT: Golf courses, residential lawns, and recreational areas also consume large amounts of nitrogenous fertilizers with little regulation on amounts used. These spaces are often over-fertilized, producing nitrogenous runoff into river systems.**

water bodies, making these stakeholders important actors. One study from 2008 determined that the combined costs of eutrophication, or nutrient-loading, in U.S. freshwaters is approximately \$2.2 billion annually, and can be traced to largely anthropogenic inputs that include excess fertilization, climate change, and reductions in the capacity for natural watershed filtration (Carpenter, 2005).

Nutrients that feed algal blooms make their way through the river systems into the outlet basins where they collect in the slow, depositional flow rates at the nexus of the river and its outlet (Chen, 2010).

#### **$L_d/X_{wl}$**

$L_d$  is a cross-shore advective distance settling time\*river outlet velocity  
 $X_{wl}$  is the imminent cross-shore length of the intertidal zone/ interflow zone  
 \*Sediment trapping requires  $L_d/X_{wl} < 1$

Seaward transport length scale ratio, describing the transport of nutrients in the water column (Chen, 2010).

Faster surface flows push the nutrients out into the warm surface waters of the basin. As this happens, longshore drift and tidal activity pushes the nutrients in towards the shore, stratifying them parallel to the coast. Longshore drift is a natural occurrence that carries sediment and particulate matter in water bodies along their shorelines in a series of uplift and deposition events. As waves move towards the shore, different segments of the wave reach the shore before others, slowing these segments down. The waves bend and deform, moving at a slight angle to the shore. The crashing of the wave on the shore creates a current parallel to the shore that extends out into shoreline shelf that extends under the water to the edge of where the basin begins (NOAA, 2018a). Deposited nutrients, and the algae that consume them, sit on or near the surface of the water bodies, allowing them to get caught up in tidal activities that push them toward the shore in this manner. Meanwhile, the basin waters stratify as they warm, because warm water is less dense than cold water, and stays at the surface, preventing vertical mixing with colder, deeper waters (Julien, 2018). Warming surface waters and lack of mixing increases the likelihood of algal bloom propagation. As climate change continues to proceed unabated, warm water stratification will increase, laying a permanent foundational condition for harmful algal bloom propagation (Dale, B. et. Al., 2018).

While freshwater and marine systems were studied as isolated incidents in earlier forms of the Harmful Algal Bloom and Hypoxia Research and Control Act, expansive science linking marine harmful algal blooms with nutrient inputs in their headwaters led to the 2017 proposal to expand the scope of research and mitigation efforts to include interactions between rivers and their outlets, and also inspired the inclusion of the Army Corps of Engineers to help manage hydrologic projects in these key



watersheds (Congress, 2017). A key measure of including these interactions is the admission that upstream nutrient sources are responsible for downstream impacts including the development of hypoxic dead zones in river basins. For example, it is now estimated that farms in the Mississippi River watershed will need to reduce ammonium-based fertilizer use by 59% to reduce the Gulf of Mexico hypoxic dead zone by approximately half its size, or 5,000 square miles (Ritzel, 2014).

### C. HYPOXIA AS A HARMFUL ALGAL BLOOM BYPRODUCT

The threshold for **hypoxia** is defined as 2 to 3 milligrams oxygen per liter of water, also referred to as 2-3 parts per million (Paerl et. al., 1998). When algal blooms die, they sink down in the water column and decompose. Algal decomposition consumes oxygen, and at the large scale of a harmful algal bloom, this process removes noticeable amounts of oxygen from the surrounding water. Algal decomposition in large amounts consumes enough oxygen to create hypoxic zones in middle and lower depths of the water body, choking marine life and generating aquatic dead zones (Gilbert et. Al., 2006). In 2017, nitrogenous flows down the Mississippi River into warm, shallow surface waters in the Gulf of Mexico created a dead zone that was 8,776 square miles in size, which is approximately the size of the US State of New Jersey (NOAA, 2017). Other at-risk areas include Puget Sound, the Florida coastline, the coastline of Southern Maine, Lake Erie, and the California Coast (USGS, 2018).

**DEFINITION: Hypoxia is a lack of oxygen in a water body, either fresh or marine. Hypoxia occurs at less than 2-3 milligrams of oxygen per liter of water (2-3 parts per million).**

## III. FEDERAL POLICIES



- The following section examines the Harmful Algal Bloom and Hypoxia Research and Control Act of 1998 as the first piece of legislation to address the issue of harmful algal blooms and hypoxia in the United States.
- The discussion continues to discuss the two subsequent, successful amendments to the Act, in 2004 and 2014 and the important additional and modifications these made to the original legislation.
- The section continues on to outline in more detail the provisions of the 2017 Amendment and the impacts of these provisions.
- The bulk of costs incurred by harmful algal blooms and hypoxia are on the local and State level.
- The act provides for Federal funding to offset these costs.



## A. HISTORY OF THE HARMFUL ALGAL BLOOM AND HYPOXIA RESEARCH AND CONTROL ACT

### i. 1998 Act

Historically, harmful algal blooms were cited as regional issues with little national recognition. Rapid industrialization and limited environmental regulation generated an increase in pollution and resulting harmful algal bloom frequency worldwide. By the mid-20th century, American researchers recognized the detriment of harmful algal blooms on aquatic ecosystems and, in 1968, experimentally demonstrated phosphorus as a main source of blooms. The 1968 experiment directly proved that phosphate detergents caused freshwater harmful algal blooms, leading to policies mandating phosphate-free detergents (Bath, 2017).

In 1997, Maryland's Pocomoke River experienced a large fish-kill and, in conjunction with algal blooms in the Gulf of Mexico (H.R. 4325), this motivated the creation of the Harmful Algal Bloom and Hypoxia Research and Control Act of 1998 (Griffith, 1999). The 1998 Act, which garnered bipartisan support because of its trans-boundary nature, established an Inter-Agency Task Force to examine the ecological and economic consequences of harmful algal blooms, and research means for reducing, mitigating and controlling such blooms. The Task Force was directed to deliver reports:

- Assessing the ecological and economic costs of harmful algal blooms and methods for controlling and reducing them within 12 months from enactment of the law;
- Assessing the ecological and economic costs of hypoxia in coastal waters and methods for controlling and reducing them within 12 months from enactment of the law; and
- Assessing hypoxia in the northern Gulf of Mexico including the sources and loads of nutrients transported by the Mississippi River to the Gulf, which contributed to such blooms and the means of reducing such nutrient loads by March 30, 2000.

Funding was appropriated for these efforts in fiscal years 1999 through 2001 to support work under, and outlined in, the Act.

### ii. Subsequent Amendments

In 2004, the Act was amended and reauthorized with bipartisan support. The 2004 Act retained the inter-agency task force and required the President of the United States to deliver a report to Congress within 12 months after the enactment of the 2004 Act that:

- Reviewed techniques for predicting harmful algal blooms and the extent and impact of such blooms, and assessing their accuracy; and
- Identified innovative research and development methods for preventing, controlling and mitigating such blooms including provision for their development.



At the request of State and local governments, the Under-Secretary of Commerce was to conduct local and regional assessments of the causes, ecological consequences and economic impact of harmful algal blooms and hypoxia events. The Secretary of Commerce was also to conduct local and regional assessments to determine potential options to control and prevent these events from happening, along with determining their potential ecological and economic costs.

Within 24 months of the enactment of the 2004 Amendments Act, the Task Force was required to submit a scientific assessment to Congress that examined freshwater algal blooms in areas such as the Great Lakes. The assessment included proposals for research to better understand the causes of freshwater harmful algal blooms and improve coordination among Federal agencies conducting research on the subject. Scientific assessments of hypoxia in coastal waterways, and of harmful algal blooms in freshwater and marine waterways, were to be submitted by the Task Force every 5 years with the first assessment of these blooms in freshwater waterways, and of these blooms in marine waterways due 24 months after the Act's enactment. The 2004 Act also required the Task Force to submit recommendations to Congress for research into preventing, controlling and mitigating harmful algal blooms within 12 months after its enactment. The Act appropriated the sum of \$23.5 million in Fiscal Year 2005, \$24.5 million in Fiscal Year 2006, \$25 million in Fiscal Year 2007 and \$25.5 million in Fiscal Year 2008 to perform work under the Act's provisions. It also set aside \$1 million annually to fund scientific research under the Act's provisions.

The Act was most recently amended and reauthorized in 2014 with bipartisan support. The 2014 Act established a national harmful algal bloom and hypoxia program and established the National Oceanic and Atmospheric Administration as the lead agency with primary responsibility for administering the Program. Additionally, The Centers for Disease Control and Prevention (CDC) was added to the Task Force. The Act made it clear that the Task Force was to develop and implement a national action strategy for reducing, mitigating, and controlling hypoxia and harmful algal blooms, not only in the northern Gulf of Mexico and other marine waterways, but also in the Great Lakes and other freshwater ecosystems. Progress reports were to be submitted every two years and the sum of \$20.5 million was appropriated annually during Fiscal Years 2014 through 2018 to perform work under the 2014 Act.

### iii. Proposed 2017 Amendments Act

The Harmful Algal Bloom and Hypoxia Research and Control Amendments Act of 2017 (S. 1057) was introduced and passed by the United States Senate on September 26, 2017. H.R.4417, a companion bill, was introduced in the United States House of Representatives.

The Harmful Algal Bloom and Hypoxia Research and Control Amendments Act of 2017 amends the Harmful Algal Bloom and Hypoxia Research and Control Act of 1998, as amended by the 2014 Act, to address some issues in the Act and its earlier amendments (Congress, 2017). The bill is designed to ensure that key stakeholders are included in the process of assessing and reporting on harmful algal blooms and hypoxia events, that the assessment process is transparent, and that communities that are impacted by harmful algal bloom events are eligible to receive Federal aid in the form of "disaster-like funds" to mitigate the resulting adverse impacts (Senate Committee on Commerce, Science, And Transportation, 2017).



The key changes to the existing law are as follows:

- Section 4001 subsection (a) is amended to add the U.S. Army Corps of Engineers to the Inter-Agency Task Force. The US Army Corps of Engineers has jurisdiction over the issuance of permits for work on inland waterways and manages major construction projects that affect waterways relevant to the Inter-Agency Task Force responsible for both assessing the ecological and economic impacts of harmful algal blooms and hypoxia and developing programs for mitigating their effects.
- Section 4001 subsection (g) is amended to require the Inter-Agency Task Force, established by the Act, to submit a scientific assessment of harmful algal blooms that occur in both marine, coastal waters and freshwater systems in the United States, including the Great Lakes, the upper reaches of estuaries, freshwater lakes, and rivers. It adds language to the Act to make it clear that such assessments shall also include blooms that originate in freshwater lakes or rivers, and that migrate to coastal waters.
- Section 4002 subsection (e) is amended by adding language in paragraph (1), mandating that the National Harmful Algal Bloom and Hypoxia Program must be promoted to local and regional stakeholders by the Undersecretary of Commerce for Oceans and Atmosphere through an internet website accessible to the public that provides information regarding the activities of the Program completed in accordance with this Act.
- A new Section 7 is added to the Act to make it clear that if there is a hypoxic event or harmful algal bloom that will have a significantly detrimental impact on the environment, the economy, or public health in any State, the Undersecretary of Commerce for Oceans and Atmosphere, and in the event of a freshwater event, the Administrator of the Environmental Protection Agency, may issue a determination, on his or her own, or at the behest of the Governor of an affected state, that there is an event of national significance. Enacting this designation will make funds available to the affected State and local governments to assess and mitigate the environmental, health, and economic impacts of the event. The Federal government will be limited to only pay half of the cost of these efforts, and the government may accept donations of money, goods and services to aid in the relief from these events.
- Section 4009 subsection (a) is amended to provide for an annual appropriation to the Undersecretary of Commerce for Oceans and Atmosphere in the sum of \$22 million annually for fiscal years 2019 through 2023, to carry out the provisions of the Act.





## B. ANALYSIS OF KEY PROVISIONS IN H.R.4417

H.R.4417 enhances the ability of the Task Force to meet the goals of the original Act and subsequent amendments.

The Army Corps of Engineers plays a critical role in the management of many waterways across the nation, operating 12,000 miles of commercial channels; managing 926 coastal, Great Lakes, and inland harbors; restoring wetlands; and issuing permits along these waterways (U.S. Army Corps of Engineers, 2018). Including the Army Corps of Engineers in the scientific research on migratory blooms, specifically marine blooms with inland headwaters, will allow for more accurate assessments of causes and possible solutions in a larger context, while including the consideration of harmful algal blooms when issuing further permits for development.

H.R. 4417 delineates criteria for designating events of national significance, which will allow Federal funds to be applied to harmful algal blooms deemed as such by the U.S. Undersecretary of Commerce for Oceans and Atmosphere, and by the Task Force (Congress, 2017). Previously, Federal funding was not directly available through the Program to State, local and tribal governments (U.S. Code, 1998). In defining some of the criteria by which national significance is determined, the 2017 Amendments Act strengthens the program's ability to execute mitigatory action and addresses the deleterious effects that can disproportionately affect a certain area.

Private donations provide a new source of funding for the Program, which the NOAA is to collect and spend, without further appropriation, as monetary donations to assist states and localities affected by major harmful algal blooms and/or hypoxic events (S. Rept. 115-145). Donations will be recorded in the budget as reductions in direct spending (S. Rept. 115-145). The Congressional Budget Office expects that any gifts will be spent within a short time span, and any net change in direct spending will be inconsequential (S. Rept. 115-145). Private donations will allow for private stakeholders to act for prevention and mitigation, furthering involvement.

Additionally, adding the website introduces a concise outlet that engages the public and private sectors with real-time updates on harmful algal blooms and hypoxia. The website also provides educational materials and scientific transparency to foster academic dialogue (Senate Committee on Commerce, Science, And Transportation, 2017). Maintaining a website about the issue and emerging research pertaining to the issue of harmful algal blooms will expand upon individual local and State efforts to report, predict, control, and mitigate harmful algal blooms and hypoxia; Florida has a concise statewide system that NOAA could model their system after (Algal Bloom Monitoring and Response).

### THE POLICY: H.R. 4417 includes the following legislative provisions:

- Adding the Army Corps of Engineers to the Inter-Agency Task Force
- Increasing access to funding mechanisms
- Defining events of 'national significance'
- Establishing a website for research publications, collaboration, and public awareness



## C. FUNDING THE POLICY SOLUTION

To determine if the funding appropriated by the bill is sufficient, it is critical to examine the direct and indirect costs of harmful algal blooms and hypoxia as well as the funding itself. The bill will allocate \$110 million from fiscal year 2019-2023, which can be mobilized according to "pay-as-you-go procedures" for direct spending (S. Rept. 115-145).

The Congressional Budget Office estimates that implementation will cost \$76 million over the 2018-2022 period, with no adverse effects on the national budget (S. Rept. 115-145). Beyond the initial funding of the bill, there are numerous economic issues related to harmful algal blooms still to be addressed, such as costs related to health effects and revenue lost in commercial fishing, tourism, and recreation. These costs and effects are estimated at approximately \$82 million per year from multiple NOAA reports (NOAA, 2014). In comparison to local cost estimates, however, this cost range is extremely conservative and does not fully account for the widespread local costs that plague affected localities. Effects from nutrient pollution is estimated to cost tourism \$1 billion annually in the United States in revenue lost alone (The Effects: Economy). Harmful algal blooms, largely spurred by such nutrient pollution, are a major contributor to this figure that overshoots the NOAA estimates of harmful algal bloom-related costs. Furthermore, health costs in a single Florida county have reached up to \$4 million annually while statewide fisheries have suffered \$18 million in losses annually accounting for almost half of the low-end estimate from the NOAA for these losses (Hogland, 2009; Anderson 2000). The bill addresses two areas of concern related to insufficient funding in response to this costly and critical national issue.

