HARRNESS

2024-2034

Harmful Algal Research and Response

A NATIONAL ENVIRONMENTAL SCIENCE STRATEGY

AN UPDATED COMMUNITY VISION ON HARMFUL ALGAE IN THE US

US National Office for Harmful Algal Blooms
Woods Hole Oceanographic Institution

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Drone view of cyanobacterial bloom (*Dolichospermum*, *Microcystis*) on the Chowan River, NC, during August 2020. No digital adjustment. *Photo credit: Hans Paerl.*

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The views expressed in these proceedings are those of participating scientists under their responsibilities and do not necessarily reflect the official policy of their organizations. Chapter 1 has been peer reviewed and approved for publication consistent with USGS Fundamental Science Practices (https://pubs.usgs.gov/circ/1367/). The contributors recognize that these recommendations comprise guidance on initial next steps in this effort. Nevertheless, they should be sufficient for interested institutions and stakeholders to articulate more detailed organizational collaborations and research priorities leading to the development of accurate and informative regional or national estimates of the effects of HABs.

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The literature cited in this report includes references in preference order from US-based researchers only, US and international collaborators, and non-US researchers where seminal findings are relevant to US HAB species. These references serve as examples but are not exhaustive since the exponential growth in publications is too vast for the scope of this document.

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LIST OF ACRONYMS

ACT	Alliance for Coastal Technologies
AERONET-OC	Aerosol Robotic Network
AI	Artificial intelligence
ART	Analytical Response Team
ASP	Amnesic Shellfish Poisoning
ASTHO	Association of State and Territorial Health Officials
ASV	Autonomous surface vehicles
AUV	Autonomous underwater vehicle
AWWA	American Water Works Association
AZP	Azaspiracid Shellfish Poisoning
BMP	Best Management Practices
BTX	Brevetoxins
C-HARM	California Harmful Algae Risk Mapping
CDC	Centers for Disease Control and Prevention
cELISA	Competitive Enzyme-Linked Immunosorbent Assay
CME	Continuing Medical Education
CP or CFP	Ciguatera (Fish) Poisoning
CyAN	Cyanobacteria Assessment Network
CYN	Cylindrospermopsin
DA	Domoic Acid
DNA	Deoxyribonucleic Acid
DO	Dissolved Oxygen
DSP	Diarrhetic Shellfish Poisoning
DTXs	Dinophysistoxins
ECOHAB	Ecology and Oceanography of Harmful Algal Blooms Research Program (NOAA)
ELISA	Enzyme-Linked Immunosorbent Assay
EPA	US Environmental Protection Agency
ESP	Environmental Sample Processor
FAIR	Findable, Accessible, Interoperable, Reusable
FDA	US Food and Drug Administration
FIFRA	Federal Insecticide Fungicide and Rodenticide Act
FISH	Fluorescence In Situ Hybridization
FWS	US Fish and Wildlife Service
GIS	Geographic Information System
GOMA	Gulf of Mexico Alliance
GOOS	Global Ocean Observing System
HA	Harmful Algae
HAB	Harmful Algal Bloom
HAB ER	Harmful Algal Bloom Event Response Program (NOAA)
HABHRCA	Harmful Algal Bloom and Hypoxia Research and Control Act
HAEDAT	Harmful Algae Event Database
HARR-HD	Harmful Algal Research and Response: Humans Dimensions

HARRNESS	Harmful Algal Research and Response: A National Environmental Science Strategy
HHENS	HABs and Hypoxia Events of National Significance
HPLC	High-performance Liquid Chromatography
HRMS	High-resolution Mass Spectrometry
ICES	International Council for the Exploration of the Sea
ICHA	International Conference on Harmful Algae
IFCB	Imaging FlowCytobot
IOC	International Oceanographic Commission
IODE	International Oceanographic Data and Information Exchange
IOOS	Integrated Ocean Observing System
ISSC	Interstate Shellfish Sanitation Conference
ITRC	Interstate Technology and Regulatory Council
IWG-HABHRCA	Interagency Working Group- Harmful Algal Bloom and Hypoxia Research and Control Act
LC-MS	Liquid Chromatography with Mass Spectroscopy
LEK	Local Ecological Knowledge
MC	Microcystin
MERHAB	Monitoring and Event Response for Harmful Algal Blooms Research Program (NOAA)
NANOOS	Northwest Association of Networked Ocean Observing Systems
NASA	National Aeronautics and Space Administration
NCCOS	National Centers for Coastal Ocean Science (NOAA)
NEPHT	National Environmental Public Health Tracking (CDC)
NEIWPCC	New England Interstate Water Pollution Control Council
NHABON	National HAB Observing Network
NHC	National HAB Committee
NIEHS	National Institute of Environmental Health Sciences
NMFS	National Marine Fisheries Service (NOAA)
NOAA	National Oceanic and Atmospheric Administration
NORS	National Outbreak Reporting System (CDC)
NPS	National Park Service
NRC	National Research Council
NRCS	Natural Resources Conservation Services (USDA)
NSF	National Science Foundation
NSP	Neurotoxic Shellfish Poisoning
OA/DTXs	Okadaic Acid/Dinophysistoxins
OBIS	Ocean Biodiversity Information System
OEHHA	Office of Environmental Health and Hazard Assessment (California)
OHHABS	One Health Harmful Algal Bloom System (CDC)
OLCI	Ocean Land Color Instrument
PAR	Photosynthetically Active Radiation
PCMHAB	Prevention, Control and Mitigation of Harmful Algal Blooms Research Program (NOAA)

