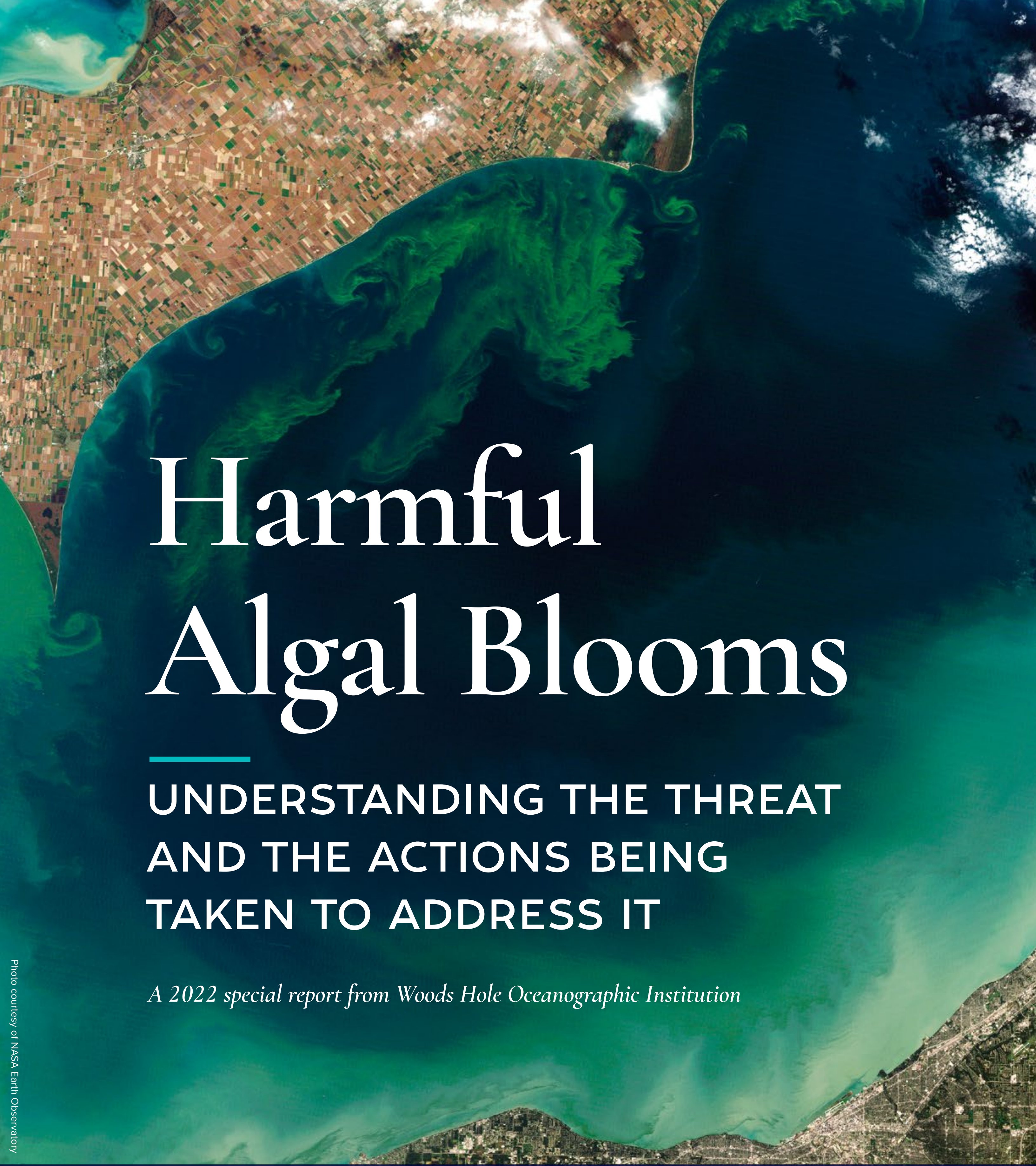

Photo courtesy of NASA Earth Observatory

Harmful Algal Blooms

UNDERSTANDING THE THREAT AND THE ACTIONS BEING TAKEN TO ADDRESS IT

A 2022 special report from Woods Hole Oceanographic Institution

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Overview of Harmful Algal Blooms (HABs)