**DEFINITION: Pay-as-you-go procedures procure funds as a lump sum in an 'as-needed' fashion. Money can be removed to finance specific projects and efforts, for harmful algal blooms of 'national significance' as they occur.**

### i. Local versus national costs

Nitrate pollution is a growing problem, and national water treatment remedies to remove nitrates from water supplies costs more than \$4.8 billion per year (Ribaud and Gottlieb, 2011). Since harmful algal blooms are dependent on a number of localized conditions, finding isolated costs of algal blooms requires analyzing costs internalized by local and State actors. One report found that in Ohio, a persistent bloom in lakes caused communities to lose between \$37 million and \$47 million in tourism dollars between 2009 and 2010, detracting from \$158 million in annual economic activity, (U.S. EPA, 2015, Davenport and Drake, 2011; Davenport et al. 2010). It is evident that costs are grossly underestimated at a national level, and a wholesome cost report on harmful algal blooms would therefore need to include detailed city- and town-incurred costs, in combination with large-scale costs, to produce a more representative cost report that will match more closely to the EPA's nutrient pollution figure. Comparatively, funding for this bill is far from sufficient to offset the costs associated with harmful algal blooms and hypoxia. The funding is, however, enough to provide key funding for research, control, and mitigation efforts.



## ii. Disparate local costs

Each state and locality experiences different costs related to harmful algal blooms and hypoxia, and these costs are constantly changing due to the variable nature of harmful algal blooms (U.S. EPA, 2015). The issue of these blooms is not one-dimensional, and multiple approaches must be taken in different regions to attend to the specific effects of harmful algal blooms and hypoxia. Even in the same category of blooms and ecosystem characteristics, impacts vary greatly. For example, in 2015 Washington State lost \$40 million from the closure of its recreational razor clam harvest (Woods Hole Oceanographic Institution, 2016), while Maine lost \$2.5 million in soft shell clam harvests from April to August 2005 (U.S. EPA, 2015; State of Maine, 2017). Despite both states feeling the economic consequences of blooms in the shellfish industry, the vast difference in scale make it challenging to identify proper allocation of Federal funds.

One example of the successful interface between economic costs and scientific monitoring comes from the State of Washington, which in spring 2015, issued early warnings of domoic acid contamination in razor clams caused by an outbreak of *Pseudo-nitzschia* on the west coast of the United States (Dyson et. al., 2010). These early warnings led to, and allowed for, selective beach openings, saving at least \$3 million per year for the state's coastal fisheries by providing more accurate and real-time information on the presence of the algae and toxins (Dyson et. al., 2010). Mitigation and research can have tangible and positive economic impacts, providing evidence for the success of the bill's intended motives.

## IV. THE IMPACT OF HARMFUL ALGAL BLOOMS



- Harmful algal blooms are variable by location, water body type (salt or freshwater), and other natural conditions. Coastal regions and insulated freshwater areas can harbor different algae species and experience unique anthropogenic drivers.
- Harmful algal blooms and hypoxia cause multifarious and highly variable effects: economic costs, environmental degradation, and diminished public health.
- With the financial burden so heavily localized, cities and States look to Federal funding and scientific support to remediate harmful algal blooms crises, and this local pressure from legislators and constituents created the need for the Harmful Algal Bloom and Hypoxia Research and Control Act of 1998 and the subsequent amendments.



## A. IDENTIFYING DIRECT AND INDIRECT COSTS

Areas and communities that endure harmful algal blooms often experience direct or indirect economic impacts. The North Atlantic Administration estimates the total nationwide costs of harmful algal blooms at approximately \$82 million annually (NOAA, 2014). The following section will demonstrate that this estimate does not accurately portray the total direct or indirect costs, as they are often absorbed at a local level and over extended periods of time. Examples of **direct costs** are cleanup activities, lost revenue for marine-related businesses, the cost of monitoring the development of blooms, and human health care costs. Examples of **indirect costs**, and socioeconomic impacts, are loss of property values, loss of biodiversity and ecosystems, and lost recreational opportunities for tourists and accompanying lost wages to residents.

| DEFINITION: Direct and indirect costs |                                                |
|---------------------------------------|------------------------------------------------|
| <b>Direct:</b><br><i>Cleanup</i>      | <b>Indirect:</b><br><i>Lost property value</i> |
| <i>Business revenue losses</i>        | <i>Lost scenery/aesthetics</i>                 |
| <i>Regulatory costs</i>               | <i>Ecosystem services lost</i>                 |

The indirect costs are challenging to measure and quantify, making it difficult to calculate the actual marginal costs associated with harmful algal blooms (Hoagland, 2002). Local taxpayers often bear the brunt of these costs. For example, Ohio spent over \$13 million treating drinking water from an affected lake in 2010 (U.S. EPA, 2015). The greatest economic losses yet may be due to diminished lakefront property values and recreational use (Dodds et al., 2009). The Harmful Algal Bloom and Hypoxia Research and Control Amendments Act of 2017 would allow the states to seek funding for up to 50%

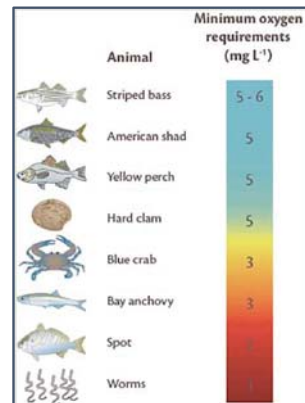
of the costs of assessing and mitigating the environmental and economic impacts of events of national significance.

## B. HABITAT AND BIODIVERSITY LOSS

Harmful algal blooms contribute to the destruction of important habitats. Algae are an important foundational link in the aquatic food chain, and they are consumed by a number of larger organisms. Certain fish species, such as the Chinese Algae Eater, the Siamese Algae Eater, the American-flag Fish, certain species of Catfish, Surgeon Fish, and Rabbitfish all consume algae - some even consume cyanobacteria and diatoms that are toxic upon contact (Norambuena et. al., 2015). Additionally, many bottom-feeders, such as freshwater shrimp, freshwater snails, and sea urchins feed on algae (Benemann, 1992). While algae form an integral part of the food chain for smaller fish species and bottom-feeders that then feed larger fish species, toxic variations of algae and large-scale blooms can be very disruptive.



Large-scale harmful algal blooms propagate on the surface of water bodies. When microalgae explode into large-scale blooms, they create a paint-like film that covers warm surface waters, preventing sunlight from reaching into the mid-depth zones of the water bodies where they occur. The lack of sunlight prevents plant life from growing in shallow waters near shorelines (Smayda et. al., 2002) as well as in deeper waters where they would otherwise support a foundational food source for marine food chains (Wolf et. al., 2017). While harmful algal blooms do produce algae that would otherwise support the bottom of the food chain, their location is in the wrong place to support foundational species of larger fish. As an example, smaller fish species and bottom-feeders that lose their source of algal feed at the bottom of the water body are, by themselves, feed sources for Seatrout, Red Drum, Flounder, Kingfish, and Sturgeon in the Gulf of Mexico (University of Southern Mississippi, 2018). At the same time, marine mammals, such as manatees, dolphins, and whales are losing their feed sources much in the same way (Landsberg, 2010).



Dissolved oxygen requirements for key commercial aquatic species (Interagency, 2010).

Aside from disruptions to the food chain, harmful algal blooms disrupt the respiratory process for animal life in the water bodies on which they propagate. When surface algal blooms die, they sink into the water bodies where they form. As they sink, they draw oxygen out of the water to decompose.

Algae can deplete water bodies of energy and oxygen required to support many of the other marine organisms listed earlier (National Science and Technology Council Subcommittee on Ocean Science and Technology, 2016). As noted earlier, marine organisms require an excess of 5ppm oxygen concentration in water to survive, grow, and reproduce. Harmful algal blooms are known to reduce these levels to 2-3ppm (Paerl et. al., 1998). When this happens, mobile marine organisms either swim toward the shore gasping for oxygen or emigrate to healthier ecosystems where they become invasive. For marine life that cannot move out of the way, or that are immobile, they die in place (Diaz, R. et. Al., 2008).

When large, aquatic organisms are removed from the ecosystem, either by human activities, such as fishing, or by changing aquatic conditions that limit their survival, the food chain disintegrates, species emigrate or die off, and even more space is made available for algae (Turner and Graneli, 2006). Diminution of species counts and populations decreases the biodiversity of the affected water body and destroys the natural processes that each stage of food chain supported, such as shrimp cleaning the bottom layers (Diaz et. al., 2008).

Harmful algal blooms cause this myriad of problems that disrupt economic activities that depends on the water bodies whose ecosystems are most affected by their propagation. In Lake Erie, when large cyanobacterial algal blooms occur, the lake-based economy experiences a 10.6% decrease in monthly purchasing of fishing permits, from a maximum of approximately 1,500 permits to 1,310 permits (Wolf



et. al., 2017). The result of the permit reduction is that there are fewer individuals who find it safe or profitable to fish under the conditions created by the bloom, hurting their local economies. In the end, apart from the destruction of the water body's food-chain, the resulting death of marine life reduces fishery catches, threatening a large, multi-state industrial sector in the United States.

## C. TOXICITY

Certain species of algae, such as cyanobacteria and *Pfiesteria*, release toxins or are otherwise dangerous to fish, other aquatic organisms, and humans (Lopez, 2008). These toxic algae strains can produce neurotoxins that injure or kill fish, whales, and other marine life, while some non-toxic, barbed algae kill fish by damaging their gills (Anderson, 2004). In 1998, over 400 California sea lions died with many others showing signs of neurological dysfunction and distress in conjunction with a diatom bloom of *Pseudo-nitzschia australis* in Monterey Bay (Scholin et. al., 2000). As noted earlier, from the 1970's to today, the global growth in the number of harmful algal blooms has been tracked through recorded events of paralytic shellfish poisoning caused by toxic *Alexandrium*.

Toxicity in the marine food chain poses a major public health risk. Smaller fish can consume toxic algae or consume bottom-feeders that consume the toxic algae. The toxins in the algae accumulate in the fatty tissue of the fish and increase in scale as bigger fish eat smaller fish, enabling the toxins to bioaccumulate up the food chain. Human consumption of fish that are caught that have consumed or come into contact with toxic algal blooms can lead to deadly or fatal public health consequences (Moore et. al., 2008). Furthermore, the algae themselves coat shoreline waters with a paint-like film of muck that can produce unwanted health effects on contact (Zingone et. al., 2000). The tourism and fisheries industries take a direct hit from this, while public health must adapt to handle cases of algal ingestion or toxic contact.

### The most commonly recognized illnesses include:

| Illness                              | Toxin                          | Source                                            |
|--------------------------------------|--------------------------------|---------------------------------------------------|
| Ciguatera Poisoning                  | ciguatera toxin                | subtropical and tropical fish                     |
| Paralytic Shellfish Poisoning (PSP)  | saxitoxins                     | bivalve and gastropod molluscs, crustaceans, fish |
| Diarrhetic Shellfish Poisoning (DSP) | okadaic acid, dinophysistoxins | molluscan shellfish                               |
| Amnesic Shellfish Poisoning (ASP)    | domoic acid                    | molluscan shellfish, crustaceans, fish            |
| Neurotoxic Shellfish Poisoning (NSP) | brevetoxins                    | bivalve and gastropod molluscs                    |
| Azaspriacid poisoning (AZP)          | azaspiracids                   | bivalve molluscs                                  |

Common illnesses experienced due to algal toxins (Getchis and Shumway, 2018).



## D. INTERNALIZING COSTS

States and other local agencies are responsible for the organization and coordination of cleanup activities in events of harmful algal blooms. Under the guidance of the Amendments Act of 2017, events of “national significance” will authorize Federal government aid covering up to 50% of clean-up costs (Congress, 2017).

### i. Public Health

Municipal governments must contend with many complicated issues when a nearby algal bloom occurs. Harmful algal blooms can shut down certain recreational areas to aquatic activities because of risks to human health on contact with toxic blooms or inhalation of airborne microalgae swept in on waves. Toxic algae can sicken or even kill humans through various routes of exposure, including dermal or ocular contact, inhalation, and oral consumption. Harmful algal blooms can cause respiratory and eye irritation, rashes, and neurological effects, can make water unsafe for swimming, and can sicken people who eat algae-exposed seafood (NOAA, 2013b). These health issues already cost the U.S. healthcare industry roughly \$20 million dollars annually. According to the NOAA, the healthcare sector absorbs 40% of the total national cost of responding to harmful algal blooms (WHOI, 2016c).

The primary exposure route of concern for human health is the consumption of fish or shellfish that is either directly contaminated by toxic algae, or that has accumulated toxins through the food chain (Grattan, Holobaugh, and Morris, 2016). For example, the dinoflagellate *Alexandrium*, which is common in Northeast U.S. coastal waters, produces saxitoxin, which is the neurotoxin that causes Paralytic Shellfish Poisoning. Symptoms in humans who eat contaminated mussels and other infected food include body numbness, respiratory distress, muscle paralysis, and death (Acres and Gray, 1978; Bonamici, 2017). Toxic exposure, and the resulting health effects, are worsening and, in fact, decadal maxima of paralytic shellfish toxins from dinoflagellates in Puget Sound, Washington, have increased five-fold since the 1950s (Ayres, 2008). Algal blooms in drinking water sources can also cause widespread problems. For example, Toledo, Ohio had to shut down its drinking water supply for a weekend in August 2014 for 500,000 residents due to an algal bloom in Lake Erie, which supplies the city’s drinking water. The Ohio National Guard supplied 33,000 gallons of water to the desperate Toledo residents (Fitzsimmons, 2017).



### ii. Recreation, Tourism, and Property Values

Harmful algal blooms can produce malodorous smells, color waterbodies red, green, and brown, and makes swimming and other water recreational activities harmful. These effects can be unappealing for vacationers and locals, who attempt to enjoy coastal regions’ scenery and amenities. A number of local Florida restaurants experienced economic losses due to harmful algal blooms (Morgan et. al., 2009). In the presence of a red tide between 1998 and 2005, **restaurant owners** lost between \$868 and \$3,734 in daily sales, as the algal bloom deterred locals from wanting to visit the restaurants, especially if they were located along the coasts (Morgan et. al., 2009). Additionally, if a harmful algal bloom results in a fish kill, restaurants that rely on local seafood will incur a potential for economic hardship. Other businesses, such as recreational boating, fishing, and vacation house rentals that rely on tourism are also impacted by a harmful algal bloom. The bloom results in individuals being less likely to visit, and according to one study, the greatest economic losses from algal blooms in the headwaters region of the Mississippi River were incurred by lakefront property whose values dropped, and recreational activity for which the number of recreators plummeted (Dodds et al., 2009). In Florida urban coastal housing markets, a 1% decrease in water clarity correlates with an average property price decrease of \$6,397 (Bin and Czajkowski, 2013).