PCR	Polymerase Chain Reaction
PHYSS	Programmable Hyperspectral Seawater Scanner
PICES	North Pacific Marine Science Organization (Pacific version ICES)
PIRE	Partners in Research and Education (NSF)
PSP	Paralytic Shellfish Poisoning
PSTs	Paralytic Shellfish Toxins
QA/QC	Quality Assurance/Quality Control
QARTOD	Quality Assurance for Real Time Data Program
qPCR	Quantitative Polymerase Chain Reaction
R&D	Research & Development
RA	Regional Associations
RDDTT	Research, Development, Demonstration, and Technology Transfer
RL	Readiness Level
RNA	Ribonucleic Acid
ROMS	Regional Ocean Modeling Systems
ROV	Remotely Operated Vehicle
SBIR/SBTT	Small Business Innovation Research/Small Business Technology Transfer
SHA	Sandwich Hybridization Assay
STLT	State, Tribal, Local, or Territorial
STX	Saxitoxin
TAC	Technical Advisory Committee
TEK	Traditional Ecological Knowledge
TOAST	Texas Observatory for Algal Succession Time Series
UAV	Unoccupied Aerial Vehicle
UCMR 4	Unregulated Contaminant Monitoring Rule 4 (EPA)
UME	Marine Mammal Unusual Mortality Event Program
USACE	US Army Corps of Engineers
USD	US dollars
USGS	US Geological Survey
WGHABD	Working Group on Harmful Algal Bloom Dynamics
WRF	Water Resources Foundation

EXECUTIVE SUMMARY[1]

Harmful and toxic algal blooms (HABs) are a well-established and severe threat to human health, economies, and marine and freshwater ecosystems on all coasts of the United States and its inland waters. HABs can comprise microalgae, cyanobacteria, and macroalgae (seaweeds). Their impacts, intensity, and geographic range have increased over past decades due to both human-induced and natural changes. In this report, HABs refers to both marine algal and freshwater cyanobacterial events.

This Harmful Algal Research and Response: A National Environmental Science Strategy (HARRNESS) 2024-2034 plan builds on major accomplishments from past efforts, provides a state of the science update since the previous decadal HARRNESS plan (2005-2015), identifies key information gaps, and presents forward-thinking solutions. Major achievements on many fronts since the last HARRNESS are detailed in this report. They include improved understanding of bloom dynamics of large-scale regional HABs such as those of *Pseudo-nitzschia* on the west coast, *Alexandrium* on the east coast, *Karenia brevis* on the west Florida shelf, and *Microcystis* in Lake Erie, and advances in HAB sensor technology, allowing deployment on fixed and mobile platforms for long-term, continuous, remote HAB cell and toxin observations. New HABs and impacts have emerged. Freshwater HABs now occur in many inland waterways and their public health impacts through drinking and recreational water contamination have been characterized and new monitoring efforts have been initiated. Freshwater HAB toxins are finding their way into marine environments and contaminating seafood with unknown consequences. Blooms of *Dinophysis* spp., which can cause diarrhetic shellfish poisoning have appeared around the US coast, but the causes are not understood. Similarly, blooms of fish- and shellfish-killing HABs are occurring in many regions and are especially threatening to aquaculture. The science, management, and decision-making necessary to manage the threat of HABs continue to involve a multidisciplinary group of scientists, managers, and agencies at various levels. The initial HARRNESS framework and the resulting National HAB Committee (NHC) have proven effective means to coordinate the academic, management, and stakeholder communities interested in national HAB issues and provide these entities with a collective voice, in part through this updated HARRNESS report.

Congress and the Executive Branch have supported most of the advances achieved under HARRNESS (2005-2015) and continue to make HABs a priority. Congress has reauthorized the Harmful Algal Bloom and Hypoxia Research and Control Act (HABHRCA) multiple times and continues to authorize the National Oceanic and Atmospheric Administration (NOAA) to fund and conduct HAB research and response, has given new roles to the US Environmental Protection Agency (EPA), and required an Interagency Working Group on HABHRCA (IWG HABHRCA). These efforts have been instrumental in coordinating HAB responses by federal and state agencies. Initial appropriations for NOAA HAB research and response decreased after 2005, but have increased substantially in the last few years, leading to many advances in HAB management in marine coastal and Great Lakes regions. With no specific funding for HABs, the US EPA has provided funding to states

1 All committee members, contributors and reviewers contributed to the formation of the Executive Summary, with the exception of Keith Bouma-Gregson (USGS) and Jennifer Graham (USGS).

through existing laws, such as the Clean Water Act, Safe Drinking Water Act, and to members of the Great Lakes Interagency Task Force through the Great Lakes Restoration Initiative, to assist states and tribes in addressing issues related to HAB toxins and hypoxia. The US EPA has also worked towards fulfilling its mandate by providing tools and resources to states, territories, and local governments to help manage HABs and cyanotoxins, to effectively communicate the risks of cyanotoxins and to assist public water systems and water managers to manage HABs. These tools and resources include documents to assist with adopting recommended recreational criteria and/or swimming advisories, recommendations for public water systems to choose to apply health advisories for cyanotoxins, risk communication templates, videos and toolkits, monitoring guidance, and drinking water treatment optimization documents.

Beginning in 2018, Congress has directed the U.S. Army Corps of Engineers (USACE) to develop a HAB research initiative to deliver scalable HAB prevention, detection, and management technologies intended to reduce the frequency and severity of HAB impacts to our Nation's freshwater resources. Since the initial HARRNESS report, other federal agencies have become increasingly engaged in addressing HABs, a trend likely to continue given the evolution of regulations (e.g., US EPA drinking water health advisories and recreational water quality criteria for two cyanotoxins), and new understanding of risks associated with freshwater HABs. The NSF/NIEHS Oceans and Human Health Program has contributed substantially to our understanding of HABs. The US Geological Survey, Centers for Disease Control and Prevention, and the National Aeronautics Space Administration also contribute to HAB-related activities.

In the preparation of this report, input was sought early on from a wide range of stakeholders, including participants from academia, industry, and government. The aim of this interdisciplinary effort is to provide summary information that will guide future research and management of HABs and inform policy development at the agency and congressional levels. As a result of this information gathering effort, four major HAB focus/programmatic areas were identified: 1) **Observing systems, modeling, and forecasting;** 2) **Detection and ecological impacts**, including genetics and bloom ecology; 3) **HAB management** including prevention, control, and mitigation, and 4) **Human dimensions**, including public health, socio-economics, outreach, and education. Focus groups were tasked with addressing a) our current understanding based on advances since HARRNESS 2005-2015, b) identification of critical information gaps and opportunities, and c) proposed recommendations for the future.