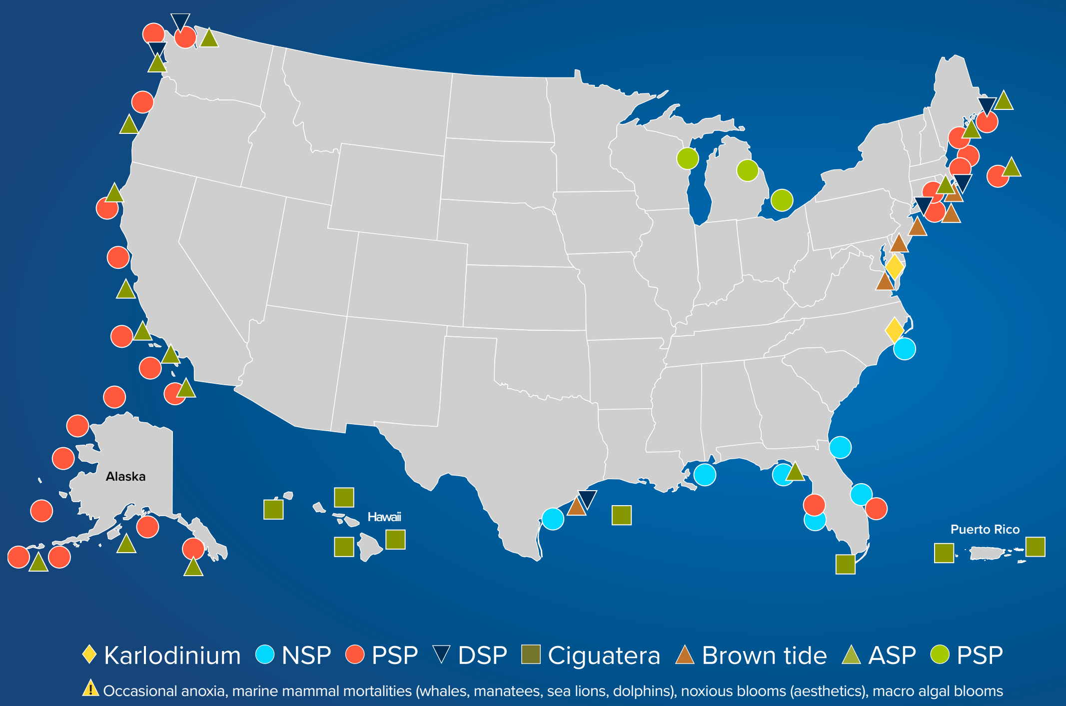
Background

Phytoplankton are mostly microscopic algae that form the base of the world's aquatic and marine food chains. These photosynthetic, single-cell organisms play a critical role in sustaining life and produce approximately half of the planet's oxygen. Although most of the thousands of phytoplankton species are beneficial, a few hundred cause harmful impacts, and under certain conditions, can rapidly multiply and accumulate into large and dense masses, creating visible "blooms".

Algal blooms that can harm humans, animals, and plants and cause impacts to aquatic environments are referred to as harmful algal blooms (HABs). Sometimes known as "red tides," HABs encompass a wide range of algal species and phenomena. Both toxic and nuisance blooms can also occur in both saltwater and freshwater environments, ranging from small, localized events affecting bays and estuaries to larger blooms that can cover coastline stretches greater than a major hurricane.[1] HAB hazards have increased in some regions over the past 40 years,[2] and are a significant problem in every U.S. coastal and Great Lakes state.[3] Scientists believe there are more toxic algal species, more affected areas, and higher economical losses today than just 30 years ago.[4]

While some HABs are expanding, others aren't. Still, a statistically significant increasing trend is evident for all U.S. HAB events combined. Part of the observed increase in some, but not all, HAB syndromes in the U.S. is a realization of the true scale of the problem, long obscured by inadequate monitoring. The increases are also linked to species dispersion and stimulation from nutrient pollution, aquaculture, and ocean warming.[5]

Cyanobacteria bloom in Lake Erie. (Photo by Aerial Associates Photography, Inc. by Zachary Haslick)