**STAKEHOLDER SPOTLIGHT: Business owners around coastal areas are directly impacted by harmful algal blooms – smells, colorful water, and dead marine life detract from tourism and unsafe marine resources harm health, increase local costs, and hurt business.**

### iii. Water Treatment

The United States spends more than \$4.8 billion to remove nitrates from water supplies each year (Ribaud and Gottlieb, 2011). Harmful algal blooms are often local events meaning that isolated costs to treat water loaded with nitrates are internalized locally and need to be examined at the State or local level. The costs for treating individual watersheds, often perpetual and increasing budget items on an annual basis, can be staggering.

| Date      | State | Waters               | Water Quality                                          | Costs (2012S) <sup>1</sup>                                                                                                                                                                                                                 |
|-----------|-------|----------------------|--------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 2010      | OH    | Grand Lake St. Marys | Blue-green algae outbreak                              | \$13,080,000 (\$3,570,000 in O&M to date) <sup>2</sup>                                                                                                                                                                                     |
| 2002-2012 | TX    | Lake Waco            | High total phosphorus and chlorophyll-a concentrations | Watershed Monitoring = \$2,597,118<br>Influent/Treated Water Monitoring = \$740,705<br>Chemical Usage = \$1,169,151<br>Plant Upgrades = \$64,877,721<br>Plant Energy Costs = \$812,755<br>Lost Revenue from purchased water = \$10,300,000 |

<sup>1</sup>Source: Davenport and Drake (2011) for Ohio; The Cadmus Group Inc. (2014) for Texas.

<sup>2</sup> Costs updated to 2012S using the construction cost index.

<sup>3</sup> For treatment installation, toxic algae testing set-up, and total O&M (excludes alum, lime, and sludge costs).

Drinking water treatment costs attributable to algal blooms (U.S. EPA, 2015 ).



## V. GROWING NATIONAL CONCERN



- The frequency of harmful algal blooms and hypoxia is increasing globally (Gupta, 1996).
- NOAA forecasts that 50-75% of blooms will be harmful in 2018 (NOAA, 2018b), and global cases of hypoxia have roughly doubled each decade since the 1960s (Diaz, 2008).
- The United States and countries around the world are noticing an increase in both severity and frequency of these blooms and resultant hypoxia, which are attributable to improved measurement techniques, which allows scientists and governmental bodies to detect blooms with improved accuracy, greater anthropogenic influence which can drive blooms, and climate change.
- The following section examines evidence of the growing harmful algal bloom and hypoxia problem, as well as trends and feedbacks that are likely to perpetuate the issue in the future.



*There has been a 30-fold increase in the number of hypoxic waters since 1960 (Interagency, 2010)*

While nutrient loading can promote algal growth, climate change is another important driver and magnifier of harmful algal blooms. The following section examines trends in harmful algal bloom frequency and severity over time and the role climate change is likely to play in the future propagation of harmful algae events. The following table previews some of the disparate ways in which climate change, and more variable and extreme weather patterns, can impact water bodies and increase likelihood of harmful algal blooms:



|                          | <u>Increase</u>                                                                                                                                                                                                           | <u>Decrease</u>                                                                                                                                                                                                                                        |
|--------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Water Temperature</b> | In many freshwater and coastal bodies, higher temperatures could allow algae species to propagate over longer seasons or over broader geographic extents (IPCC, n.d.).                                                    | Some harmful algal strains prefer colder waters; their presence, currently restricted to high latitudes, shift with wider temperature fluctuations (Anderson et al. 2012).                                                                             |
| <b>Water Circulation</b> | In deeper ocean waters, warmer temperatures can promote greater rates of ocean upwelling, returning nutrient-rich water to the surface and feeding algal blooms in areas where they would not otherwise exist (Xiu 2012). | In freshwater and shallow coastal regions, as sea surface temperatures generally rise, thermal stratification will reduce water mixing, creating conditions preferential for algae growth (Hazen et al. 2015).                                         |
| <b>Water Levels</b>      | Along coastlines, climate change will trigger global sea level rise, increasing the extent of shallow waters along the edge of continental plates, where algae thrive (U.S. EPA Office of Water, 2013).                   | As climate changes, many inland water bodies will experience greater evapotranspiration, reduction in headwaters, and increased extraction for human use; shallower waters mean higher nutrient concentrations and warmer temperatures (Vincent 2009). |

## A. INCREASED FREQUENCY

Warming temperatures create longer warm-weather seasons, which provide algae with ideal environmental conditions in which to bloom. Since the 1960s, the global number of dead zones in water bodies attributable to harmful algal blooms has doubled each decade (Diaz and Rosenberg, 2008). Furthermore, per the Intergovernmental Panel on Climate Change, climate change has directly caused several North American lakes' "stratified periods" to lengthen by 2–3 weeks and move up in the calendar by 20 days as the thermal properties of water shift earlier in the season (IPCC, n.d.). Since 1960, hypoxic areas have increased 30-fold (Diaz and Rosenberg, 2008). These conditions are ideal for diatomic harmful algal blooms that are less affected by hydrological turbulence and turnover than dinoflagellate harmful algal blooms. As these conditions persist, the Chesapeake Bay, as an example of an economically critical and densely populated marine watershed, experienced an increase in frequency of blooms for several harmful algal strains in recent years as a direct result of nitrogen inputs from





agriculture and urban land use combining with climatically changing conditions (Diaz and Rosenberg, 2008).

- From 1991 to 2008, number of *Prorocentrum minimum* bloom events per year doubled
- Annual occurrences of *Kalrodinium veneticum* blooms grew six-fold in a five-year period, indicating an extension of the growing season
- The number of yearly cyanobacterial blooms increased from 13 in the 1990s to 23 in the 2000s (Li, 2015)

More unpredictable weather events from a changing climate have subjected the Chesapeake Bay to more frequent, small blooms that occur outside of the region's typical algal bloom cycle (Diaz and Rosenberg, 2008). Changes in tidal patterns and winds are largely responsible for these alterations (Diaz and Rosenberg, 2008). While local areas may prepare themselves for predictable, naturally occurring blooms, like those that often occur at the end of spring and summer, increasing unpredictability of climate and resultant blooms leave local infrastructure vulnerable in the long-term.

Climate change may affect inter-annual oscillations as well. The El Niño Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO) and the Pacific Decadal Oscillation (PDO), may increase harmful algal blooms and facilitate movement along the oscillatory pathways (Alvarez-Salgado et al., 2003). The harmful dinoflagellate *Gymnodinium catenatum* was higher than average in the northern Iberian Peninsula during the mid-1980s as the NAO index shifted, causing a transition from downwelling conditions to upwelling conditions (Alvarez-Salgado et al., 2003). Humans can directly cause the transport of harmful algal blooms, as well, such as the red-tide causing dinoflagellates *Pyrodinium sp.* and *Alexandrium sp.* that were transported to Australian waters from Southeast Asia via ballast water (Alvarez-Salgado et al. 2003; "Ballast Water").

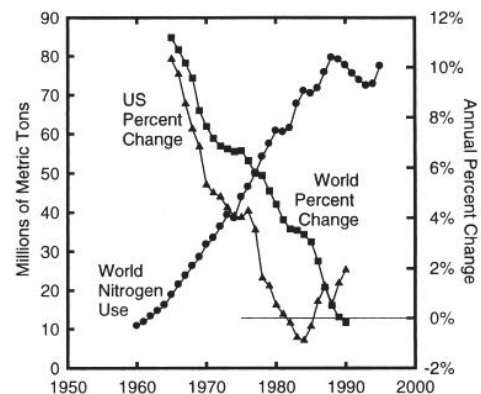
## B. INCREASED SEVERITY

Algal bloom severity has increased in recent years. Hypoxic dead zones that result from these increases have been traced back to greater anthropogenic influences and human development. Examples of this are areas around the coastlines of the United States and Europe where human development economically prizes coastal property (Diaz and Rosenberg, 2008). In addition to affecting the frequency of blooms, climatic changes on a global scale also impact the severity of harmful algal blooms, exacerbating the already worsening blooms that are resulting from heightened anthropogenic, nutrient-rich inputs into water bodies. For example, when the frequency of blooms increases, hypoxic zones become so frequent that recovery of oxygen levels is impossible in between typical bloom seasons. The inability to re-oxygenate waters leads to chronic hypoxia and the accumulation of nutrients in the sediment at the bottom of the water body. These conditions fuel perpetual anoxia, or a complete lack of oxygen in the water body (Diaz and Rosenberg, 2008).



One example of the increased severity in blooms over time is in the economically important area of Lake Erie. Lake Erie accounts for more than \$50 billion per year in water-related industries, such as fishing, recreation, and tourism (Watson et al. 2016; Michalak et al. 2013). Revenue from these activities is imperiled by algal blooms, which can make beaches and waterways unappealing or unhealthy, and poison fish and shellfish. In 2011, Lake Erie experience its most severe bloom in history, covering an area greater than 230 square miles, which was 2.5 times more severe than any previous bloom. Harmful algal blooms in this region have been increasing steadily since the 1990s due in large part to coastal anthropogenic nutrient inputs, and to a lesser extent a combination of climatic and land use changes. In the 2011 example, the region experienced particularly warm and stagnant conditions, leading to increased water stratification that exacerbated the bloom. While climatic conditions increased the scale of the bloom, its severity was exacerbated by the fact that the main forms of propagating algae, *Microcystis* and *Anabaena*, were both toxic.

Events like this do not represent unfounded peaks. The 2011 Lake Erie bloom reflected constantly increasing hypoxic conditions for two decades, and climate models predict that the turbulent, large storms, which contributed to the 2011 bloom (directly prior to the bloom, there was a massive resuspension of nutrients in the water column), will continue to increase in frequency, in some cases, rising in likelihood by up to 50% (Michalak et al. 2013).

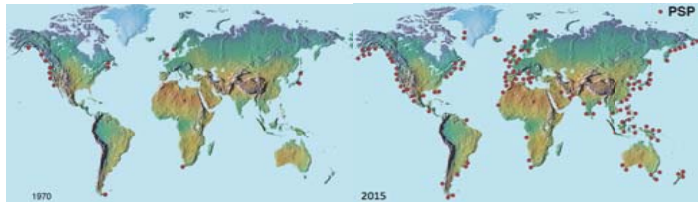


Nitrogen Fertilizer Use (Tg) over time, per the U.S. National Institutes of Health (Frink et. al., 1999).



## C. GREATER DISTRIBUTION

Scientists regularly find at least one form of harmful algae in every single U.S. state and territory, including landlocked and low-density states; key coastal states, like California and Florida, experience tidal and seasonal blooms from a wide range of different freshwater and saltwater strains (WHOI, 2016a).



Distribution of global paralytic shellfish poisoning (red points), 1970 and 2015 (WHOI, 2017).

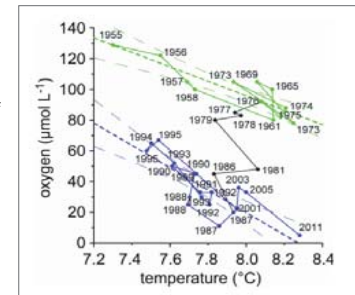
Changes in temperature as a result of climate change favor certain algal strains, increasing the possibility for harmful algal blooms of that type of algae (U.S. EPA Office of Water, 2013). Increases in temperature also result in greater evaporation and salinity, increasing the reach of saltwater harmful algal blooms (U.S. EPA Office of Water, 2013). The increase in reach is not homogenous, and it is important to note that some algal species also thrive in cold water, such as the dinoflagellate *Alexandrium tamarense*. If climate in a particular region gets colder, the likelihood of some algal bloom types will increase (Anderson et. al., 2012). Dangerous potential for harmful algal blooms to move from freshwater to saltwater or vice versa also brings any of their dangerous effects to different locations where they were not previously known or felt (H.R. 4417). As harmful algal blooms and hypoxia continue to spread throughout coastal areas across the United States, these issues become more pressing for many politicians. These issues, however, are still inequitable as some regions experience more intense, frequent, and widespread harmful algal blooms than others due to a variety of factors:

- Conversion of land from vegetation to other uses can cause complicated downstream impacts, not only when considering which crops to grow on farmland, but when considering more broad uses for land bordering water bodies.
- Permeable surfaces, such as soil, hold nutrients and prevent direct runoff into water bodies more so than impervious surfaces, such as asphalt (Frazer, 2005).
- Vegetation sequesters nutrients from being picked up by water on land, which prevents nutrient loading into downstream water bodies (Zuazo and Pleguezuelo, 2008).
- Both of these considerations are important when considering remediation techniques for areas heavily impacted by blooms, such as Lake Erie.



## D. POSITIVE AND NEGATIVE FEEDBACKS

Both harmful algal blooms and hypoxia are prone to natural feedbacks, or responses, that either counteract the original events ("negative feedbacks") or reinforce them ("positive feedbacks"). When seeking to project the future frequency and severity of harmful algal blooms and hypoxia, it is critical that scientists and policymakers examine the likelihood of these feedback mechanisms to accurately predict impacts and set thresholds for mitigation.



Basin-averaged oxygen concentration vs. water temperature in the Black Sea, 1955–2011 (Friedrich et. al. 2014).

### i. Climatological Feedbacks

Modeling climate temperature feedbacks on algal blooms is challenging at a global scale, as water bodies may react differently to changes in temperature.

Additionally, if a lake is stratified, warming may increase the stratification, decreasing the amount of nutrients in a particular location (Adrian et. al., 2009).

In a lake that has different characteristics, warming may also result in nutrients being recycled or moving throughout the water in a different way (Adrian et. al., 2009).

The link between global temperatures and hypoxia is much clearer. Current ocean models predict a 1-7% global decrease in oxygen concentrations over the next century, as sea surface temperatures warm (Friedrich et. al., 2014). The decrease in oxygen concentrations will increase the prevalence and possibility for more widespread hypoxia. Additionally, the U.S. Environmental Protection Agency notes that global sea levels could rise up to one meter by the year 2100, expanding the spatial extent of shallow waters near coasts, where marine harmful algal blooms and hypoxia are often found in combination with each other (U.S. EPA Office of Water, 2013).

In contrast, climate change will reduce water levels in inland bodies where nitrogenous and phosphoric runoff accumulates. These accumulations will be accelerated both by directly accelerating negative evaporative fluxes and by reducing inflows from headwaters (Vincent, 2009; U.S. EPA, 2017a). In hotter and drier conditions, nearby human populations will be forced to draw even more from nearby reservoirs for drinking water and irrigation, driving a key form of **anthropogenic environmental feedbacks** in a changing climate (U.S. EPA, 2017a; IPCC, n.d.). Assuming nutrient inputs stay the same, shallower waterways will still see overall nutrient concentrations increase, amplifying algal

**DEFINITION: Anthropogenic environmental feedbacks are human responses to a non-human phenomenon, such as drought, that then impacts the natural environment.**



bloom likelihood and density. However, temperature increases are also coupled in many climate models with more extreme weather. Intense storms and flooding events flush crop fields and urban land of nutrients meaning that climate change not only reduces water content but also increases nutrient inputs, doubly impacting concentrations – in fact, a 1°C rise in temperature last century correlated with a 4% increase in global total runoff, though the exact mechanisms of causation are debated (IPCC, n.d.).