The vision statement for HARRNESS 2024-2034 has been updated, as follows: *"Over the next decade, in the context of global climate change projections, HARRNESS will define the magnitude, scope, and diversity of the HAB problem in US marine, brackish and freshwaters; strengthen coordination among agencies, stakeholders, and partners; advance the development of effective research and management solutions; and build resilience to address the broad range of US HAB problems impacting vulnerable communities and ecosystems."*

This will guide federal, state, local and tribal agencies and nations, researchers, industry, and other organizations over the next decade to collectively work to address HAB problems in the United States.

Key Priorities and Recommendations

1. OBSERVING SYSTEMS, MODELING, AND FORECASTING

Key priorities identified under this focal area include the development of more flexible and lower-cost sensor technologies (validated against higher-cost systems to determine any potential loss in data resolution) for HAB species and their toxins, and synchronous alignment of contextual environmental data streams (e.g., cell and toxin concentrations with atmospheric/water column data) at local and regional scales to better match the input needs of forecasting/early-warning models. Another key priority is the development of shared national capacity (informed by regional investments) for standardization of sensor deployment practices and data processing, visualization, and dissemination. Indeed, it was recommended that an integrated US National HAB Observing Network (NHABON) be implemented across the freshwater-to-marine continuum. NOAA is leading the effort to define NHABON and secure operational funding to sustain regional ocean and Great Lakes observing and early warning demonstration projects in collaboration with the Integrated Ocean Observation System (IOOS) Regional Associations. Follow-on efforts to adapt NHABON for observation and early warning of HABs in inland waters are needed.

Such advances in monitoring, modeling, and forecasting must be sustained with programmatic support at state and federal levels with multiagency investment and coordination. These efforts should incorporate evaluation of model and forecast effectiveness and relevance to stakeholders so real-time adjustments using assimilated in situ sensor data can better serve those needs. New sensor technologies must be transitioned from R&D to operations where relevant, and the output of models needs to be made more accessible and understandable to users. Finally, in situ observing data for HAB cells and their toxins should be incorporated into current ecosystem and food web models, and the community should work towards inclusion of molecular data that reveal species-specific dynamics. The ultimate goal is to predict HAB impacts with sufficient lead times such that prevention, control, and mitigation strategies can be implemented effectively.

2. DETECTION AND ECOLOGICAL IMPACTS OF HAB CELLS AND TOXINS, INCLUDING GENETICS AND BLOOM ECOLOGY

Improvement in the detection of known and newly discovered HAB species and toxins requires continued support for assay development to ensure rapid turnaround, robust sensitivity, specificity, user utility, and reduced cost. These approaches should also allow for multiplexing where possible, in vitro toxin screening, and near real-time results to support management decisions, as well as methods standardization. To that end, continuation and expansion of expertise and training opportunities (in traditional and emerging techniques) are needed for taxonomists, chemists, toxicologists, and molecular biologists.

Basic research needs to span a full range of topics, from cellular-level processes to ecosystem-level interactions. Full advantage should be taken of next-generation molecular tools, e.g., full genome and individual gene sequencing of HAB species to identify toxin synthesis pathways, and proteomics/metabolomics techniques to enhance understanding of physiological processes. Application of 'omics' technologies will advance our understanding of gene expression, algal physiological responses, and synergistic impacts on HAB-impacted organisms as a function of environmental variables, including co-occurring pollutants and stressors. Additional research is needed on the fate, transfer, biotransformation, and toxicity of emerging toxins (especially those that are tumor-promoting or lead to chronic effects) and their routes of exposure, persistence, and transport in aquatic ecosystems. Data from laboratory-based animal exposure studies should be complemented with data generated from wildlife. This can lead to better understanding of the consequences of human exposure to HABs via various routes of exposure (including drinking water), development of exposure guidance for drinking and recreational waters as well as fish and shellfish harvesting, and the ability to predict biotic responses to toxins in the environment. Epidemiology studies involving human exposure to HAB toxins are needed. Additionally, cell and toxicity thresholds and their regional differences remain to be characterized for several HAB toxins and secondary metabolites.

Sustainable long-term monitoring of HABs, their toxins and associated environmental parameters is needed to identify regional and local drivers, thereby enhancing predictive capabilities. Our current knowledge of the diversity of harmful algal species and their impacts throughout bloom initiation, maintenance and termination highlights the need to assess biological interactions at the strain, species, and community levels. Studies on the dispersal and transport of bottom-dwelling (benthic) algae as well as transient, resting life cycle stages in bottom sediments are needed to provide a better understanding of bloom dynamics. The roles of competitors, parasites, viruses, and bacteria during various HAB stages should be examined under natural field conditions, thus requiring holistic multivariate approaches and modeling.

The need for centralized production and dissemination of toxin analytical standards and reference materials (from US and international sources), and establishment of a national repository for curated and archived genomic DNA for use by researchers, was recognized by HARRNESS 2005-2015, and it continues to be a high priority over the next decade to sustain all efforts listed above. These initiatives will involve: 1) use of photobioreactor technology to produce sufficient algal biomass for toxin extraction; 2) provision of toxin mixtures in suitable matrices; 3) development of best practices for use of reference materials; and 4) a centralized listing of sources and expertise that can provide guidance on use of these materials for specific applications.

3. HAB MANAGEMENT AND EVENT RESPONSE: PREVENTION, CONTROL, AND MITIGATION

For HAB prevention (longer-term actions taken to reduce the incidence and extent of HABs prior to their initiation), key priorities include the reduction of nutrients (land- and waterbody-based) and limitation of cell dispersal and proliferation. Assessment of the most effective nutrient reduction approaches using modeling, watershed-scale monitoring, and improved reduction of point (e.g., wastewater treatment) and nonpoint sources (e.g., atmospheric deposition, agricultural and urban runoff) are recommended. To address HAB dispersal and proliferation, feasible methods must be identified at appropriate spatial scales such as the enhanced restoration of grazer populations and/or implementation of ballast water treatment. Further, enhancing communication and education will prevent the anthropogenic actions that may lead to HABs and minimize the impacts (especially to vulnerable communities). Strategies for the prevention of HABs will also need to incorporate the predicted effects of climatic changes into their assessments.