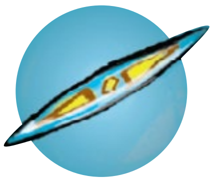


Coastal waters of the United States are subject to most of the major HAB poisoning syndromes and impacts. These include paralytic shellfish poisoning (PSP), neurotoxic shellfish poisoning (NSP), amnesic shellfish poisoning (ASP), ciguatera poisoning (CP), brown tides (BT), cyanoHABs, and a number of other HAB phenomena such as fish kills, shellfish mortalities, and widespread marine mammal mortalities. The map depicts the various HAB poisoning syndromes and other impacts in the U.S. Each “Event” noted on the map is considered to be something that constituted a quarantine, closure or management decision where toxicity was detected exceeding regulatory limits. It is not practical to indicate the location of every CyanoHAB, which are found in all 50 states, so widespread CyanoHAB problems are denoted for the Great Lakes only.

Data used to create these maps are compiled annually by the U.S. National Office for Harmful Algal Blooms, and entered into the Harmful Algae Event Database (HAEDAT) maintained by the ICES Science and Communications Center in Vigo, Spain.

Defining the problem: why HABs are important

HABs are significant due to the different kinds of risks they pose and the impacts they can have on human and aquatic health. Some HABs produce toxins that are dangerous to humans as well as wildlife, including marine mammals, fish, shellfish, and plants. Toxins can accumulate in the tissue of shellfish and other filter feeding marine organisms that inadvertently consume toxic algae. When other animals—marine mammals, seabirds, or people—eat contaminated fish and shellfish, they can ingest high enough concentrations of toxins to cause illness, neurological disorders, or even death.[6]



Algal blooms that are non-toxic can still be very harmful due to their sheer mass and high density of cells, which can ultimately cause a broad array of ecosystem-wide impacts.

HABs can also cause damage through physical means. Some species have sharp spines that can become lodged in the gills of fish and shellfish, causing injury and restricting their ability to take in oxygen, leading to death by suffocation.

Beyond the potential direct harm to humans, marine organisms, and aquatic ecosystems, HABs can disrupt drinking water supplies and cause severe economic impacts to fishery resources, aquaculture, and local recreation and tourism industries. These impacts can especially hurt local communities by decreasing business activity and diminishing the quality of the environment.

Clam diggers at low tide on the Oregon coast. (Photo iStock/ WestWindGraphics)

Impacts of HABs

Human Health

The toxins produced by HABs are dangerous to humans and can cause a range of illnesses and health effects including neurological disorders, gastrointestinal issues, respiratory infections, liver and kidney damage, paralysis, and even death. When blooms appear, people are at risk of exposure through skin contact in the water or breathing algal toxins that become airborne in tiny droplets or mist. Exposure can also occur by drinking water containing algal toxins or eating contaminated seafood products.

Toxins enter aquatic food chains when filter feeding shellfish like mussels, clams, oysters, and scallops ingest toxic algae. Fish can accumulate toxins by ingesting toxin-producing HAB cells or their grazers, or via uptake and transfer of algal toxins from the consumption of other fish.[7] Shellfish and fish with accumulated toxins can be harmful to people if consumed, though with the exception of ciguatera toxins, most HAB toxins are only found in fish organs and viscera, and not in the flesh to any significant degree.

The poisoning syndromes that specific toxins can cause in people include ciguatera poisoning as well as amnesic, diarrhetic, neurotoxic, azaspiracid, and paralytic shellfish poisoning. All of the shellfish poisoning syndromes are known problems within the U.S. and its territories, with some affecting large expanses of coastline.[8] Of all the poisoning

syndromes associated with HABs, ciguatera poisoning is the most frequently reported seafood-related illness in the U.S., and the most common foodborne illness related to fish consumption in the world.[9]

HABs that occur in freshwater, like the Great Lakes and other drinking water sources, are dominated by the cyanobacterium *Microcystis*, which produces a liver toxin that can cause gastrointestinal illness and liver damage.[10] Other potentially harmful cyanobacteria species are also found in lakes, ponds and river systems throughout the U.S.[11]

Wildlife and Domestic Animals

Algal toxins and cyanotoxins that accumulate in fish and shellfish present a significant threat to wildlife species at higher trophic levels that consume these food sources.