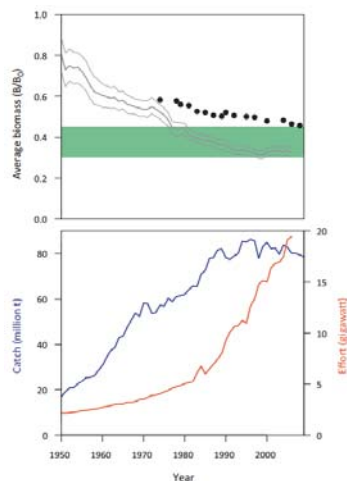
Land use changes also impact the magnitude of climate change, along with direct inputs of nutrients into water bodies, as described above. Covering land bodies with vegetation may sequester carbon from the atmosphere, since photosynthetic plants take carbon dioxide out of the atmosphere, reducing the amount of the potent greenhouse gas available to promote global warming. Growing vegetation around water bodies does not only filter nutrients from surrounding soils, but acts to reduce the impacts of climate change, preventing the positive feedback loop of warming temperatures and bloom propagation (Searchinger et al. 2008).

One further feedback involves temperature rise and moisture levels. Increasing temperatures in particular regions, especially dry regions, can reduce water levels by increasing evaporation rates. Drought can reduce the inflow of water into bodies, both fresh and marine, which can reduce vertical mixing of the water column and increase the stratification which already has increased from temperature rise. This can lead to blooms exacerbating. Additionally, outflows can also decrease from as bodies dry up, which can prevent tidal mixing and the diffusion of blooms, concentrating them further (Paerl and Huisman 2008). For salt water bodies, this can increase the salinity of the body, which can be favored by certain species of cyanobacteria for growth (Paerl and Huisman 2008).

## ii. Ecological Feedbacks

Hypoxia and algal toxins may also directly disrupt the aquatic food chain. When harmful algal blooms lead to hypoxic conditions, it is possible to see thousands to millions of fish dying on the shore as a result of a singular fish kill (Parsons et. al., 2006). Fish kills, emigration away from hypoxic zones, or death of marine species in the hypoxic zone devastate ecosystems by removing keystone species, disrupting the food chain, and/or introducing more competition in healthier, nearby ecosystems (Hale et. al., 2016; Turner and Graneli, 2006). Furthermore, as a positive feedback on harmful algal blooms exists, as more algae persist in water bodies with fewer larger aquatic predators to consume them.

Anthropogenic overfishing also removes important predator fish species from the aquatic ecosystem. The



Top: Average biomass of global fish stocks over their original, non-fishing values ( $B_0$ ).  
Bottom: Fishing catch and effort over time (Worm and Branch, 2012).



removal has effects that are felt throughout the entire food chain (Turner and Graneli, 2006). Since 1950, global fish catches have quadrupled and the average biomass in fish stocks is now roughly 40% of non-fishing levels, as seen in the figure on the previous page (Worm and Branch, 2012). When fishermen prioritize commercially valuable species at **upper trophic levels**, the smaller fish populations blossom and over-consume zooplankton that keep phytoplanktonic algae in check (Turner and Graneli, 2006). The resulting propagation of algal blooms further inhibits fish populations, create trophic disequilibrium and generating a positive feedback for harmful algae.

**DEFINITION: A trophic level is a unit of hierarchy in a food chain. Organisms residing on upper trophic levels are larger predators that consume the organisms that exist below them.**

## VI. SCIENTIFIC TOOLS TO MEASURE AND ADDRESS HARMFUL ALGAL BLOOMS AND HYPOXIA



The section below will analyze the scientific methodology behind four key components to mitigating harmful algal blooms and hypoxia:

- Monitoring
- Prediction and Modeling
- Prevention
- Remediation

Each method will include an examination of benefits and costs to alternative solutions and varying implementation tactics by strain or location, to detail the ways in which H.R.4417 does or does not support the most effective solution strategies for the myriad of harms introduced by harmful algal blooms. Finally, this section will consider the appropriate cases for use of each method, independently and in concert, and how scientists and policymakers can measure success.

### A. MONITORING HARMFUL ALGAL BLOOMS AND RELATED PHENOMENA

Harmful Algal Blooms engender many negative consequences that require scientific remediation. To properly address these issues, harmful algal blooms and many associated issues require monitoring. Monitoring helps the scientific community learn more about the patterns, trends, and thresholds associated with harmful algal blooms. The most impactful solutions start at the source of a problem, in this case with nutrient pollution. It is important to begin by monitoring harmful algal bloom causes, such as nutrient pollution caused by point and nonpoint sources.

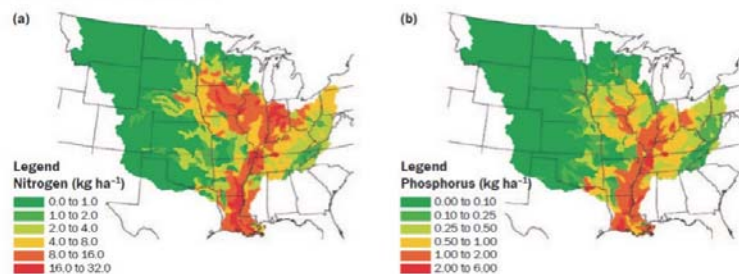


## i. Monitoring Agricultural Nutrients

Farm fertilization accounts for 41% of nitrogen runoff into the Gulf of Mexico, and fertilizers are a key contributor to eutrophication across the United States (“The Challenge of Tracking,” n.d.). The U.S. Department of Agriculture (USDA), U.S. Environmental Protection Agency, and U.S. Geological Survey (USGS) determine source, transport, and destination of nutrients by monitoring “edge-of-field areas,” streams, and rivers (“National Science,” 2016). While the relationship between nutrient inputs and harmful algal blooms varies by strain and context, scientists can use case studies to build generalized trends. The Gulf of Mexico, for instance, receives more than 1.5 million tons of annual nitrogen inflow and contains an 8,776 mi<sup>2</sup> dead zone (Goolsby and Battaglin, 1997). The Mississippi River/Gulf of Mexico Watershed Nutrient Task Force aims to reduce the dead zone to 5,000 mi<sup>2</sup> by 2035 (Meter et al., 2018) by eliminating 59% of May nitrogen inputs.

**DEFINITION:** Edge-of-field areas are monitoring sites places at the edge of crop fields to measure the quality and quantity of agricultural runoff (USGS). These areas are useful indicators for the nutrient pollution that feeds harmful algal blooms.

(a) Nitrogen and (b) phosphorus yields from the landscape (all land uses) delivered to the Gulf of Mexico as predicted by the Conservation Effects Assessment Project modeling framework.



The USDA’s Conservation Effects Assessment Project (CEAP) focuses on measuring and spatially projecting nutrient inputs (Mississippi River/Gulf of Mexico Nutrient Task Force, 2017).

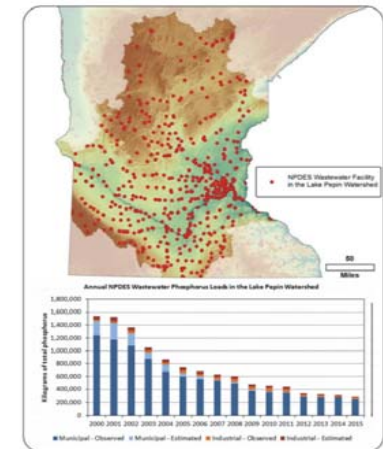
As the major source of nutrients into many major water bodies, nutrient monitoring on land is critical to understanding downstream impacts (“National Science,” 2016). Monitoring seasonal variation in blooms can permit nutrient users, like farmers, to tailor their fertilizer usage to the corresponding environmental conditions (“National Science,” 2016). The tailoring efforts can include not only the amount of nutrients to add to a land area, but also to the use of water, the tilling of the soil, and other important factors (“National Science,” 2016).



## ii. Monitoring Non-Agricultural Nutrient Sources

A large percentage of nutrient loading into U.S. waterways comes from agricultural runoff, but other sources contribute to nutrient loading on a watershed-by-watershed basis. These additional sources include atmospheric deposition, aquaculture discharges, and wastewater seepage, all three of which are forms of “wet deposition.” Wet deposition of nitrogen and phosphorus transports fossil fuel emissions from the atmosphere into the water and onto land, adding more nutrients for algae (Hill, 2005; Anderson and Downing, 2006). Scientists estimate that 35-40 kilograms of nitrogen are deposited on each hectare of land annually as “dry” deposition (materials that fall to land or water bodies as particulates, and not accompanied by water), about three to four times that coming from wet deposition (Goulding, 1990). According to the U.S. National Institutes of Health, the 95% safety level for eutrophication is roughly 3-10 kilograms of nitrogen per hectare (Frink et. al., 1999), so dry atmospheric deposition of nitrogen alone presents significant risk of eutrophication. Nutrient loading from agricultural runoff nearly guarantees it.

There are also significant point sources of nutrient pollution that present opportunities for policy intervention. While the contribution from aquaculture (the process of farming fish as commodities) to nutrient loading supplies 0.9% of human input to the nitrogen cycle, this contribution can be higher in watersheds with more aquaculture sites, creating a geographically stratified problem (Verdegem, 2013). Additionally, nutrients from wastewater can feed harmful algal blooms if there is accidental or intentional **sewage dumping** (Goolsby and Battaglin 1997). In 2015, the Indiana Department of Environmental Management set a statewide sanitary wastewater treatment standard of 1.0 mg/L total phosphorus for dischargers of more than one million gallons of water per day



Reduction in phosphorus pollution to a Lake Pepin Watershed in Minnesota, as a response to regulatory mechanisms (Mississippi River/Gulf of Mexico Nutrient Task Force, 2017).

(Mississippi River/Gulf of Mexico Nutrient Task Force, 2017). Similar legislation in Minnesota to meet their goal of 45% reduction of total nitrogen discharge by 2040 has yielded a significant reduction in phosphorus pollution in local

### STAKEHOLDER SPOTLIGHT:

**Municipal wastewater treatment treats nutrient pollution near urban areas. The treatment requires more intensive investment in wastewater treatment that may mean higher expenses for cities, particularly for smaller towns that might need to absorb the cost of hiring external consultants – these costs are borne by taxpayers.**



watersheds, as seen in the figure above (Mississippi River/Gulf of Mexico Nutrient Task Force, 2017).

Regulatory thresholds like these can have a significant impact on point sources of nutrient pollution that lead to harmful algal blooms.

### iii. Monitoring Aquatic Nutrient Concentrations

Nutrient concentrations in water are indicative of harmful algal bloom severity. NOAA measures bioavailable nutrients in Lake Erie to project the severity of the annual blue-green algae bloom (Lake Erie Harmful Algal Bloom Seasonal Forecast, 2018). The U.S. Federal Inter-Agency Task Force determines nutrient loads using nutrient concentrations and freshwater inflow, and monitors concentrations monthly to see changes over time ("National Science," 2016). Currently, there are four fixed buoy sensors on Lake Erie and forty optic sensors in the Mississippi River Basin to calculate nutrient concentrations (U.S. Department of Commerce, n.d.; "National Science," 2016). The SPARROW (USGS' SPATially Referenced Regressions on Watershed) model, the APEX (USDA's Agricultural Policy Environmental Extender) tool, and the SWAT (Soil and Water Assessment Tool) can all be used to model coastal nutrient loading ("National Science," 2016). By improving monitoring precision and sampling frequency, scientists determine nutrient thresholds that trigger harmful algal blooms for individual algae species. As harmful algal blooms develop, it is imperative to monitor toxin levels (both in water and in seafood), hypoxia levels, algae concentrations, and algae species, in order to ensure both public health and ecosystem risks.

### iv. Monitoring Toxin Accumulation

Toxins produced by certain species of algae, but not all, are known to cause illness for humans and animals (U.S. EPA, 2018a). Humans, wildlife, and pets can come into contact with a variety of toxins through skin contact like swimming, contaminated water consumption and contaminated food consumption (NOAA, 2013b). The Monterey Bay Aquarium Research Institute designed the Environmental Sample Processor (ESP), a robot that travels through waterways, measuring properties such as microorganism density and toxin concentrations (Anderson et al., 2017). Sensors on Environmental Sample Processors (ESPs) can detect toxins and 28 species of algae as blooms form. This tool was useful for tracking the 2015 toxic *Pseudonitzschia* bloom along the U.S. west coast and supplying early risk warnings for coastal communities ("National Science," 2016). Additionally, the National Shellfish Sanitation Program regularly checks for toxin presence in shellfish to minimize this contact ("National Science," 2016) and buoy sensors can track toxin levels in U.S. waterways (US Department of Commerce, n.d.).

### v. Monitoring Harmful Algal Blooms and Hypoxia

Tracking concentrations of toxic algae is useful for anticipating health impacts, but policymakers also need data on algal density to understand when and where harmful algal blooms can lead to hypoxia. Dissolved oxygen levels below 2-3 parts per million hold the potential to kill marine organisms and destroy underwater environments (U.S. EPA, 2018b). Monitoring dissolved oxygen levels helps inform scientific models and lead management decisions ("National Science," 2016). State and Federal agencies



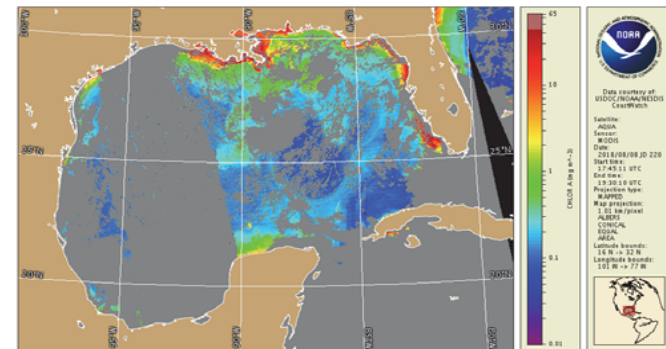
work together to monitor hypoxic levels using water buoys or research vessels like NOAA's Oregon II in the Gulf of Mexico ("National Science," 2016).

Even prior to formation of hypoxia, scientists have several techniques to measure algae concentrations using **chlorophyll**, which is found in plants and cyanobacteria.

**DEFINITION:** Chlorophyll is a green pigment found in all plants and photosynthesizing bacteria that allow the organisms to absorb light for the creation of energy and biomass. The pigment is useful for tracking the presence of algae in aquatic environs.

- The World Health Organization's threshold for safe chlorophyll in water is 10 mg/m<sup>3</sup> and shortwave infrared radiation allows researchers to monitor when aquatic concentrations exceed that threshold (NOAA, 2018a; Anderson, 2017).
- USGS uses *in vivo* fluorometry (IVF) to spot cyanobacteria that can produce toxins and harmful algal blooms (Kiesling, 2008). An IVF sensor is submerged in water and uses light to detect cyanobacteria's chlorophyll pigments, and these chlorophyll concentrations help scientists identify algal distribution patterns (Anderson, Boerlage and Dixon, 2017).
- Woods Hole's Imaging FlowCytobot, an aquatic robot similar to the Environmental Sample Processor (ESP) is used to identify algal species and concentrations (Seltenrich, 2014).

Since each variety of algae have different parameters that make them harmful and can require a unique mitigation technique, scientists can use species-specific data to identify blooms that have reached harmful concentrations.



NOAA uses short-wave infrared radiation (SWIR) to monitor chlorophyll concentrations in the Gulf of Mexico. Anything above 10ug/m<sup>3</sup> exceeds World Health Organization recommended thresholds (NOAA, 2018c)





Previous monitoring has not been successful at predicting these complex blooms, so it has been difficult to determine bloom frequency over time. As the blooms differ by species and location, there is no single way to combat all harmful algal blooms. Therefore, improving monitor, research and forecasting is imperative. For example, Inter-Agency Task Force has taken steps to improve nutrient concentration monitoring after realizing their **sampling schedule** was incapable of taking weather events like high rainfall into account or identifying pollution from the air or groundwater. The Task Force invested in sensors that can continuously measure these small changes in nutrient levels in U.S. waterways like the Mississippi River Basin and Lake Erie (“National Science,” 2016). Additionally, the Amendments Act of 2017 will add the Army Corps of Engineers, a group already involved in harmful algal bloom monitoring around the country in states, such as Oregon (Clyde et. al., 2016).