Control of HABs (typically short-term actions to destroy HAB cells and/or their toxins) is especially challenging and will require increased federal interagency and state-federal cooperation, as well as independent evaluation of control strategies. The following aspects need to be addressed: 1) assessment of broader ecological impacts of control measures, 2) evaluation of existing regulatory barriers for field testing of control strategies, streamlining of their approval, and identification of suitable test areas to evaluate novel control technologies, and 3) determination of the cost effectiveness, scalability, and feasibility of control measures.

The risks and costs of HAB impacts, including socioeconomic impacts, should be weighed against those of various management and event response strategies. Specific tools are needed to protect human health, as well as to safeguard our pets, domestic livestock, farmed fish and shellfish, and wildlife by enhancing the surveillance and development of biomarkers and therapeutics for toxin-associated illnesses, and by educating growers and veterinarians. It is important to optimize drinking water treatment for the removal of cyanotoxins and to develop seafood processing methods to reduce toxin concentrations to safe levels.

A comprehensive National HAB Event Response (ER) program is needed to realize recommendations from the last HARRNESS and the 2008 HAB Research, Development, Demonstration, and Technology Transfer (RDDTT) National Workshop Report. Monitoring and Event Response for HABs (MERHAB) and Rapid HAB Event Response (HAB-ER) need to be developed for inland freshwater bodies to expand regional and local HAB mitigation and response capacity. Management of freshwater HABs imposes new challenges, perhaps requiring use of monitoring systems adapted to a smaller scale (e.g., drones) in addition to remote satellites, development of appropriate action limits to initiate toxin analysis, and establishment of guidance levels for toxins in drinking and recreational waters. Rapid tests for cell/toxin detection are needed for use by managers and community groups at remote marine locations, including offshore federal waters as aquaculture activities expand. Resource managers should be engaged wherever possible, e.g., via participation in conferences and proposal formulation. Continued federal coordination through the IWG-HABHRCA and other means is key to funding critical cross-agency, cross-disciplinary, and comparative research studies required to develop the understanding needed to determine how drivers like changes in climate will impact HABs, especially the interaction between climate and anthropogenic drivers. Federal leadership is also critical to sustain successful regional HAB observing forecasting pilot programs with operational funding through new programs like the proposed National HAB Observing Network (NHABON). At the domestic level, support of regional efforts and coordination of cross-agency research funding is sorely needed, e.g., via implementation of NHABON. In addition, the US HAB community should also continue to expand binational cooperation with border nations and maintain leadership on various international bodies promoting scientific and management exchange such as the Harmful Algal Bloom and GlobalHAB Programmes of the UNESCO Intergovernmental Oceanographic Commission (IOC), and the newly formed UN Decade Harmful Algal Bloom Solutions (HAB-S) Programme.

4. HUMAN DIMENSIONS, INCLUDING PUBLIC HEALTH AND TRIBAL IMPACTS, SOCIOECONOMICS, AND OUTREACH AND EDUCATION

While a considerable amount is known about the adverse health effects of fish and shellfish contamination by marine toxins, much less is known about the acute effects from exposure to freshwater HABs or of the chronic effects from both marine and freshwater toxins in food, drinking and recreational waters, and aerosols. Additional epidemiological and toxicological studies can provide information such as biomarkers of exposure and biological effects to help people better prepare for and respond to HABs. The most informative studies will include community groups with potentially different susceptibility to HAB toxins. For freshwater systems, additional studies could be designed to provide data needed to support enactment of formal regulations for harvesting animals and plants potentially affected by cyanotoxins, establishment of federal water quality criteria, and assessment of water body impairment. Increased interagency coordination in conducting and funding research is important to overcome institutional and jurisdictional hurdles and to improve HAB programs.

Monitoring programs could encompass interconnected freshwater bodies and the freshwater-to-marine continuum to include cyanobacteria. More information is needed about the transport mechanisms of planktonic and benthic cyanobacterial HABs, and the dynamics, toxin production, and life cycles of cyanobacteria that form benthic and buoyant mats. Studies are also needed to understand how the increasing frequency and intensity of storms, droughts, hurricanes, marine and inland heat waves (and other hydrological events) affect HAB events, human and animal exposures, and health impacts.

Increased emphasis should be given to: 1) assessing the socioeconomic effects of HAB events and including those impacts in forecasts, 2) establishing federal research programs dedicated to evaluating societal impacts, and 3) using of community-level surveys to improve estimates of the economic toll of HABs in the US. This should include direct HAB-associated losses and the costs of responding to them. A key priority is to assess and build community resilience to future HABs and, in doing so, consider the cumulative effects of these disturbances with those resulting from natural events or human activities.

Many HAB-related needs of specific communities (e.g., tribal, indigenous communities), such as information on potential contamination of waters used for recreation and subsistence harvesting, have not been adequately addressed. The needs of these specific communities could be identified using focus groups and other methods to gather qualitative data. Follow-on action items could include activities such as: 1) creation of a tribal HAB data storage platform, 2) development of regional, tribal-led monitoring programs in marine and freshwaters, 3) inclusion of mammalian tissues in toxin monitoring programs, 4) integration of local/traditional tribal ecological knowledge into long-term monitoring, and 5) establishment of biotoxin laboratories to support tribal subsistence and commercial fisheries. The ability to provide communities with information about higher trophic species most affected by a HAB event could be supported by toxin and food web studies and improved food web models.

Enhancing efforts to develop outreach and education approaches underpin all efforts mentioned above. This relies on increasing awareness of HABs and their health and ecological effects. Community engagement should tailor outreach efforts to specific target groups such as shellfish growers, pelagic and coastal fisheries, and other industry sectors; the medical community, including tribal and indigenous health care providers; and the public. Ultimately, the goal is to better translate and communicate scientific information and the risks of HAB exposure to a highly diverse audience using multiple platforms, including social media. Further, the need for training of personnel (tribal leaders, community scientists [building on the National Phytoplankton Monitoring Network], local managers, industry, etc.) in the use of state-of-the-art field-based cell and toxin detection methods is recognized. This will serve to directly engage these groups with understanding HAB events and the environmental drivers that support them.