Florida red ties have had devastating impacts on wildlife, including threatened marine mammal species such as manatees, while on the U.S. west coast, blooms of domoic-acid producing *Pseudo-nitzschia* diatoms sicken and kill seals and sea lions each year. In freshwater systems, cyanobacteria toxins have been implicated as the cause of mass mortalities of fish and birds and have also been tied to the death of pets and livestock that may be exposed through drinking contaminated water or licking themselves after bodily exposure.[12] Additionally, cyanobacterial biomass frequently accumulates as clotted mats, posing a particular threat to dogs who may lick or eat the toxic mats.[13]

Algal toxins, like brevetoxins found in red tides, can impact sea life at every trophic level from shellfish to marine mammals like these swimming manatees. (Photo courtesy of NOAA)

Economic

HABs can have significant economic consequences for public health, commercial fisheries, recreation and tourism, aquaculture, and food markets. Blooms can impact local tourism-focused businesses and force shellfish farms and commercial fishery operations to close. They can result in lost revenue for coastal and lakefront economies that rely on revenue from visitors and vacationers, and even decrease coastal and lakefront property values.

Results of various economic studies in the literature suggest that crude national estimates of the economic effects of HABs are on the order of $\$10^7$-$10^8$ annually. An earlier nationwide estimate (in 2000) of the average annual costs of HABs is approximately $78 million (in 2021 dollars), of which public health is the largest component (nearly $35 million), followed by the effect on commercial fisheries ($29 million), recreation and tourism ($10 million), and spending for monitoring and management ($3 million).[14] Average annual costs tend to mask the significance of individual HAB events, some of which greatly exceed the annual average for the entire country.[15] Moreover, the direct effects of HABs can propagate through regional economies, causing negative impacts to other sectors.[16]

In addition to the direct economic costs of HAB events, industries and communities can incur indirect or hidden costs that are difficult to quantify. These can include wild fish kills and lost opportunities to harvest untapped shellfish resources; slower economic activity in food processing and aquaculture; ongoing expenses for human illnesses; or declines in consumer confidence related to seafood purchases and recreational charter trips.[17]

Photo by iStock.com/Dale Fornoff

Women harvest aquaculture shellfish in Zanzibar. (Photo courtesy of Hauke Kite-Powell, © Woods Hole Oceanographic Institution)

Social and Cultural

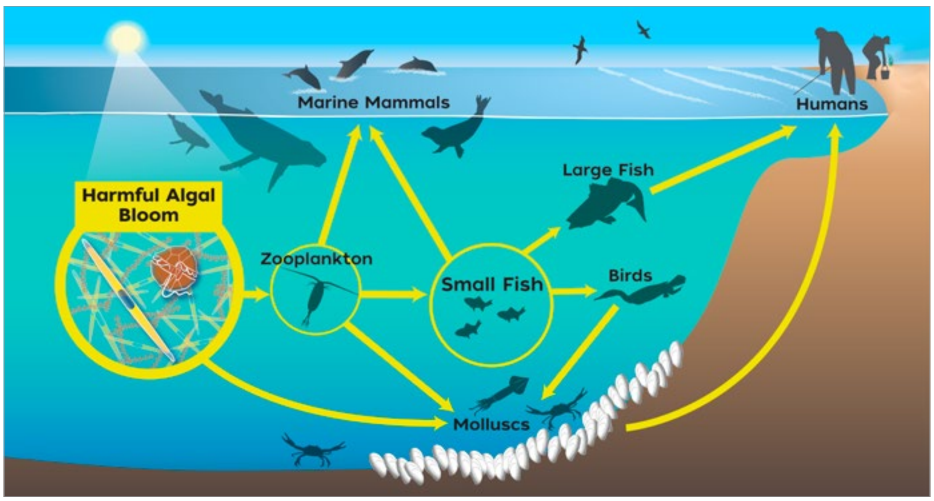
HABs can adversely affect local people who depend on coastal and freshwater resources to meet social and economic needs. HAB events pose a serious threat to indigenous coastal communities by disrupting cultural practices and contributing to food insecurity from loss of subsistence harvest.[18] The impacts of HABs can also diminish the well-being and culture of local communities through degradation of local aesthetics, disruption of recreational activities, and losses to traditional ways of life that contribute to a community's collective identify.[19]