**DEFINITION: Sampling schedules are the timing at which sample collection happens. The timing can have a big impact on how scientists look at data to make decisions. When viewing a nutrient pollution, large, intermittent storms often create a lot of runoff. A sampling schedule that does not coincide with those storms may skew results.**

#### vi. Monitoring Environmental and Public Health

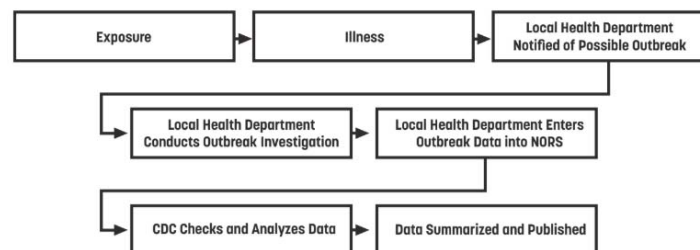
Since the establishment of the Harmful Algal Blooms Inter-Agency Task Force with the passage of the 1998 Act, key member agencies have made significant strides to collaborate with one another and with local stakeholders to track the health impacts of harmful algal blooms. This effort is a critical one, as it allows policymakers to accurately assess the costs of harmful algal blooms on their constituents and protect them from danger. These efforts will be made accessible to the public and scientists who were not participants in the research through a public website providing information about activities completed by programs under the Harmful Algal Bloom and Hypoxia Research and Control Amendments Act of 2017.

Two examples of public health tracking services include the Oregon Health Authority, which identifies human illnesses tied to harmful algal bloom toxins, and the Cyanobacterial Assessment Network (CyAN), a collaborative network of four Federal agencies using satellites to quantify public exposure risk to harmful algal blooms (U.S. EPA, 2014; Oregon Health Authority, 2018). Additionally, the U.S. Centers for Disease Control and Prevention (CDC), which was added to the Inter-Agency Task Force in a 2014 amendment, tracks both human illness and fish kills with their One Health Harmful Algal Bloom System, providing a health survey that is unique for its incorporation of ecological damage (One Health Harmful Algal Bloom System, 2017).

In cases of harmful algal bloom exposure, local agencies undergo the following process in collaboration with the CDC and its National Outbreak Reporting System (NORS):



#### Steps health officials take when an individual has been exposed to a HAB toxin:



*Notification and analysis pathway for illness reporting (Getchis and Shumway, 2018).*

## B. PREDICTION AND MODELING

As monitoring techniques improve and create a body of knowledge about harmful algal bloom development conditions, scientists can develop better predicting and modeling tools. These tools are critical to our understanding of harmful algal bloom concentrations and dispersal patterns. Algae are microscopic and, as aquatic organisms, can travel widely and exist in both concentrated and diffuse aggregates. One way to circumvent these challenges to monitoring algae, is to employ space borne sensors (“National Science,” 2016). These satellites can analyze **reflected solar radiation** from space off the earth’s surface, examining differences in light and heat profiles that are emitted to space (Reif, 2011). This can be completed on the regional and global scale, though not more locally, to pinpoint phytoplanktonic blooms (“National Science,” 2016). Not only can this permit researchers to analyze current and past blooms captured using this sensing, but it can provide a basis for predictions, to understand the future of algal blooms and their impacts.

**DEFINITION: Reflected solar radiation: When light from the sun, or solar radiation, hits the Earth, much of it is reflected back to outer space. Satellites pointed towards Earth can use reflected radiation to see colors and temperature patterns that indicate where algae occur.**

Models created from a combination of satellite images, research and wind predictions have helped NOAA create a harmful algal bloom forecasting system for the annual red tide bloom in the Gulf of Mexico (“National Science,” 2016). Satellite images can detect blooms from ocean color and tracked their transport based on particle movement. With forecasting tools in place, scientists can effectively direct prevention efforts to reduce harmful algal bloom destruction.





## C. UPSTREAM PREVENTION

### i. Nutrient Reduction

Nitrogen fertilizers not only contribute via runoff significantly to downstream algal blooms and hypoxia, but are also a major source of atmospheric nitrous oxide,  $N_2O$ , a powerful greenhouse gas (Shcherbak, Millar, and Robertson, 2014). Nutrient management on farms can lower nutrient runoff, but implementation has been slow (Stuart et al., 2015). For farmers, economic gains from increased crop yields far outstrip fertilizer costs, creating a short-term incentive to over-fertilize beyond what crops can absorb. In addition, some surveys indicate that farmers receive most of their information on nutrient management from fertilizer companies, who may necessarily promote the use of fertilizers, regardless of the consequences and externalities. The surveys highlight a great need for better outreach from university agriculture sciences departments to working farmers (Stuart et al., 2015). These surveys and other studies point to the need for working with farmers and other stakeholders to share information and to develop policies that support farmers as they shift to responsible nutrient management techniques (Stuart et al., 2015). The public accessible website that is provisioned by The Amendments Act of 2017 in part can help disseminate this necessary information.

One management approach calls for farmers to use the “4Rs:” applying fertilizer at the right rate, right time, right place, and right formulation to maximize the fertilizer uptake by the plants and to minimize loss to the atmosphere or runoff (IFA Task Force on Fertilizer Best Management Practices, 2009). The U.S. Department of Agriculture, which encourages no-till farming, cover cropping, and other nitrogen-conserving practices, found that about two-thirds of the total cropland in the United States was not farmed using these optimized approaches, indicating a tremendous opportunity for improvement (Ribaud and Gottlieb, 2011). It is critical to monitor and measure nutrients both on land and in water bodies, in order to understand the spatiotemporal distribution of bloom inputs. Soil sampling and buoy-based water monitoring may help achieve this (Bremner and Keeney, 1966; DiStefano and Gholz, 1986; U.S. Department of Commerce, n.d.).

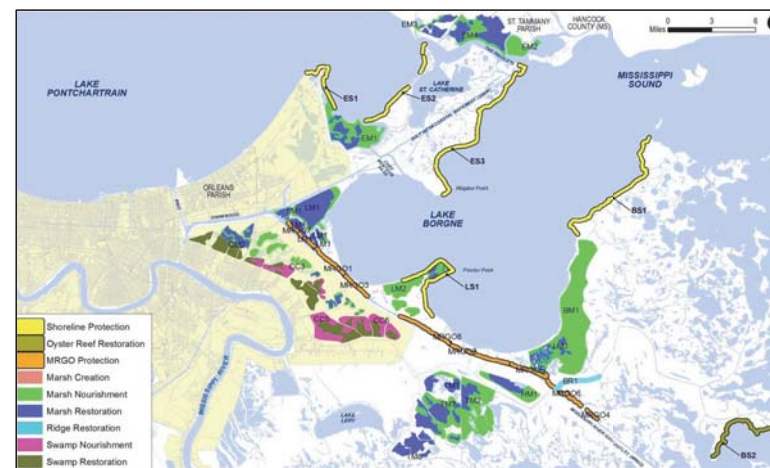
### ii. Wetlands Restoration

Vegetated wetlands along water bodies slow runoff and absorb nutrients in the water, and can dramatically reduce nutrient loading in downstream water bodies (Levy, 2017). Expanding farmland and residential developments have encroached on wetlands, destroying over 800,000 acres of wetlands in the United States since the 1950s, but efforts are underway to restore these areas, reducing downstream eutrophication and harmful algal blooms, as well as providing other important ecosystem

**STAKEHOLDER SPOTLIGHT: Coastal Property - River, lake, and ocean-side properties are valuable for aesthetics, access to recreation, and proximity to key access points. Wetlands across the US have been removed or filled to make way for upscale homes, farms, ports, and other facilities dependent on or beneficial from the waterway. The recreation lobby, in particular, is wealthy and powerful. Engaging and educating this lobby is critical for policymakers to make headway on wetland restoration.**



services (U.S. Army Corps of Engineers, 2012; Dahl, 2009). However, significantly reducing nitrogen runoff could require wetland creation or restoration at vast scales; one estimate indicates that 22,000  $km^2$ , or about 1%, of the Mississippi Basin, would need to be restored in order to reduce nitrogen loading in the Gulf of Mexico by 40% (Levy, 2017; Mitsch, Day, Zhang, and Lane, 2005). Such a restoration effort would be costly upfront and could generate resistance from farmers asked to give up arable land for wetlands restoration, and may impact farmers that border water bodies more than those inland; however, this could reduce pressure on farmers to lower their fertilizer use, while meeting the same end (Mitsch et al., 2005). Strategic restoration could focus on the most cost-effective wetland restorations: those predicted to capture the most nitrogen runoff for the least money (Ribaud and Gottlieb, 2011). The addition of the U.S. Army Corps of Engineers, the agency with jurisdiction over the issuance of many permits governing such restoration work, and responsible for the construction of many such projects, to the Task Force under the Harmful Algal Bloom and Hypoxia Research and Control Amendments Act of 2017 will ensure that the U.S. Army Corps of Engineers addresses these issues when it issues permits or engages in construction projects affecting inland and marine waterways.



*The U.S. Army Corps of Engineers has been undergoing restoration of 57,000 acres of Gulf coast habitat and wetlands through the Mississippi River Gulf Outlet (MRGO) Restoration Plan, finalized in 2012 (U.S. Army Corps of Engineers, 2012).*



## C. REMEDIATION

### i. Clay Flocculation

**Clay flocculation** is an approach whereby specialized clays are sprayed into water to aggregate harmful algal cells in flocs, or clumps, for easy removal. In 1996, workers in South Korea extracted 90 to 99% of the dinoflagellate *C. polykrikoides*, with no reported fish mortality, and saved \$99 million in fishery losses in the first year, by using clay flocculation (Sengco and Anderson, 2004). Modified clays have been effectively utilized near China's Fangchenggang nuclear power plant, as well, which has been damaged by large algal colonies (Yu, Song, Cao, and Liu, 2017). Clay flocculation has not seen field testing within the United States, only controlled lab testing, leading to a limited understanding of real world practical effects within the United States, (U.S. EPA, 2002). Flocculation may have unintended consequences: it temporarily increases turbidity of the water and increases dissolved phosphorus (which could potentially exacerbate some blooms), and the clay can be toxic to some beneficial aquatic organisms. These potential harms must be weighed against the known damage from harmful algal blooms; thus, there is still significant scientific controversy about these downstream treatment methods (Sengco and Anderson, 2004).

**DEFINITION: Flocculation is the chemical process through which small particles clump together into groups, or 'flocs.' Clay can be used to instigate this clumping, drawing together nearby algal cells that stick to the clay for removal.**

### ii. Alum Treatment

The application of aluminum sulfate, or alum, to a water body functions similarly to clay flocculation, but targets the nutrient inputs rather than the algal outgrowths; as a result, alum is used to mitigate phosphorus pollution in lakes (U.S. EPA, 2015). Alum precipitates as a floc, aggregating phosphorus into a floc, settling into the lake sediment, and forming a barrier that prevents re-release of nutrients into the water. Studies have proven that, in a relatively cost-effective manner, alum treatment can reduce average lake phosphorus concentrations from 277 µg to 71 µg per liter of water over four years, and has directly resulted in the disappearance of some toxic cyanobacterial blooms (Brattebo et. al, 2017)

### iii. Biological Treatment

Introduction of aquatic predators is another possible method for treating existing harmful algal blooms (Turner and Granéli, 2006). Scientists struggle to predict predator-prey dynamics in harmful algal blooms, as many predators consume prey selectively and some algae strains provide chemical defenses to predation (Harvey and Menden-Deuer, 2012). Promoting beneficial conditions for zooplankton, adding zooplankton, and/or removing predators of zooplankton are all methods to increase predation of harmful algae; however, toxicity of harmful algae still poses a problem for predators (U.S. EPA, n.d.).



One plan to control algae in Twin Lake, Minnesota consists of three steps -- removing plankton consuming fish (planktivores), adding pike and bass (piscivores), and monitoring migration patterns -- at a total cost of \$13,970 per acre of lake (Chandler, 2013). Similarly, rotifers, copepods, and copepod nauplii all increased consumption of *K. rotundatum* from 13% to 67% during a peak bloom in the Patuxent River estuary of Chesapeake Bay (Sellner, 1991). However, experimentally introducing predators to ecosystems generates controversy among scientists and raises concern from the public (D. Anderson, personal communication, July 11, 2018). Researchers must be wary of the adaptive behavior of varying algae stains in response to predators, as introduction has been shown to cause algae to flee and coalesce even more quickly than they would have otherwise, creating larger blooms (Harvey et. al, 2012).

### iv. Chemical Inhibitors

When utilized creatively, there are natural chemical inhibitors to algal propagation that can provide extremely cost-effective solutions either independent of or in concert with other remediation tactics. For instance, barley straw placed along the edges of lakes and watersheds and degrade, releasing a chemical that inhibits algal growth (Chandler, 2013).

### v. Aeration and Oxygenation

Manipulating air within freshwater bodies is another form of mitigation for harmful algal blooms; in particular, oxygenating downstream waters may reduce cyanobacteria and their related toxins (Dent et. al., 2014, Zhou et. al., 2016). **Aeration** is the pumping of air using a diffuser near the bottom of a freshwater body forming blooms that rise and create vertical circulation, causing cyanobacteria to migrate vertically, reducing propagation and increasing oxygen circulation (U.S. EPA, n.d.). Aeration with column flotation of pre-reagentized gas bubbles is capable of removing algae and phosphorus. Direct Air Filtration has the potential to remove algae, 5–7 µm Giardia oocysts, 4–5 µm cryptosporidium oocysts, humic water treatment, algae from heavily algae laden waters, (Rubio, 2002). Oxygenation adds oxygen gas into the hypoxic zones, caused by harmful algal blooms, to provide adequate oxygen levels for other organisms to survive and circulate the water column (U.S. EPA, n.d.). Costs, as well as the lack of real world testing, makes oxygenation a method that is continuous and

**DEFINITION: Aeration is the process by which air is inserted or dissolved in a liquid substance, like water.**

| Study                                         | State | Waterbody                       | Description                                                                   | Capital Costs (2012\$) <sup>1</sup> | Annual O&M Costs (2012\$/yr) <sup>1</sup> |
|-----------------------------------------------|-------|---------------------------------|-------------------------------------------------------------------------------|-------------------------------------|-------------------------------------------|
| <b>Aeration System</b>                        |       |                                 |                                                                               |                                     |                                           |
| Berkshire Regional Planning Commission (2004) | MA    | Onota Lake                      | Deep-hole system.                                                             | \$355,621 - \$411,772               | \$49,912                                  |
| ENSR Corporation (2008)                       | MA    | Lovers Lake and Stillwater Pond | Hypolimnetic aeration only. Based on vendor quote.                            | \$94,907                            | \$5,260                                   |
| ENSR Corporation (2008)                       | MA    | Lovers Lake & Stillwater Pond   | Artificial circulation                                                        | \$117,195                           | \$7,990                                   |
| Chandler (2013)                               | MN    | Twin Lake                       | Solar powered system.                                                         | \$139,157                           | \$4,945                                   |
| Chandler (2013)                               | MN    | Twin Lake                       | Bubbler system.                                                               | \$232,424                           | \$34,616                                  |
| City of Lake Stevens (2013)                   | WA    | Lake Stevens                    | Actual costs over 6 years, includes power consumption, staffing, and repairs. | Not reported                        | \$35,000 - \$110,000                      |

Recent Examples of Aeration Cost in U.S. Lakes. (EPA, n.d.).