Common priorities that crosscut the four thematic groups were identified (see Table A). Addressing the identified priorities and ensuring the effective management of HABs and their toxins will require increased interagency cooperation at local, state, federal, and international levels. HAB events are extremely complex. They require a multidisciplinary approach for their detection, prevention, control, and mitigation, and for communication about their risks. Identified needs include basic research into the causes and impacts of HABs; assay and sensor development; and monitoring, modeling, and forecasting activities that produce data to support public health decision-making and activities. Specific regional management needs also need to be addressed, along with networking of large data sets that engage and support the activities of a broad array of stakeholders. The aim of this contribution is to recognize all these aspects to guide development of strategies for preventing harm over the next decade of HAB events.

Table A. Common priorities of the four HARRNESS thematic groups

- Infrastructure for various forms of data and reference material curation and storage
- Integration and standardization of methods across freshwater and marine water bodies
- Further determination of regulatory concentration thresholds for cells/toxins
- Support for long-term (years), spatially diverse data series
- Efforts to address multiple co-occurring HABs
- Evaluation of HAB issues in the context of other stressors, most notably the accelerated changes in climate projected in the next decade
- Increased partnerships and coordination to fulfill these multifaceted efforts
- Address the interactive effects of natural, human-derived and climate drivers of HABs in the context of management.

Overall, addressing the above priorities and ensuring the effective management of HABs and their toxins will require increased interagency cooperation at the local, state, federal, and international levels, as well as sustained and commensurate funding effort.

BACKGROUND[2]