Ecosystems

Marine and freshwater ecosystems are especially vulnerable to the detrimental effects of HABs, which can disturb ecosystem functions, impair water quality, impact food web dynamics, and harm aquatic health. Both toxic and non-toxic blooms can cause a wide range of detrimental effects at the ecosystem level. Toxic HAB species can cause fish kills and illnesses in mammals and birds as toxins move up the food chain.[20] Toxins can be harmful or lethal at many levels in aquatic food webs and can remain viable for months as they are able to settle into the sediment of lakes and coastal marine areas, creating a long-term exposure route.[21]

Non-toxic blooms, while not directly harmful, present a threat to ecosystems through their high biomass accumulation. Blooms can cover large areas of the water's surface, blocking light from entering the water column and reaching plants and algae. Unable to photosynthesize, these organisms—including aquatic plants, algae, and tiny organisms, such as diatoms—may struggle to survive.[22]

An additional risk to ecosystems begins to develop when a high-biomass bloom has run its course and begins to die-off. The resulting decay of dead algae can deplete oxygen within the water column, creating deadly conditions known as hypoxia and anoxia, which can harm ecosystems and result in fish kills. The indirect effects of low oxygen can be substantial and include loss of suitable habitat and decline in biological diversity.[23]



Algal toxins that accumulate in the marine food web can harm a wide spectrum of species including mollusks, marine mammals, seabirds, and humans. (Illustration by Natalie Renier, Woods Hole Oceanographic Institution).

Drinking Water Resources

HABs and toxin-producing cyanobacteria are increasingly found in freshwater systems and drinking water sources in every U.S. state. Drinking waters with high levels of cyanotoxins can cause taste and odor problems and a host of serious health problems in people.

Contaminated waters can be a major cost burden to water treatment plants, which face a difficult task of not only removing the toxins but doing so in a safe and cost-effective way.[24] Algal mats can also interfere with reservoir operations by clogging drinking water and hydroelectric intakes.

HAB outbreaks in drinking water supplies can have severe consequences. While conventional water treatment processes can generally remove cyanobacterial cells and low levels of toxins, water systems may face challenges providing drinking water during a severe bloom event, when high levels of cyanobacteria and cyanotoxins are present in drinking water sources.[25] The State of Ohio declared a state of emergency after algal toxins (*microcystin*) were found in the City of Toledo's water supply at levels exceeding the safety threshold for drinking water, which sickened 110 people and left approximately 500,000 people without drinking water for three days.[26]

Toxic and non-toxic HABs in coastal waters also pose a threat to seawater desalination plants in terms of the risk of neurotoxins and skin-irritating compounds in treated water, as well as the potential damage to plant operations from compounds that clog intake filters and foul membrane surfaces.[27]

Photo by iStock.com/fizkes

Actions to Address HABs

To better understand the threat of HABs, scientists across multiple disciplines such as oceanography, ecology, engineering, economics, and human health are actively investigating how and why blooms arise, including the causes for toxicity and how toxins are distributed through food webs. By enhancing our collective knowledge about HABs, researchers can inform more effective mitigation strategies and communities can improve the way they cope and respond to the adverse effects of dangerous blooms.