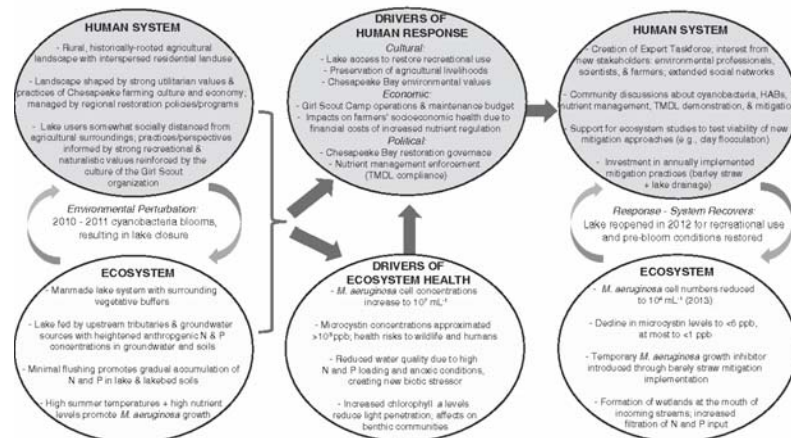
difficult to employ to mitigate harmful algal blooms, posing more of a symptomatic solution than a fundamental one (U.S. EPA, n.d.; Conley, 2009).

## VII. STAKEHOLDER CONSENSUS AND CONTROVERSY



- As described above, harmful algal blooms impact and are impacted by a wide range of stakeholder groups, such as the farmers who use fertilizer, local fishermen who rely on aquatic resources for their livelihoods, and politicians who represent constituents losing public safety and property values.
- Like many politically-charged terms, “harmful algal blooms” carries with it many connotations and contexts, which differentially engage various actors. Below we discuss the consensus among these actors regarding the causes and effects of algal blooms and areas of controversy.

### Case Study: Lake Williston (Chesapeake Bay Watershed)



The above schematic showcases the complex network of key indicators, stakeholders, and responses as observed by natural scientists and anthropologists at the site of a harmful *Microcystis aeruginosa* bloom in part of the Chesapeake Bay watershed (Dolah et al., 2015).



## A. CONSENSUS

Over time, scientists have reached broad consensus on the issue of harmful algal blooms. In 1968, a controlled lake experiment by the International Institute of Sustainable Development determined **causality** between phosphorus inputs and algal growth, and the mechanisms of algal growth and tracking have garnered broad scientific consensus (Bath, 2017). This provides both scientists and policy makers with the certainty needed to address harmful algal blooms on a large scale and proceed confidently. In 2003, the EPA hosted a broad panel of harmful algal bloom experts from many governmental and non-governmental institutions, unanimously agreed on the following definitions and concepts (Heisler, 2008):

**DEFINITION:** Causality between two events means that one is proven to cause the other. In scientific research, it is important to determine causality between two occurrences, like nutrient pollution and algal blooms, to ensure that they are not just a coincidence and that changing one variable will predictably impact the other.

- Harmful algal blooms are increasing in the U.S. and worldwide.
- Anthropogenic nutrient pollution from over-fertilization drives many harmful algal blooms.
- Specific nutrient mixes drive particular harmful algal blooms.
- Managing watershed nutrient inputs, such as sewer discharges, can lead to substantial decreases in harmful algal blooms.
- Continued research is necessary to understand, predict, and mitigate blooms.

There is also a political consensus regarding the efficacy of H.R.4417 and the mechanisms for its implementation. The 2017 Amendments Act has garnered bipartisan support, like the previous amendments in 2004 and 2014 (Senate Committee on Commerce, Science, And Transportation, 2017), as well as the original act, which was passed unanimously in 1998 (105th Congress, 1998).

## B. CONTROVERSY

While political and scientific consensus exists regarding the biological and ecosystem impacts of harmful algal blooms, and the connection between harmful algal blooms and hypoxic dead zones, conflicting interests still hinder appropriate mitigation of harmful algal bloom events. Furthermore, while we understand the impacts of specific inputs into water bodies on harmful algal blooms, not all causes and interacting forces are known or understood, and blooms are extremely complex issues, that are still the subjects of much complicated, scientific research. Therefore, the Harmful Algal Blooms and Hypoxia Amendments Act of 2017 calls for scientific assessments of such events and grants to develop and implement effective methods to intervene and mitigate the frequency, severity, and impacts of such events.



### i. Source Limitation

While we have noted that farm fertilization accounts for a large proportion of nutrient runoff that leads to harmful algal blooms, this is complicated to address and the relationship is not 1:1. Nutrient management on farms can reduce nutrient runoff, but implementation has been slow and other factors, such as climate, can confound this relationship (Stuart, 2015). Farmers may resist these practices due to concerns about increased cost, increased effort, and particularly the fear of reduced crop yields. Insurance against crop losses, coupled with education campaigns and other incentives, like H.R. 4417's proposed website, could encourage wider adoption of these practices (Ribauda and Gottlieb, 2011).

Harmful algal blooms are harmful to both marine wildlife and ecosystems and they can have disastrous impacts on aquaculture industries. Certain farmed fish face the risk of being killed in just hours if they are exposed to toxic algae. For instance, in 1987, Atlantic salmon valued at over \$500,000 died due to phytoplankton blooms (WHO, 2016). Since harmful algal blooms pose a potential economic threat to aquaculture industries, these industries are eager to see mitigation efforts implemented. However, aquaculture nutrients are associated with nutrient overloading that may cause harmful algal blooms, so it is reducing their own nutrients; thus, their own productivity may not be the solution the aquaculture industry favors (Paerl, 1997). Fisheries that deplete high level predators may lead to trophic cascades that deplete grazers and decrease predation on harmful algal blooms (Turner, 2006). Reducing nutrients for fish food and taking away certain species, harmful algal blooms are reducing revenues by at least \$20 million (Anderson, 2000). Evidently, aquaculture has a vested interest in mitigation methods that do not hinder their own activities, so selective support of the industry should be expected.

Among accelerating nitrogen inputs, atmospheric deposition is one of the most rapidly increasing sources of nutrients to the coastal zone. Estimations suggest that 20-40% of nitrogen inputs are ultimately derived from urban, industrial, or agricultural sources (Duce, 1986; Fisher and Oppenheimer, 1991; Paerl, 1997). Atmospheric deposition is a complex issue and is difficult to determine which stakeholders should reduce their atmospheric deposition as this might be associated with efficiency and revenue loss. The National Atmospheric Deposition Program (NADP) has, for instance, expressed concern about the Electric utility deregulation. This policy is beneficial for the industries, but there is concern that deregulation of utilities may increase the use of coal and resultant emissions from large power plants, will negatively change the amount chemical substances deposited in the atmosphere (USGS, 2000). Government regulation is a method to reduce deposition, such as has been utilized in the Chesapeake Bay area, in which the EPA applied the Clean Air Act regulations and Clean Air Interstate Rule to reduce nitrogen loads by 15 million pounds annually (U.S. EPA, 2007). However, in the face of changing national policies and industry lobbying, reduction in atmospheric loading faces many challenges.

### ii. Restoration Efforts

The restoration of **wetlands** is one of the main methods used to reduce nutrients levels and improve the water quality in different water bodies in the United States; the method is currently being used to



**DEFINITION: Wetlands are vegetative land where aquatic and terrestrial systems meet, typically consisting of marshes or swamps. Wetlands are critical, natural barriers for flooding, runoff, and pollution.**

restore the water quality in Lake Erie (U.S. EPA, n.d.). Maintaining and restoring wetlands has also been a significant factor of the watershed protection strategy for the Mississippi River (Sparks, 1992). The scientific knowledge about successful wetland restoration and creation is well documented. However, it is important to point out that the status of scientific knowledge about wetland restoration and creation differs by wetland location, function, and type. (Kusler and Kentula, 1990a).

While wetland restoration could effectively reduce the harmful effects of harmful algal blooms, which would be favored by homeowners and small businesses, not all players are eager for such an approach. Controversies include conflict over which landowners should give up property for wetland restoration; who would pay for such restoration (Federal, State, or local governments, or private organizations); and who would have access to restored wetlands and for what uses.

Additionally, remediation methods like clay flocculation and predator introduction have also been tied negative ecosystem effects, leading some scientists to call for further research prior to large-scale adoption (Beaulieu et. al., 2005). For instance, clay flocculation methods often uses a coagulant that have increased the likelihood of suspended sediment and, as a result, damage to filter-feeding organisms (Beaulieu et. al., 2005). In larger doses, clay flocculation may negatively affect coastal flows and the pH level if applied in large doses (Stace E, 1992). In one biological treatment study, introduction of predators altered phytoplankton movement, and their fleeing patterns led to a three-fold increase in net algal populations as more algae encountered one another (Harvey et. al., 2012). Due to the nature of algal predatory avoidance patterns and the vast complexity of algal species, predator introduction could cause bloom growth rather than reduction. Federal funding through H.R.4417 will support further research into these remediation methods to ameliorate scientific controversy around their efficacy and safety.

### iii. Climate Change

Climate change mechanisms, such as warming temperatures, are known to exacerbate the conditions that favor algal blooms. However, climate change is largely controversial. Better understanding the mechanisms around climate change exacerbation can help to reduce controversy. Such methods include (Hallegraeff, 2010):

- improved global ocean observation systems (GOOS; e.g. argo floats, ocean gliders, coastal moorings and coastal radar, multi-wavelength and variable fluorometers, and optical sensors)
- investment in the infrastructure of the international marine-science community
- improved data communication and administration capabilities in order to provide open searchable access and routine delivery to relevant users
- increased national and international cooperation (e.g. GEOHAB)



## VIII. CONCLUSION AND LOOKING AHEAD



The Harmful Algal Bloom and Hypoxia Research and Control Amendments Act of 2017 comprises a critical extension of Federal funding for research into the worsening impacts of harmful algae in freshwater and coastal ecosystems around the United States. As climate change, nutrient pollution, and development patterns amplify conditions for severe algal blooms around the country, the U.S. government will face increasing public pressure from constituents who not only recognize the broader ecological ramifications of these blooms, but also directly see their aesthetic impacts, feel their economic harm, and face their public health consequences. The Amendments Act of 2017 undertakes efforts to expand the capacity of the Federal government in predicting, preventing, and responding to these events by:

- Adding the Army Corps of Engineers to the Inter-Agency Task Force to aid in mitigation efforts;
- Enabling public knowledge-sharing through a website and regular scientific assessments; and
- Designating events of national significance, which warrant Federal disaster aid.

While each of these mandates can help reduce harmful algal blooms and hypoxia, no aspect of the Act directly addresses known anthropogenic inputs to harmful algal blooms, holds contributing parties accountable, or sets a clear path for remediation. Should the legislation pass, the Inter-Agency Task Force must collaborate with stakeholders detailed in this report to set targets that account for a wide variety and complexity of algal strains, environments, and human contexts. To evaluate success in monitoring, prevention, and remediation, we recommend the Task Force consider the following indicators:

- Decrease in watershed nutrient inputs, particularly from agricultural fertilization
- Restoration of natural buffer mechanisms, such as estuarial wetlands
- Reduction in harmful algal bloom spatial and temporal extent, density, and toxicity
- Reduction in hypoxic zone area
- Amelioration of associated economic losses and public health cases
- Improvement in aquatic biota size, community interactions, and habitat quality

In this report, we have repeatedly focused on the localized costs of harmful algal blooms, but taking a local perspective also provides reasons for optimism. After two decades of Federal funding for scientific research, monitoring and management techniques are more sophisticated than ever, and communities from Washington State to the Gulf of Mexico are experiencing the benefits of early warning systems, genetic tracking, buoy technology, and wetlands restoration (Benson, 2011). With the addition of stakeholder collaboration, Federal aid dispersal, and increased research funding, the Harmful Algal Bloom and Hypoxia Research and Control Amendments Act of 2017 will look build upon these success stories.



## IX. REFERENCES

- 115th Congress (2017). Harmful Algal Bloom Research and Control Amendments Act of 2017, H.R.4417. Retrieved from <https://www.congress.gov/bill/115th-congress/house-bill/4417/>.
- Acres, J., and Gray, J. (1978). Paralytic shellfish poisoning. *Canadian Medical Association Journal*, 119(10), 1195–1197.
- Adrian, R., O'Reilly, C. M., Zagarese, H., Baines, S. B., Hessen, D. O., Keller, W., Winder, M. (2009). Lakes as sentinels of climate change. *Limnol. Oceanography*, 56(6), 2283–2297.
- Alvarez-Salgado, X.A., F.G. Figueiras, F.F. Perez, S., Groom, E. Nogueira, A. Borges, L. Chou, C.G., Castro, G. Moncoiffe, A.F. Rios, A.E.J. Miller, M., Frankignoulle, G. Savidge, and R. Wollast. (2003). The Portugal coastal counter current of NW Spain: New insights on its biogeochemical variability. *Progress in Oceanography* 56:281–321.
- Anderson, D. (2012). HABs in a Changing World: A Perspective on Harmful Algal Blooms, Their Impacts, and Research and Management in a Dynamic Era of Climatic and Environmental Change. *Harmful Algae*, 3(17), 3–17.
- Anderson, D., Gilbert, P., Burkholder, J. (2002). Harmful Algal Blooms and Eutrophication: Nutrient Sources, Composition, and Consequences. *Estuaries*, 25(4), 704–726.
- Anderson, D. M. (2004). The Growing Problem of Harmful Algae. *Oceanus Magazine*, 43. Retrieved from [https://www.whoi.edu/cms/files/dfino/2005/4/v43n1-anderson\\_2387.pdf](https://www.whoi.edu/cms/files/dfino/2005/4/v43n1-anderson_2387.pdf)
- Anderson, D. M., Cembella, A. D., and Hallegraeff, G. M. (2012). Progress in Understanding Harmful Algal Blooms: Paradigm Shifts and New Technologies for Research, Monitoring, and Management. *Annual Review of Marine Science*, 4(1), 143–176.
- Anderson, K. A., and Downing, J. A. (2006). Dry and wet atmospheric deposition of nitrogen, phosphorus and silicon in an agricultural region. *Water, Air, and Soil Pollution*, 176(1–4), 351–374.
- Ayres, D. (2008). Harmful Algal Blooms: The Challenges On The Nation's Coastlines. Retrieved from <https://www.researchgate.net/publication/264416296>
- Ballast water and the transport of harmful algae. *Florida Fish and Wildlife Conservation Commission*. Retrieved from <http://myfwc.com/research/redtide/research/scientific-products/ballast-water/#>
- Bath, S. (2017). What Are Algal Blooms and Why Do They Matter? Retrieved from <https://www.iisd.org/blog/what-are-algal-blooms-and-why-do-they-matter>
- Beaulieu, S. E., Sengco, M. R., and Anderson, D. M. (2005). Using clay to control harmful algal blooms: deposition and resuspension of clay/algal flocs. *Harmful Algae*, 4(1), 123–138.
- Benemann, J. (1992). Microalgae Aquaculture Feeds. *Journal of Applied Phycology*, 4(3), 233–245. Retrieved from <https://link.springer.com/article/10.1007/BF02161209>
- Benson, M. H. (2011). Scientists Work to Predict and Prevent Algae Blooms. Retrieved from <http://ocean.si.edu/ocean-life/plants-algae/scientists-work-predict-and-prevent-algae-blooms>