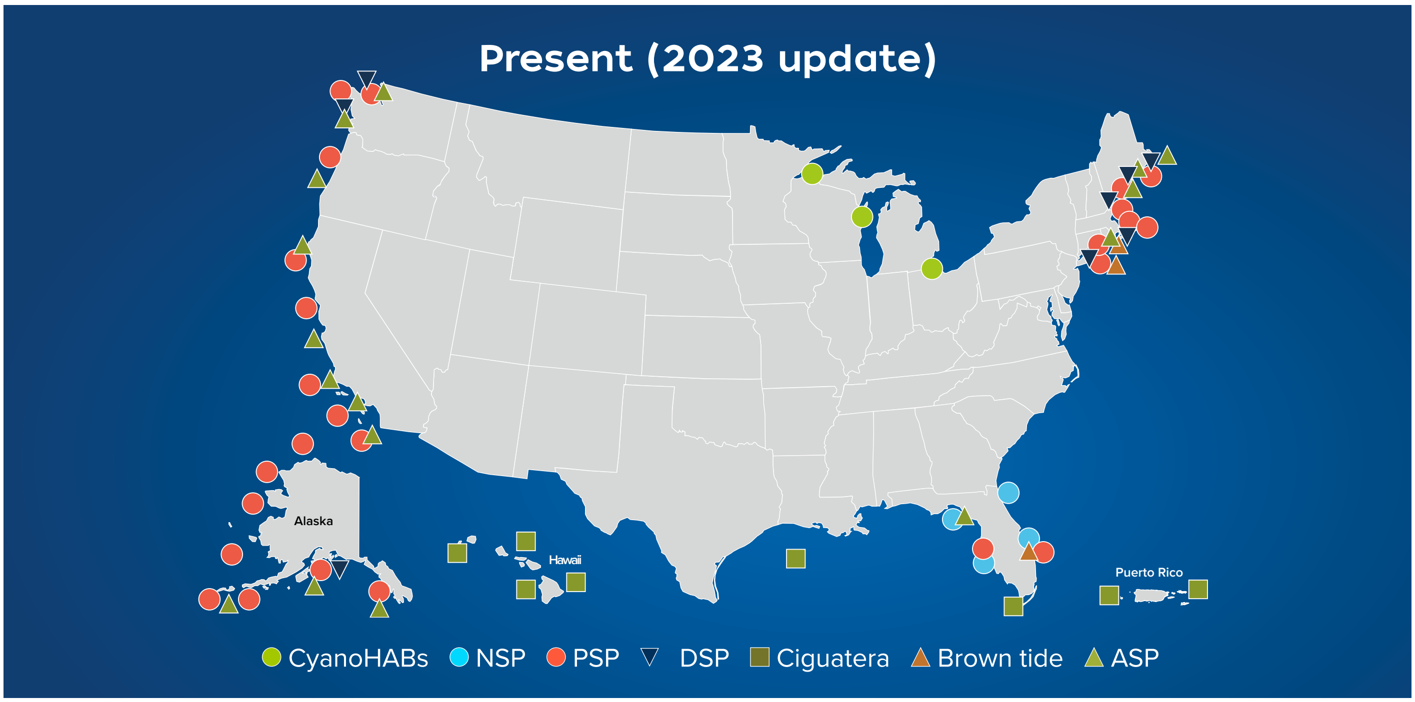
Scope of the Harmful Algae Problem

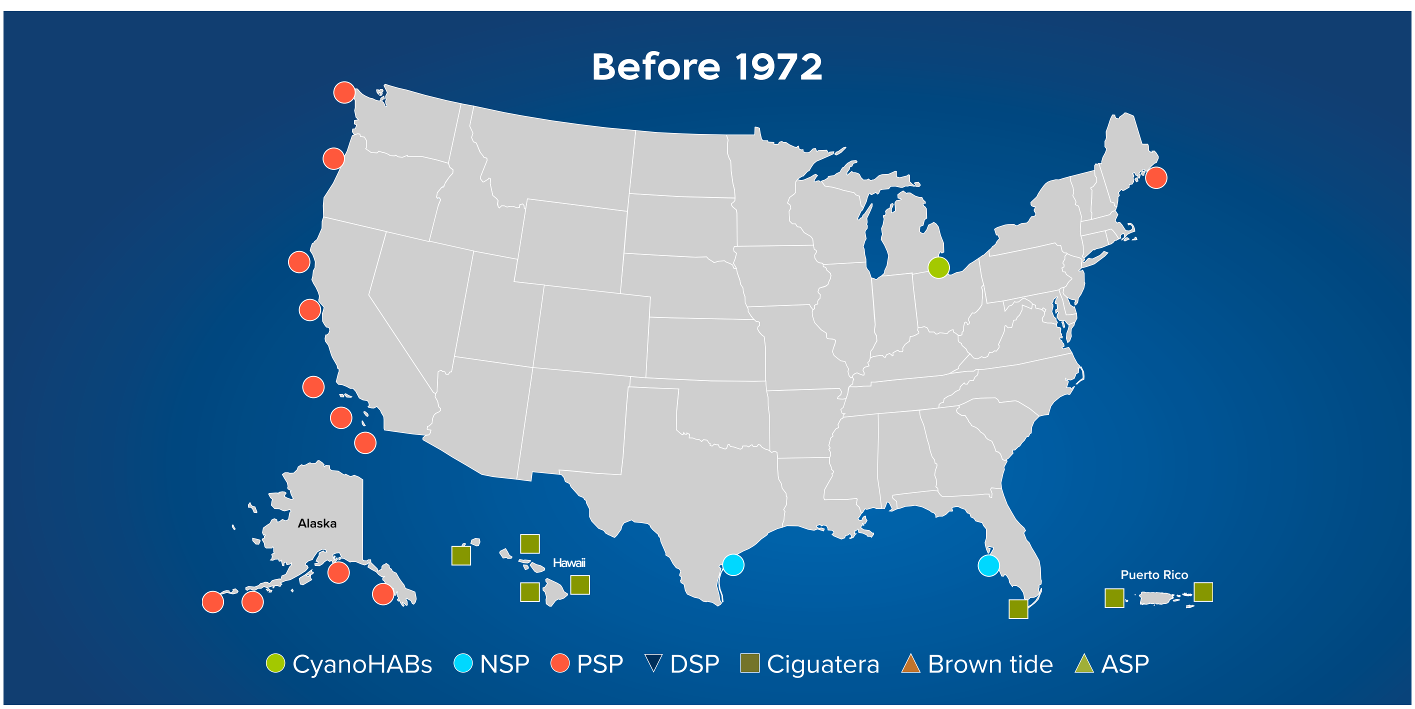
The geographic distributions of marine harmful algal blooms (HABs) have expanded in some regions over the past decades (Figs. A and B), attributable to multiple factors, including human activities, changes in climate, and natural processes. Though some perceived increases in HAB events have been the result of increased monitoring, in many regions of the world HABs have been increasing in frequency and intensity (Hallegraef et al., 2021). Freshwater HABs have also increased dramatically. HAB intensification in some regions of the world (Anderson et al., 2021; Hallegraeff et al., 2021) has impacted seafood imports to the US (including fishery and aquaculture products). The total quantity of seafood consumed in the US has increased since the 1990s, while per capita consumption has remained relatively constant (Shamshak et al., 2019). Although the US is heavily reliant on the importation of seafood, it is imperative to safeguard US fishery and freshwater and marine aquaculture products from the threat of algal toxins to allow its safe domestic consumption as well as export in the years ahead.

The broad scope of the HAB problem in marine and freshwaters is illustrated by the diversity of HABs highlighted in this report (Table B), which impact every state in the US through adverse effects on human health, fisheries, drinking water, food supplies, municipality functions, recreation, property values, and wildlife and domestic animal health and survival. HAB events affect public health, causing a variety of syndromes (Tables C, D) through multiple routes of biotoxin exposure (ingestion, dermal contact, and inhalation from aerosols) associated with multiple toxins (e.g., neurotoxic effects of paralytic shellfish toxins [PSTs], brevetoxins [BTXs], anatoxins, guanitoxin, ciguatoxins [CTXs], and domoic acid [DA]; gastrointestinal effects of diarrhetic shellfish poisoning [DSP]; hepatotoxic and carcinogenic effects of microcystins). Concerns regarding biotoxin accumulation in food supplies have prompted restrictions on fishery and shellfish harvesting, and disruptions to drinking water systems have been reported. Resulting economic losses affect multiple industries in freshwater, nearshore, and offshore waters and have recognized social consequences that can differentially affect high-risk communities (e.g., subsistence harvesters). HABs also compromise aquatic ecosystem health by reducing available dissolved oxygen (during bloom decomposition), attenuating light for photosynthesis in seagrasses and other submerged aquatic vegetation, and altering and impacting food webs through toxin production. The continued trend of increasing nutrient-impaired freshwaters, urbanization and exploitation of coastal nearshore and offshore waters, and the frequency and intensity of natural disasters such as hurricanes further exacerbates the problem.

2 All committee members, contributors and reviewers contributed to the formation of the Background, with the exception of Keith Bouma-Gregson (USGS) and Jennifer Graham (USGS).

Fig. A. and B. The distribution and frequency of harmful algal bloom events in the US as of 2023 (A, top panel) compared with records available prior to 1972 (B, bottom panel). Data are derived from HAEDAT - the IOC-ICES-PICES Harmful Algal Event database (http://haedat.iode.org/), which was originally established by the ICES-IOC Working Group on Harmful Algal Bloom Dynamics in the 1990s to compile bloom data from participating countries. As of 2023, the database contained over 970 records from the US. All reports entered into HAEDAT must meet a strict definition of a 'harmful algal event' in which the bloom must be associated with a negative impact or management action (e.g, toxin accumulation in seafood above levels considered safe for human consumption; damage to ecosystems, wildlife or domestic animals; socioeconomic impacts; precautionary closures of harvesting areas based on toxic phytoplankton cell numbers). See Anderson et al. (2021) for more information.





The scope of the HAB problem is exemplified by notable events and 'hotspots' occurring within US inland waterways and along its shores. For example, a massive 2015 *Pseudo-nitzschia* west coast bloom event led to a simultaneous shellfishery closure across three states (WA, OR, CA; McCabe et al., 2016). During the 2014 Toledo (Ohio) water crisis, a dense, toxic *Microcystis*-dominated bloom was transported from Maumee Bay towards the city water intake, prompting a two-day "do not drink" advisory due to concerns about the presence of potentially harmful levels of toxins in finished drinking water supplies (Alliance for the Great Lakes, 2019). In 2011, the Great Atlantic Sargassum Belt formed in the tropical Atlantic Ocean (Lapointe et al., 2018) and has remained an annual feature (except for 2013) that develops seasonally in response to increasing nitrogen availability in the Atlantic basin (Lapointe et al., 2021). It is now considered the largest algal bloom on our planet. Across the US, HAB activity continues to exhibit varying trends in frequency, intensity, and geographic range, and is often associated with the emergence of new species/strains and toxins (Anderson et al., 2021). Additionally, the socioeconomic impacts vary significantly depending on region(s) and sector(s) affected, species/toxins involved, and event size and duration (see Proc. of the Workshop on the Socio-economic Effects of HABs in the US, 2021).