Environmental Monitoring

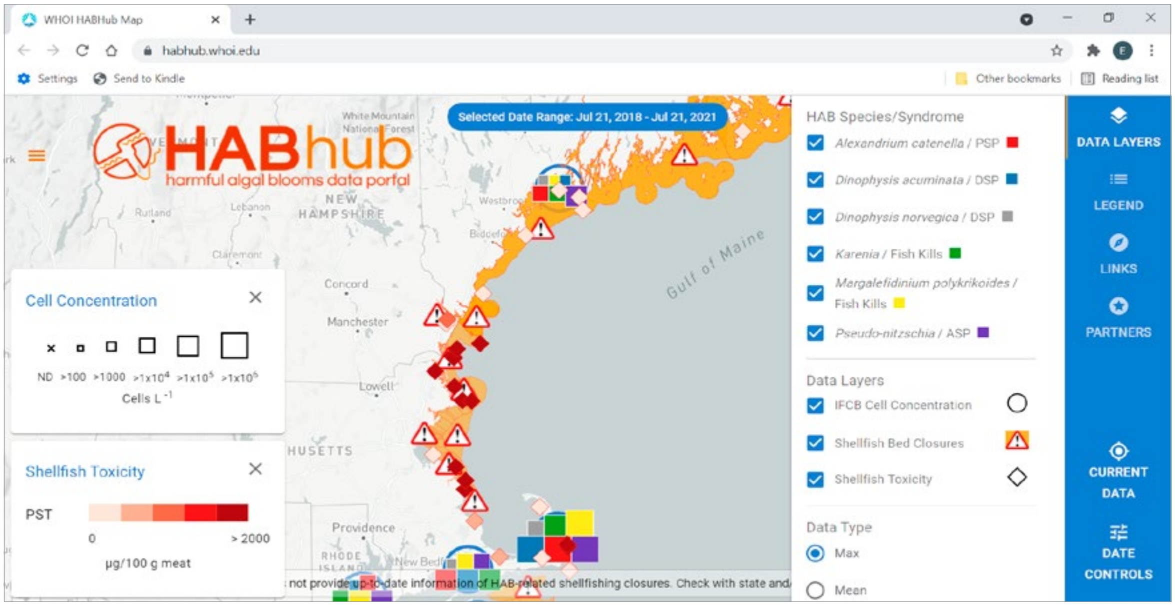
While researchers are aware of the many factors that contribute to HABs, how these factors come together to create a bloom of a specific species of algae is not well understood in many regions.[28] Water quality monitoring is a widespread approach that scientists are using to answer this question and many others about the environmental conditions, processes, and triggers that not only spur the growth of HABs but lead to the development of harmful toxins.

Advanced monitoring tools include sensors, instruments, and real-time technologies for measuring light, temperature, chlorophyll, dissolved organic material, nutrient concentrations, and more. Data that is collected and analyzed may provide deeper insights on the environmental conditions driving HAB development and growth, including duration and toxicity levels. Novel monitoring technologies are being deployed in monitoring efforts to directly count HAB cells or measure their toxins in situ and transmit the data to shore.[29] When used concurrently with water quality instruments or measurements, these technologies allow scientists to provide early warning of blooms, as well as to identify conditions that might be indicative of HAB development—allowing state agencies, municipalities, and water resource managers to make more informed decisions and develop effective strategies for managing HABs.

WHOI scientists developed a powerful new instrument called the Imaging FlowCytobot (IFCB), an underwater microscope that uses a combination of flow cytometric and video technology to capture high resolution images of suspended particles in real-time.[30] The images, collected at a rate of 8-10 per second, are transmitted via the web to computers on land that use machine learning and image recognition software to rapidly identify HAB species and abundance.[31] Another autonomous instrument known as the Environmental Sample Processor (ESP) uses molecular biology techniques to identify and quantify target HAB species, allowing scientists to better measure toxin concentrations.

Scientists can also use a multi-corer to collect individual sediment core samples from the ocean bottom, which are then examined for the presence of seed-like cysts—an important life stage of some HAB species.[32] In some regions, such as the Gulf of Maine, data on the distribution and abundance of *Alexandrium* cysts are used in forecasting models to predict bloom intensity.

Shellfish farmer Dan Ward pulls up an Imaging FlowCytobot (IFCB) from one of his shellfish beds in Falmouth, Massachusetts. The instrument takes up to 12 photos of plankton cells per second, and uses specialized algorithms to identify harmful algal species that produce toxins. (Photo by Daniel Hentz, © Woods Hole Oceanographic Institution)



Monitoring data from the HAB Observing Network-New England (HABON-NE) are presented in interactive maps and plots. Shellfish farmers, resource managers, and others can access the information from a central web portal, the WHOI HAB Hub.

HAB Forecasting and Prediction

Similar to a weather forecast, HAB forecasting is a critical strategy for both identifying the formation of blooms and providing early warning to state and local agencies to prepare. Compared to weather forecasts, the development of HAB forecast models presents a significant challenge as they require not only accurate simulation of water motion and properties, but often must also incorporate the dynamics of the HABs themselves.