- Bielle, D. (2014). Deadly Algae are Everywhere, Thanks to Agriculture. *Scientific American*. Retrieved from <https://www.scientificamerican.com/article/deadly-algae-are-everywhere-thanks-to-agriculture/>
- Bin, O., and Czajkowski, J. (2013). The Impact of Technical and Non-technical Measures of Water Quality on Coastal Waterfront Property Values in South Florida. *Marine Resource Economics*, 28(1), 43–63.
- Brattebo, S.K., Welch, E.B., Gibbons, H.L., Burghdoff, M.K., Williams, G.N. and Oden, J.L. (2017). Effectiveness of alum in a hypereutrophic lake with substantial external loading. *Lake and Reservoir Management*, 33(2), 108-118.
- Bremner, J. M., and Keeney, D. R. (1966). Determination and Isotope-Ratio Analysis of Different Forms of Nitrogen in Soils: 3. Exchangeable Ammonium, Nitrate, and Nitrite by Extraction-Distillation Methods Soil Science Society of America Journal, 30(5), 577–582.
- Carmichael, W. W. (1994). The Toxins of Cyanobacteria. *Scientific American*, 270(1), 78–86.
- Carpenter, S. (2005). Eutrophication of Aquatic Ecosystems: Bistability and Soil Phosphorus. *National Academy of Sciences of the United States*, 102(29), 10002-10005.
- CDC. (2017). One Health Harmful Algal Blooms System (OHHABS). Retrieved from <https://www.cdc.gov/habs/ohhabs.html>
- Chandler, K. (2013). Feasibility Report for Water Quality Improvements in Twin Lake. Retrieved from [http://www.bassettcreekwmo.org/application/files/8814/4581/9268/Item\\_5Aiii\\_TwinLakeFeasibilityStudy-Final.pdf](http://www.bassettcreekwmo.org/application/files/8814/4581/9268/Item_5Aiii_TwinLakeFeasibilityStudy-Final.pdf)
- Chen, S., Geyer, R., Sherwood, C. and Ralston, D. (2010). Sediment Transport and Deposition on a River-Dominated Tidal Flat: An Idealized Model Study. *Journal of Geophysical Research: Oceans*, 115(C10).
- Clyde, G.A., Emery, E.B. and Tackley, K.L. (2016). Harmful Algal Blooms: A U.S. Army Corps of Engineers Perspective. Retrieved from [https://acwi.gov/monitoring/conference/2016/1\\_tuesday\\_may3/C2/NWMC\\_2016\\_C2\\_Clyde\\_secure.pdf](https://acwi.gov/monitoring/conference/2016/1_tuesday_may3/C2/NWMC_2016_C2_Clyde_secure.pdf)
- Conley D.J., Bonsdorff, E., Carstensen, J., Destouni, G., Gustafsson, B.G., Hansson, L.A., Rabalais N.N., Voss M. and Zillén, L. (2009). Tackling Hypoxia in the Baltic Sea: Is Engineering a Solution? *Environmental Science and Technology*, 43(10), 3407-3411.
- Creekmore, L. (1999). Algal Toxins. *U.S. Department of the Interior and U.S. Geological Survey Field Manual of Wildlife Diseases*. Washington D.C.: U.S. Department of the Interior and U.S. Geological Survey.
- Dahl, T. E. (2009). Status and Trends of Wetlands in the Conterminous United States 2004 to 2009. Retrieved from <https://www.fws.gov/wetlands/documents/Status-and-Trends-of-Wetlands-in-the-Conterminous-United-States-2004-to-2009.pdf>
- Dale, B., Edwards, M. and Reid, P.C. (2018). Climate Change and Harmful Algal Blooms. *Ecological Studies*, 189, 367-378.
- Dent, S., Beutel, M., Gantzer, P., Moore, B. (2014). Response of Methylmercury, Total Mercury, Iron, and Manganese to Oxygenation of an Anoxic Hypolimnion in North Twin Lake, Washington. *Lake and Reservoir Management*, 30(2).
- Diaz, R. J. and Rosenberg, R. (2008). Spreading Dead Zones and Consequences for Marine Ecosystems.



- Science*, 321(5891), 926-929.
- DiStefano, J. F., and Gholz, H. L. (1986). A proposed use of ion exchange resins to measure nitrogen mineralization and nitrification in intact soil cores. *Communications in Soil Science and Plant Analysis*, 17(9), 989–998. <https://doi.org/10.1080/00103628609367767>
- Dodds, W., and Smith, V. (2016). Nitrogen, Phosphorus, and Eutrophication in Streams. *Ecology and Evolutionary Biology*, 6, 155-164. Retrieved from <https://www.fba.org.uk/journals/index.php/IW/article/viewFile/909/545>
- Dodds, W.K., Bouska, W.W., Eitzmann, J.L., Pilger, T.J., Pitts, K.L., Riley, A. J., Schloesser, J.T., and Thornburgh, D.J. (2009). Eutrophication of U.S. Freshwaters: Analysis of Potential Economic Damages. *Environmental Science and Technology*, 43(9), 12-9.
- Dolah, E. R. V., Paolisso, M., Sellner, K., and Place, A. (2015). Employing a Socio-Ecological Systems Approach to Engage Harmful Algal Bloom Stakeholders. *Aquatic Ecology*.
- Duce, R.A. (1986). The impact of atmospheric nitrogen, phosphorus, and iron species on marine biological productivity. *The Role of Air-Sea Exchange in Geochemical Cycling*. Netherlands: Springer.
- Dyson, K., and Huppert, D. D. (2010). Regional economic impacts of razor clam beach closures due to harmful algal blooms (HABs) on the Pacific coast of Washington. *Harmful Algae*, 9(3), 264–271.
- Fisher, D. and Oppenheimer, M. (1991). Atmospheric Nitrogen Deposition and the Chesapeake Bay Estuary. *Ambio*, 20(3/4), 102-108. Retrieved from <http://www.jstor.org/stable/4313793>
- Fitzsimmons, E. G. (2017). Tap Water Ban for Toledo Residents. *The New York Times*.
- Florida Department of Environmental Protection. (n.d.) Algal Bloom Monitoring and Response. Retrieved from <https://floridadep.gov/DEAR/Algal-Bloom>
- Florida Fish and Wildlife. (2018). Current Red Tide Status. Retrieved from <http://myfwc.com/redtidestatus>
- Frazer, L. (2005). Paving Paradise: The Peril of Impervious Surfaces. *Environmental Health Perspectives*, 113(7).
- Friedrich, J., Janssen, F., Aleynik, D., Bange, H. W., Boltacheva, N., Çagatay, M. N., ... Wenzhöfer, F. (2014). Investigating hypoxia in aquatic environments: diverse approaches to addressing a complex phenomenon. *Biogeosciences*, 11(4), 1215–1259.
- Frink, C. R., Waggoner, P. E., and Ausubel, J. H. (1999). Nitrogen fertilizer: Retrospect and prospect. *Proceedings of the National Academy of Sciences of the United States of America*, 96(4), 1175–1180.
- Garcia, M., Soto, F., Gonzalez, J., Becas, E. (2008). A Comparison of Bacterial Removal Efficiencies in Constructed Wetlands and Algae-Based Systems. *Ecological Engineering*, 32(3), 238-243.
- Getchis, T., and Shumway, S. (2018). *Harmful Algae: A Compendium Desk Reference* (Rep.). CT: Wiley.



- Gliber, P., Anderson, D., Gentien, P., Graneli, E. and Sellner, K. (2006). The Global, Complex Phenomena of Harmful Algal Blooms. *Oceanography*, 18(12), 136-147.
- Glibert, P. M., and J. M. Burkholder. The Complex Relationships Between Increases in Fertilization of the Earth, Coastal Eutrophication and Proliferation of HABs. *Ecological Studies Ecology of Harmful Algae*, 2006, pp. 341–354. doi:10.1007/978-3-540-32210-8\_26.
- Goolsby, D.A., Battaglin, W.A. (1997). Sources and Transport of Nitrogen in the Mississippi. *U.S. Geological Survey*. Retrieved from <https://co.water.usgs.gov/midconherb/html/st.louis.hypoxia.html>
- Grattan, L.M., Holobaugh, S., and Morris, J.G. (2016). Harmful algal blooms and public health. *Harmful Algae*, 57(B), 2-8.
- Griffith, D. (1999). Exaggerating Environmental Health Risk: The Case of the Toxic Dinoflagellate *Pfiesteria*. *Human Organization*, 58(2), 119–127.
- Guiry, M. (2012). How Many Species of Algae Are There? *Journal of Phycology*, 48(5).
- Gupta, B. K. S., Turner, R. E. and Rabalais, N. N. (1996). Seasonal oxygen depletion in continental-shelf waters of Louisiana: Historical record of benthic foraminifera. *Geology* 24(3), 227–230
- Hale, S. S., Cicchetti, G., and Deacutis, C. F. (2016). Eutrophication and Hypoxia Diminish Ecosystem Functions of Benthic Communities in a New England Estuary. *Frontiers in Marine Science*, 3.
- Hallegraeff, G.M. (1993). A Review of Harmful Algal Blooms and their Apparent Global Increase. *Phycologia*, 32(2), 79-99.
- Hallegraeff, G.M. (2010). Ocean Climate Change, Phytoplankton Community Responses, And Harmful Algal Blooms: A Formidable Predictive Challenge. *Journal of Phycology*, 46(2), 220–235.
- Harmful Algal Bloom Research and Control Act, 33 U.S.Code §§ 4000–4009 (1998).
- Harvey, E. L., and Menden-Deuer, S. (2012). Predator-Induced Fleeting Behaviors in Phytoplankton: A New Mechanism for Harmful Algal Bloom Formation? *PLoS ONE*, 7(9).
- Heisler, J., Gilbert, P., Burkholder, J., Anderson, D., Cochlan, W., Dennison, W.... Suddleson, M. (2008). Eutrophication and Harmful Algal Blooms: A Scientific Consensus. *Harmful Algae*, 3(13).
- Hill, K. A., Shepson, P. B., Galbavy, E. S., and Anastasio, C. (2005). Measurement of Wet Deposition of Inorganic and Organic Nitrogen in a Forest Environment. *Journal of Geophysical Research: Biogeosciences*, 110(G2).
- Hilton, J., O'Hare, M., Bowes, M. and Jones, J. (2006). How Green is my River? A New Paradigm of Eutrophication in Rivers. *Science of the Total Environment*, 365(3), 66-83.
- Hoagland, P., Anderson, D.M., Kaoru, Y., White, A.W. (2002). The economic effects of harmful algal blooms in the United States: Estimates, assessment issues, and information needs. *Estuaries*, 25(4).
- Hoagland, P., Jin, D., Polansky, L. Y., Kirkpatrick, B., Kirkpatrick, G., Fleming, L. E., and Backer, L. C. (2009). T The Costs of Respiratory Illnesses Arising from Florida Gulf Coast *Karenia brevis* Blooms. *Environmental Health Perspectives*, 117(8), 1239–1243.



- Hoagland, P., Scatasta, S. (2006). The Economic Effects of Harmful Algal Blooms. *Ecology of Harmful Algae*, (189), 391-402.
- Huisman, J., Codd, G. A., Paerl, H. W., Ibelings, B. W., Verspagen, J. M. H., and Visser, P. M. (2018). Cyanobacterial blooms. *Nature Reviews Microbiology*, 16(8), 471–483.
- Interagency Working Group on Harmful Algal Blooms, Hypoxia, and Human Health (2010). Scientific Assessment of Hypoxia in U.S. Coastal Waters. Retrieved from <https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/hypoxia-report.pdf>
- IPCC. (n.d.). Linking climate change and water resource: impacts and responses. Retrieved from <https://www.ipcc.ch/pdf/technical-papers/ccw/chapter3.pdf>
- Julien, P. (2018). *River Mechanics*. Cambridge, UK: Cambridge University Press.
- Kibria, G., Nugegoda, D. and Fairclough, R. (1997). The nutrient content and the release of nutrients from fish food and faeces. *Hydrobiologia*, 357(165).
- Kiesling, R.L., Gary, R.H., and Gary, M.O., (2008). Monitoring indicators of harmful Cyanobacteria in Texas: U.S. Geological Survey Fact Sheet 2008–3009. Retrieved from <https://pubs.usgs.gov/fs/2008/3009/>
- Kusler, J.A., and Kentula, M.E. (1990). Wetland Creation And Restoration: The Status Of The Science Vol. 2. Retrieved from [https://www.epa.gov/sites/production/files/2015-08/documents/wetland\\_creation\\_and\\_restoration\\_-\\_the\\_status\\_of\\_the\\_science\\_vol\\_2\\_1.pdf](https://www.epa.gov/sites/production/files/2015-08/documents/wetland_creation_and_restoration_-_the_status_of_the_science_vol_2_1.pdf)
- Landsberg, J. (2010). The Effects of Harmful Algal Blooms on Aquatic Organisms. *Fisheries Science*, 10(2), 113-390.
- Lopez, C.B., Jewett, E.B., Dortch, Q., Walton, B.T., Hudnell, H.K. (2008). Scientific Assessment of Freshwater Harmful Algal Blooms. Interagency Working Group on Harmful Algal Blooms, Hypoxia, and Human Health of the Joint Subcommittee on Ocean Science and Technology. Retrieved from <https://www.who.edu/files/serve.do?id=41023andpt=10andp=19132>
- Michalak, A.M., Anderson, E.J., Beletsky, D., Boland, S., Bosch, N.S., Bridgeman, T.B., ... Zagorski, M.A. (2013). Record-setting algal bloom in Lake Erie caused by agricultural and meteorological trends consistent with expected future conditions. Retrieved from <http://www.pnas.org/content/110/16/6448>
- Mississippi River/Gulf of Mexico Watershed Nutrient Task Force. (2017). 2017 Report to Congress. Retrieved from [https://www.epa.gov/sites/production/files/2017-11/documents/hypoxia\\_task\\_force\\_report\\_to\\_congress\\_2017\\_final.pdf](https://www.epa.gov/sites/production/files/2017-11/documents/hypoxia_task_force_report_to_congress_2017_final.pdf)
- Moore, S., Trainer V., Mantua, N., Parker, M., Laws, E., Backer, L. and Fleming, L. (2008). Impacts of Climate Variability and Future Climate Change on Harmful Algal Blooms and Human Health. *Environmental Health*, 7(2), S4.
- Morgan, K. L., Larkin, S.L., and Adams, C.M. (2009). Firm-Level Economic Effects of HABs: A Tool for Business Loss Assessment. *Harmful Algae*, 8(2), 212–218.
- National Science and Technology Council Subcommittee on Ocean Science and Technology. (2016).