Table B. Types of harmful algae that are considered in this report, including their habitat, impacts on human health, macrofauna, and/or the environment. Some examples of species are given; for toxic algae the human syndrome caused is indicated in parentheses. ASP: amnesic shellfish poisoning, PSP: paralytic shellfish poisoning, NSP: neurotoxic shellfish poisoning, DSP: diarrhetic shellfish poisoning. Some pelagic species can produce benthic cysts; cyanobacteria may also occur in brackish water.

HARMFUL ALGAL TYPE	HABITAT	EXAMPLES OF SPECIES	IMPACTS
ECOSYSTEM DISRUPTIVE	Marine-Planktonic	*Aureococcus anophagefferens* *Aureoumbra lagunensis*	Cause brown tide. Impact submerged aquatic vegetation (via light attenuation). Can be toxic to bivalve mollusks.
TOXIC	Marine-Planktonic	*Pseudo-nitzschia* spp. (ASP) *Alexandrium* spp. (PSP) *Karenia brevis* (NSP) *Dinophysis spp.* (DSP)	Toxigenic. Affect humans & can be toxic to macrofauna (shellfish, fish, birds, aquatic mammals, and domestic animals).
	Marine-Benthic	*Gambierdiscus* spp. (ciguatera) *Prorocentrum lima* (DSP)	
	Freshwater-Planktonic Cyanobacteria	*Microcystis aeruginosa* *Planktothrix* spp. *Raphidiopsis* spp.	
	Freshwater-Benthic Cyanobacteria	*Microcoleus*, *Phormidium*, and *Microseira*	
FISH-KILLING	Marine-Planktonic	*Karlodinium veneficum* *Heterosigma akashiwo* *Pfiesteria piscicida* *Chattonella marina* *Chaetoceros* spp. *Ceratium furca*	Toxic to fish (ichthyotoxic). *Pfiesteria* spp. can also affect human health. Cause gill damage via mechanical effects (spines).
HIGH-BIOMASS	Marine-Planktonic Microalgae Macroalgae Freshwater Cyanobacteria (planktonic and benthic)	*Ceratium furca* *Sargassum* spp. *Microcystis* spp. *Aphanizomenon* spp. *Dolichospermum* spp. *Oscillatoria* spp.	Can cause low oxygen zones (anoxia/hypoxia) and/or suffocation due to mucus production. Taste-and-odor compounds impact drinking water sources.

Table C. Marine HAB-associated human syndromes and conditions caused by exposure to marine algal toxins in ingested seafood.

	Syndrome or Condition					
	Ciguatera poisoning (CP)	**Neurotoxic shellfish poisoning (NSP)**	**Paralytic shellfish poisoning (PSP)**	**Amnesic shellfish poisoning (ASP)**	**Diarrhetic shellfish poisoning (DSP)**	**Azaspiracid shellfish poisoning (AZP)**
Toxin-producing organism	Dinoflagellates *Gambierdiscus* spp.	Dinoflagellates *Karenia brevis, Karenia papilionacea*	Dinoflagellates *Gymnodinium catenatum*, *Pyrodinium bahamense*, *Alexandrium* spp.	Diatoms *Pseudo-nitzschia* spp.	Dinoflagellates *Dinophysis* spp., *Prorocentrum* spp.	Dinoflagellates *Azadinium Amphidoma* spp.
Toxin(s)	Ciguatoxins, Maitotoxin, Scaritoxin	Brevetoxins[a]	Saxitoxins	Domoic acid	Okadaic acid & dinophysistoxins	Azaspiracids
Foods likely to be contaminated	Reef-associated fish and gastropods	molluscan shellfish (gastropods and bivalves)	molluscan shellfish (gastropods and bivalves), lobsters, crabs, finfish (specifically pufferfish)	molluscan shellfish (gastropods and bivalves), crabs, finfish	molluscan shellfish (bivalves and gastropods)	molluscan shellfish, crabs
Short-term symptoms	Nausea, vomiting, diarrhea, stomach pain	Nausea, vomiting, diarrhea, stomach pain; numbness of lips, tongue, and throat; dizziness	Nausea, vomiting, diarrhea, shortness of breath, irregular heartbeat, numbness of mouth and lips, weakness	Nausea, vomiting, diarrhea, stomach pain, shortness of breath, irregular heartbeat, abnormal hot and cold sensations, memory loss, disorientation, seizures, possibly coma	Nausea, vomiting, diarrhea, stomach pain, possibly chills, headache, fever	Nausea, vomiting, diarrhea, stomach pain
Long-term symptoms	Abnormal hot and cold sensations, pain, weakness; low blood pressure	Unknown	Unknown	Amnesia (short-term memory loss)	Unknown	Unknown
Treatment	Supportive care (treatment of symptoms), possibly IV mannitol	Supportive care	Supportive care, possibly respiratory support	Supportive care, especially for older people and those with kidney disease	Supportive care	Supportive care

[a]Inhalation of aerosolized brevetoxins causes respiratory irritation, including coughing, bronchoconstriction and dypnea (difficulty breathing).
Source: modified from the Department of Health and Human Services: Centers for Disease Control and Prevention. www.cdc.gov/habs

Table D. Common toxin classes produced by cyanobacteria.