HAB forecasting systems integrate remote sensing, meteorological data, and regional hydrographic data collected from monitoring programs to model and predict the timing and extent of blooms. For example, the Harmful Algal Bloom (HAB) Operational Forecast System, developed by the National Oceanic and Atmospheric Administration (NOAA), relies on satellite imagery, field observations, models, public health reports, and buoy data to identify whether a bloom of algae is likely to contain a toxic species, where it is, how big it is, where it's headed, and if it could become more severe in the near future.[33]

Another example is the Algal Bloom Monitoring System from the National Centers for Coastal Ocean Science (NCCOS), which delivers a suite of bloom detection products in the form of geographic based images for use in locating, monitoring and quantifying algal blooms in coastal and lake regions of the U.S.[34] A major development that shows promise to improve HAB forecast models is the implementation of a National HAB Observing Network (NHABON),[35] envisioned as a network of regional instrument arrays capable of collecting in situ data on HABs and important contextual parameters. As scientists collect more data and incorporate those into their models, they will be better able to forecast future outbreaks, much as is done with meteorological data assimilated into weather forecast models.[36]

Mitigation Strategies

Several mitigation strategies are being tested and developed to address HAB outbreaks once they occur. One approach involves spraying a modified clay mineral over an active bloom. In the water, the clay particles bond together and combine with other particles, including HAB cells, as they begin to sink. This process, known as flocculation, is commonly used in drinking water and wastewater treatment to remove contaminants. Clay can remove not only the HAB cells, but 70% or more of some HAB toxins.[37] The flocculation and sinking process can rupture and kill the algae cells or destroy them as they are carried to the seafloor and buried in sediments.[38]

Mineral clay dispersal is used in other countries and is currently being investigated in the ocean waters off the west coast of Florida, where large blooms of the toxic alga *Karenia brevis* are nearly annual events. Two WHOI-led projects are underway in this regard, one funded by the state of Florida through the Mote Marine Laboratory Red Tide Mitigation and Technology Development Initiative, and the second by NOAA's Prevention, Control, and Mitigation of HABs program (PCMHAB).

Another mitigation approach being investigated includes injecting bloom-affected waters with nano-sized bubbles filled with ozone, which destroys HAB cells. Artificial reefs are also being evaluated as a solution for controlling red tides. Working with artificial reef designer Ocean Habitats, the City of Bradenton Beach, Florida, installed more than a dozen miniature artificial reefs. Shellfish and other organisms on the reefs filter water as they feed, and in the process, sift out red tide cells and impair the bloom's ability to proliferate.[39]

Schematic diagram of the processes involved in HAB control using clay flocculation. Clay is sprayed over the water surface where it removes HAB cells through flocculation with the tiny clay particles. This "floc"then sinks, aggregating with other flocs in such a way that additional cells are captured by the net of material as it sweeps through the water column. (Illustration by Natalie Reiner, © Woods Hole Oceanographic Institution)