- Harmful Algal Blooms and Hypoxia Comprehensive Research Plan and Action Strategy: An Interagency Report. Retrieved from [https://cdn.coastalscience.noaa.gov/page-attachments/research/FINAL\\_USEC%20signed%20-%20Progress%20and%20Implementation%20Report\\_HABHRCA.pdf](https://cdn.coastalscience.noaa.gov/page-attachments/research/FINAL_USEC%20signed%20-%20Progress%20and%20Implementation%20Report_HABHRCA.pdf)
- NOAA. (2013a). Harmful Algal Bloom Forecasts. Retrieved from [https://tidesandcurrents.noaa.gov/hab\\_info.html](https://tidesandcurrents.noaa.gov/hab_info.html)
- NOAA. (2013b). Gulf of Mexico Harmful Algal Bloom Health Information. Retrieved from [https://tidesandcurrents.noaa.gov/hab/gomx\\_health.html](https://tidesandcurrents.noaa.gov/hab/gomx_health.html)
- NOAA. (2014). Why do harmful algal blooms occur? Retrieved from [https://oceanservice.noaa.gov/facts/why\\_habs.html](https://oceanservice.noaa.gov/facts/why_habs.html)
- NOAA. (2017). *Gulf of Mexico 'Dead Zone' is the Largest Ever Measured*. Retrieved from <http://www.noaa.gov/media-release/gulf-of-mexico-dead-zone-is-largest-ever-measured>
- NOAA. (2018a) Currents: Longshore Drift. Retrieved from [https://oceanservice.noaa.gov/education/tutorial\\_currents/03coastal2.html](https://oceanservice.noaa.gov/education/tutorial_currents/03coastal2.html)
- NOAA. (2018b). Lake Erie Harmful Algal Bloom Seasonal Forecast. Retrieved from [https://nccospublicstor.blob.core.windows.net/hab-data/bulletins/lake-erie/current/bulletin\\_current.pdf](https://nccospublicstor.blob.core.windows.net/hab-data/bulletins/lake-erie/current/bulletin_current.pdf)
- NOAA. (2018c). MODIS / Aqua NIR-SWIR Ocean Color Products. Retrieved from [https://www.ospo.noaa.gov/Products/ocean/color/swir\\_chla\\_daily.html](https://www.ospo.noaa.gov/Products/ocean/color/swir_chla_daily.html)
- NOAA. (2018d). What is nutrient pollution? Retrieved from <https://oceanservice.noaa.gov/facts/nutpollution.html>
- Norambuena, F., Hermon, K., Skrzypczyk, V., Emery, J., Sharon, Y., Beard, A., and Tuchini, G. (2015). Algae in Fish Feed: Performances and Fatty Acid Metabolism in Juvenile Atlantic Salmon. *PLoS ONE*, 10(4). Retrieved from <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4398455/>
- Oregon Health Authority (2018). HAB Public Health Advisory Guidelines. Retrieved from <https://www.oregon.gov/oha/PH/HEALTHYENVIRONMENTS/RECREATION/HARMFULALGAE/BLOOMS/Documents/HABPublicHealthAdvisoryGuidelines.pdf>
- Paerl, H.W. (1995). Coastal eutrophication in relation to atmospheric nitrogen deposition: Current perspectives. *Ophelia*, 41(1), 237-259.
- Paerl, H.W. (1997). Coastal eutrophication and harmful algal blooms: Importance of atmospheric deposition and groundwater as "new" nitrogen and other nutrient sources. *Limnology and Oceanography*, 42(5), 1154-1165.
- Paerl, H.W., and Huisman, J. (2008). Blooms like it hot. *Science* 320, 57-58.
- Paerl, H., Pinckney, J., Fear, J. and Peierls, B. (1998). Ecosystem Responses to Internal and Watershed Organic Matter Loading: Consequences for Hypoxia in the Eutrophying Neuse River Estuary, North Carolina, USA. *Marine Ecology Progress Series*, 166, 17-25.
- Parsons, G. R., Morgan, A., Whitehead, J. C., and Haab, T. C. (2006). The welfare effects of *pfisteria*-related fish kills: A contingent behavior analysis of seafood consumers. *Agricultural and Resource Economics Review*, 35(2), 348-356.



- Pitcairn, C., Leith, I., Sheppard, L., Sutton, M., Fowler, D., Munro, R., Tang, S. and Wilson, D. (1998). The Relationship Between Nitrogen Deposition, Species Composition and Foliar Nitrogen Concentrations in Woodland Flora in the Vicinity of Livestock Farms. *Proceedings of the First International Nitrogen Conference*, 4(18), 41-48.
- Ribaudo, M.O. and Gottlieb, J. (2011). Point-nonpoint trading – can it work? *Journal of the American Water Resources Association*, 47(1): 5-14.
- Ritzel, B. (2014). Gulf of Mexico's Hypoxic Dead Zone. Retrieved from [https://www.researchgate.net/publication/269470554\\_Gulf\\_of\\_Mexico's\\_Hypoxic\\_Dead\\_Zone](https://www.researchgate.net/publication/269470554_Gulf_of_Mexico's_Hypoxic_Dead_Zone)
- Rosenfeldt, E. (2015). Harmful Algal Blooms. Retrieved from [https://www.hazenandsawyer.com/uploads/downloads/Harmful\\_Algal\\_Bloom\\_White\\_Paper\\_v7.pdf](https://www.hazenandsawyer.com/uploads/downloads/Harmful_Algal_Bloom_White_Paper_v7.pdf)
- Round, F. E., Crawford, R. M., and Mann, D. G. (1990). *Diatoms: Biology and Morphology of the Genera*. Cambridge University Press.
- Rubio, J., Souza, M.L and Smith, R.W. (2002). Overview of Flotation As a Wastewater Treatment Technique. *Minerals Engineering*, 15, 139-155.
- Scholin, C., Gulland, F., Doucette, G., Benson, S., Busman, M., Chavez, F., Cordaro, J., DeLong, R., De Vogelaere, A., Harvey, J., Haulena, M., Lefebvre, K., Lipscomb, T., Loscutoff, S., Lowenstine, L., Marin, R., Miller, P., McLellan, W., Moeller, P., Powell, C., Rowles, T., Silvagni, P., Silver, M. (2000). Mortality of Sea Lions Along the Central California Coast Linked to a Toxic Diatom Bloom. *Nature International Journal of Science*, 403(1), 80-84.
- Searchinger, T., Houghton, R.A., Heimlich, R., Dong, F., Elobeid, A., Fabiosa, J., Tokgoz, S., Hayes, D. and Yu T.H. (2008). Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change. *American Association for Advancement of Science*, 319(5867), 1238-1240.
- Sellner, K., Doucette, G., Kirkpatrick, G. (2002). Harmful Algal Blooms: Causes, Impacts, and Detection. *Microbial Biotechnology*, 30, 383-406.
- Sellner, K. G., Lacouture, R.V., Cibik, S.J., Brownlee, S. and Brindley, G.A. (1991). Importance of a winter dinoflagellate-microflagellate bloom in the Patuxent River estuary. *Estuarine Coastal Shelf Science*, 32.
- Seltenrich, N. (2014). Keeping tabs on HABs: New tools for detecting, monitoring, and preventing harmful algal blooms. *Environmental Health Perspectives*, 122(8).
- Senate Committee On Commerce, Science, And Transportation. (2017). Report on S.1057. Retrieved from <https://www.congress.gov/115/crpt/srpt145/CRPT-115srpt145.pdf>
- Sengco, M. R. and Anderson, D. M. (2004). Controlling Harmful Algal Blooms Through Clay Flocculation. *Journal of Eukaryotic Microbiology*, 51(2).
- Sherry, L. L. and Charles, M. A. (2007). Harmful Algal Blooms and Coastal Business: Economic Consequences in Florida. *Society and Natural Resources*, 20(9), 849-859.
- Sirivdhin, T. and Gray, K. (2005). Factors Affecting Denitrification Rates in Experimental Wetlands Field and Laboratory Studies. *Ecological Engineering*, 26(2), 167-181.



- Smayda, T. (2002). Turbulence, Watermass Stratification, and Harmful Algal Blooms: An Alternative View and Frontal Zones as "Pelagic Seed Banks". *Harmful Algae*, 1(2002), 95-112.
- Smithsonian Institution. (2011). *Karenia brevis*. Retrieved from [http://www.sms.si.edu/irlspec/Kareni\\_brevis.htm](http://www.sms.si.edu/irlspec/Kareni_brevis.htm)
- Sparks, R. (1992). The Upper Mississippi River. Pages 406-412 in National Research Council (ed.), *Restoration of aquatic ecosystems: Science, technology, and public policy*. National Academy Press, Washington, DC.
- State of Maine: Department of Marine Resources. (2017). Maine's 2016 Commercial Marine Resources Top \$700 Million for the First Time. Retrieved from <https://www.maine.gov/dmr/news-details.html?id=732546>
- Turner, J. T., and Granéli, E. (2006). "Top-Down" Predation Control on Marine Harmful Algae. *Ecological Studies Ecology of Harmful Algae*, 355-366.
- UNESCO. (2017). Harmful Algal Blooms (HABs) and Desalination: A Guide to Impacts, Monitoring and Management. Retrieved from <http://unesdoc.unesco.org/images/0025/002595/259512E.pdf>
- University of Southern Mississippi. (2018) Interesting Gulf and Coastal Fishes. Retrieved from <http://gcrl.usm.edu/public/fish/gulf.and.coastal.fishes.php>
- Urquhart, E. A., Schaeffer, B. A., Stumpf, R. P., Loftin, K. A., and Werdell, P. J. (2017). A method for examining temporal changes in cyanobacterial harmful algal bloom spatial extent using satellite remote sensing. *Harmful Algae*, 67, 144–152.
- U.S. Army Corps of Engineers. (2012). New Orleans District > Missions > Environmental > MRGO Ecosystem Restoration. Retrieved from <http://www.mvn.usace.army.mil/Missions/Environmental/MRGO-Ecosystem-Restoration/>
- U.S. Army Corps of Engineers. (2018). Mission Statement. Retrieved from <https://www.usace.army.mil/Missions/>
- U.S. Department of Commerce, N. (n.d.). Western Lake Erie Sampling. Retrieved July 28, 2018, from [https://www.glerl.noaa.gov/res/HABs\\_and\\_Hypoxia/habsMonWLE.html](https://www.glerl.noaa.gov/res/HABs_and_Hypoxia/habsMonWLE.html)
- U.S. EPA. (2002). ECOHAB: Control of Harmful Algal Blooms using Clay. Retrieved from <https://cfpub.epa.gov/ncer/abstracts/index.cfm/fuseaction/display.highlight/abstract/1014>
- U.S. EPA. (2007). Evaluation report. Retrieved from <https://www.epa.gov/sites/production/files/2015-11/documents/20070228-2007-p-00009.pdf>
- U.S. EPA. (2014). Cyanobacteria Assessment Network (CyAN). Retrieved July 28, 2018, from <https://www.epa.gov/water-research/cyanobacteria-assessment-network-cyan>
- U.S. EPA. (2015). A Compilation of Costs Data Associated with the Impacts and Control of Nutrient Pollution. Retrieved from <https://www.epa.gov/sites/production/files/2015-04/documents/nutrient-economics-report-2015.pdf>
- U.S. EPA. (2017a). Climate Impacts on Water Resources. Retrieved from [https://19january2017snapshot.epa.gov/climate-impacts/climate-impacts-water-resources\\_.html](https://19january2017snapshot.epa.gov/climate-impacts/climate-impacts-water-resources_.html)



- U.S. EPA. (2017b). Nutrient Pollution: The Problem. Retrieved from <https://www.epa.gov/nutrientpollution/problem>
- U.S. EPA. (2018a). Nutrient Pollution: Harmful Algal Blooms. Retrieved from <https://www.epa.gov/nutrientpollution/harmful-algal-blooms>
- U.S. EPA. (2018b). Hypoxia 101. Retrieved from <https://www.epa.gov/ms-htf/hypoxia-101>
- U.S. EPA. (n.d.) What are some measures to prevent cyanobacterial blooms in surface waters? Retrieved from <https://www.epa.gov/nutrient-policy-data/control-and-treatment#what1>
- U.S. EPA, Office of Water. (2013). Impacts of Climate Change on the Occurrence of Harmful Algal Blooms. Retrieved from <https://www.epa.gov/sites/production/files/documents/climatehabs.pdf>
- USGS. (2017). Tracking the Bad Guys: Toxic Algal Blooms. Retrieved from <https://www.usgs.gov/news/tracking-bad-guys-toxic-algal-blooms>.
- USGS. (2018). Satellite Imagery Can Track Harmful Algal Blooms. Retrieved from <https://www.usgs.gov/news/satellite-imagery-can-track-harmful-algal-blooms>
- Vincent, W. F. (2009). Effects of Climate Change on Lakes. *Encyclopedia of Inland Waters*. Retrieved from <https://www.sciencedirect.com/science/article/pii/B9780123706263002337?via%3Dihub>
- Watson, S.B., Miller, C.J., Arhonditsis, G.B., Boyer, G.L., Carmichael, W.W., Charlton, M.N., ... Wilhelm, S.W. (2016). The re-eutrophication of Lake Erie: Harmful algal blooms and hypoxia. *Harmful algae*, 56, 44-66 . DOI:10.1016/j.hal.2016.04.010
- WHOI. (2016a). Aquaculture Losses. Retrieved at: <https://www.whoi.edu/redtide/impacts/aquaculture-losses>
- WHOI. (2016b). Distribution of HABs in the U.S. Retrieved from <https://www.whoi.edu/redtide/regions/us-distribution>
- WHOI. (2016c). Economic Impacts. Retrieved from <http://www.whoi.edu/redtide/impacts/economic>
- WHOI. (2017). Distribution of HABs throughout the world. Retrieved from <https://www.whoi.edu/redtide/regions/world-distribution>
- WHOI. (n.d.). Brown Tides and Redfielders. Retrieved from <https://www.whoi.edu/oceanus/v2/article/images.do?id=142309>
- Wolf, D., Georgic, W., and Klaiber, H. A. (2017). Reeling in the damages: Harmful algal blooms impact on Lake Eries recreational fishing industry. *Journal of Environmental Management*, 199, 148-157.
- Worm, B., and Branch, T. A. (2012). The future of fish. *Trends in Ecology and Evolution*, 27(11), 594–599.
- Wu, X., and Mitsch, W. J. (1998). Spatial and temporal patterns of algae in newly constructed freshwater wetlands. *Wetlands*, 18(1), 9–20.



- Xiu, P., Chai, F., Curchitser, E. N., and Castruccio, F. S. (2018). Future changes in coastal upwelling ecosystems with global warming: The case of the California Current System. *Scientific Reports*, 8(1).
- Yeo, S., Binkowski, F., and Morris, J. (2004). Aquaculture Effluents and Waste By-Products Characteristics, Potential Recovery, and Beneficial Reuse. Retrieved from [https://lib.dr.iastate.edu/ncrac\\_techbulletins/6](https://lib.dr.iastate.edu/ncrac_techbulletins/6)
- Yu, Z., Song, X., Cao, X. and Liu, Y. (2017). Mitigation of Harmful Algal Blooms Using Modified Clays: Theory, Mechanisms, and Applications. *Harmful Algae*, 69, 48–64.
- Zhou, K., Hu, Y., Zhang, L., Yang, K., Lin, D. (2016). The Role of Exopolymeric Substances in the Bioaccumulation and Toxicity of Ag Nanoparticles to Algae. *Scientific Reports*, 6.
- Zingone, A., Enevoldsen, H. (2000). *The Diversity of Harmful Algal Blooms: A Challenge for Science and Management*. Ocean and Coastal Management, 43(9), 725-748.
- Zuazo, V. H., and Pleguezuelo, C. R. (2008). Soil-Erosion and Runoff Prevention by Plant Covers: A Review. *Agronomy for Sustainable Development*, 28(1), 65-86.