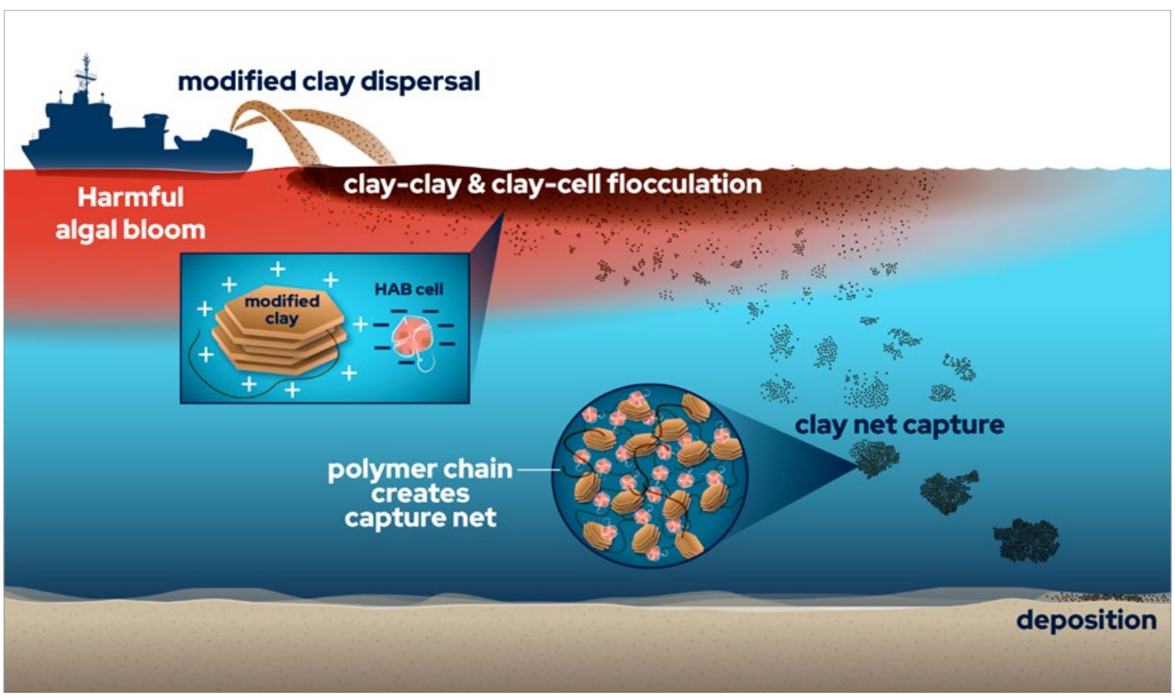


Photo by Matthew Barton, © Woods Hole Oceanographic Institution

HAB Research Efforts at WHOI

WHOI is actively engaged in ongoing work to gain a more thorough understanding of the HAB problem for better managing and mitigating the risks that they pose. Included below are some of WHOI's active research projects.

HARMFUL ALGAL BLOOM COMMUNITY TECHNOLOGY ACCELERATOR

To develop effective strategies and technologies for monitoring and communicating the risk of algal toxins to human and ecosystem health, a WHOI-based group is working with several research institutions and California universities to help deploy IFCBs off the California coast to image, identify, and count plankton species in the water and report data to shore in real-time.

VALUE OF THE PACIFIC NORTHWEST HAB FORECAST

Led by scientists at WHOI's Marine Policy Center in collaboration with the University of Washington, Washington State Department of Fish and Wildlife, and the Oregon Department of Fish and Wildlife, this project will estimate the economic benefits of the Pacific Northwest HAB Bulletin, a forecasting tool that helps managers decide how and when to open and close shellfisheries along the Washington and Oregon coasts that have been adversely affected by marine algae that produce the toxin domoic acid.

ASSESSING SOCIETAL IMPACTS OF HARMFUL MACROALGAE BLOOMS IN THE CARIBBEAN

WHOI's Marine Policy Center is working with the University of Rhode Island to examine how periodic blooms of free-floating Sargassum and subsequent mitigation efforts in the Caribbean affect social resilience across multiple dimensions, including economic impacts, human wellbeing, local ecological knowledge, and individual attitudes, values, and behaviors.

Other projects are focused on the tropical fish poisoning problem called ciguaterra which occurs when toxic microscopic algae attached to seaweeds are then eaten by small fish which are in turn eaten by the larger carnivores, with the toxin transferred to and accumulating within those top levels. Recent findings include the discovery that among the multiple algal species that can produce ciguatoxin, some are "superbugs" that can be as much as 1000 times more toxic than other species. This work highlights the need for new technologies that allow scientists to label the highly toxic species so they can be easily distinguished from harmless forms, thereby focusing management efforts on those that represent the most significant risk, even at very low cell concentrations.

TROPHIC TRANSFER AND EFFECT OF HAB TOXINS IN ALASKAN MARINE FOOD WEBS

The goal of this project—co-led by WHOI senior scientist Don Anderson in collaboration with NOAA and federal, state and tribal organizations—is to model the movement and impacts of HAB toxins in Arctic and Subarctic food webs and reveal the extent of their impacts on human and natural ecosystems.

Additionally, a number of research projects are being conducted through the Woods Hole Center for Oceans and Human Health in the areas of HAB dynamics related to physiological and behavioral plasticity in natural populations; how climate variability influences HAB dynamics; the effects of early-life exposure to HAB toxins on neurobehavioral changes; and preventing human exposure to HAB toxins by improving community HAB knowledge and awareness and fostering collaboration.

ONLINE RESOURCES ARE AVAILABLE

HABs are a significant global problem and are growing worse in some regions. However, new technologies and approaches are being developed which are leading to improved management and mitigation. For more information on HABs, several useful online resources are available. These include:

- *The U.S. National Office for Harmful Algal Blooms*
- *Woods Hole Center for Oceans and Human Health*
- *Anderson Lab at WHOI*
- *The National Oceanic and Atmospheric Administration*

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