	Microcystins	**Nodularin**	**Cylindrospermopsin**	**Anatoxins**	**Saxitoxin**
Variants	Over 250 variants with varying toxicity	Nodularin-R and nine additional variants	7-epi-cylindrospermopsin, 7-deoxy-cylindrospermopsin, 7-deoxy-desulpho-cylindrospermopsin, 7-deoxydesulpho-12-acetylcylindrospermopsin	Anatoxin-a Homoanatoxin-a Dihydroanatoxin-a Homodihydroanatoxin-a	Over 50 variants with varying toxicity
Common toxin-producing organism	*Microcystis, Dolichospermum, Planktothrix, Oscillatoria*	*Nodularia, Nostoc*	*Raphidiopsis, Dolichospermum, Oscillatoria, Planktothrix, Aphanizomenon*	*Dolichospermum, Aphanizomenon, Cuspidothrix, Microcoleus, Planktothrix, Raphidiopsis*	*Aphanizomenon, Cuspidothrix, Dolichospermum, Microseira, Microcoleus, Planktothrix, Scytonema*
Organ impacts	Liver, stomach	Liver, stomach	Liver, kidneys, stomach	Nervous system	Nervous system
Symptoms from exposure	*Ingestion*: Diarrhea, vomiting, headache, acute hepatitis, jaundice *Inhalation*: upper respiratory irritation. *Dialysis*: liver hemorrhage or liver failure	*Ingestion*: Diarrhea, vomiting, headache, acute hepatitis, jaundice	*Ingestion*: Diarrhea, vomiting, nausea, gastroenteritis, liver inflammation, kidney damage *Inhalation*: upper respiratory irritation	*Ingestion*: Muscle twitching, burning, numbness, drowsiness, salivation, respiratory paralysis *Inhalation*: upper respiratory irritation	*Ingestion:* Muscle twitching, burning, numbness, drowsiness, headache, vertigo, respiratory paralysis *Inhalation*: upper respiratory irritation

Source: modified from CDC HAB-Associated Illness webpage, www.cdc.gov/harmful-algal-blooms/communication-resources/index.html; and ITRC Strategies for Preventing and Managing Harmful Cyanobacterial Blooms (HCB-1), https://hcb-1.itrcweb.org/.

The Need for an Update of HARRNESS

The present HARRNESS plan, "Harmful Algal Research and Response: A National Environmental Strategy 2024-2034", provides an update of the state of the science since the previous decadal HARRNESS plan (2005-2015), identifies key information gaps in the context of our current knowledge, and presents forward-thinking solutions. This new report builds on major accomplishments of past efforts that are highlighted in four broad sections comprising topics under the following themes: 1) Observing Systems, Modeling, and Forecasting; 2) Detection and Ecological Impacts; 3) HAB Management, and 4) Human Dimensions.

The need for an update arose in response to the documented proliferation and intensification of HAB events in some regions, the number of new algal species, strains and toxins being discovered, the impacts from macroalgae (distribution shown in Fig. C) and the significant advances in technological tools that can provide early warning of blooms and further our knowledge of what drives these events. Noteworthy since the previous report is the increased awareness of HABs in freshwater ecosystems and human exposure to cyanotoxins via recreational use and drinking water (Fig. D). Additionally, freshwater, and marine ecosystems (and watersheds) are now viewed as a continuum and an integrated system rather than regarded as functioning in isolation.

The need for re-evaluation of research and management priorities also arose from concerns regarding the accelerated effects of climatic changes (increasing temperatures, acidification, sea level rise, extreme weather events), perhaps most evident in polar regions but also occurring regionally and with varying intensity in temperate and tropical/subtropical zones. The development and use of new technologies (especially the rapidly growing application of advanced molecular and so-called 'omics' approaches), field-deployed instrumentation, and advances in analytical capabilities, continue to offer significant opportunities for HAB detection, monitoring, and impact assessment in response to these environmental changes. Further, these tools have led to modeling efforts that allow promising forecasting capabilities (implemented so far primarily in the marine environment). Technological advances are also supporting a movement towards an integrated US National HAB Observing Network (NHABON).

Since the previous HARRNESS, there has also been an increased awareness of the risks associated with multiple HABs and their toxins due to: a) the discovery of novel pathways of exposure, transfer, and fate of HAB toxins through aquatic food webs that affect human consumers of seafood, b) the recognition of high differential susceptibility to HAB toxins among animal species and over the course of their development, and c) the potential significance of sublethal chronic effects vs. better known acute and short-term effects. Together, the implications of synergistic effects due to often co-occurring HABs, evidence that even HABs of the same species differ regionally in their dynamics and impacts, and recognition of the need to maintain species biodiversity within aquatic ecosystems, have highlighted the need for better understanding.

A major outcome from the previous HARRNESS was the creation of the National Harmful Algal Bloom Committee (NHC; https://hab.whoi.edu/national-hab-committee/), which falls under the umbrella of the National HAB Office (https://hab.whoi.edu/). The NHC was established for the purpose of providing a collective voice of the academic, management, and stakeholder communities interested in national HAB issues. Duties of the committee include: fostering the initiatives outlined in HARRNESS, garnering support among a variety of stakeholders, interfacing with the Interagency Working Group (IWG-HABHRCA) on HABs, hypoxia, and human health, promoting interactions with HAB-related national and international programs (such as GlobalHAB), responding to requests from Congress or federal and state entities for information or guidance on HAB issues, leading the charge to update HARRNESS, forming ad hoc technical advisory committees as needed, raising the visibility and understanding of HAB issues nationally, and communicating all of the aforementioned efforts to the greater HAB community through the biennial National HAB Conference, and list servers and websites maintained by the National HAB Office.

Finally, new federal efforts have been initiated that contribute to HAB control and management and increase the involvement of federal agencies in various aspects of HAB response. Additionally, the regulatory environment in the US has evolved since the previous HARRNESS was published and may thus provide new opportunities for HAB prevention/mitigation/control. Figure E outlines the timeline for legislative activity and Appendix II lists HAB-related reports that have helped guide these efforts (also see Fig. F).

This new report builds on major accomplishments of past efforts that are highlighted in four broad sections comprising topics under the following themes: 1) Observing Systems, Modeling, and Forecasting; 2) Detection and Ecological Impacts; 3) HAB Management, and 4) Human Dimensions.

Fig. C. Map showing the distribution of estuarine and coastal marine harmful macroalgal blooms (by phylum) in North America and Hawaii, including the Laurentian Great Lakes. Figure reproduced with permission from Lapointe et al. (2018). See also photo of the brown macroalga *Sargassum* in the Caribbean (Fig. 3.4).

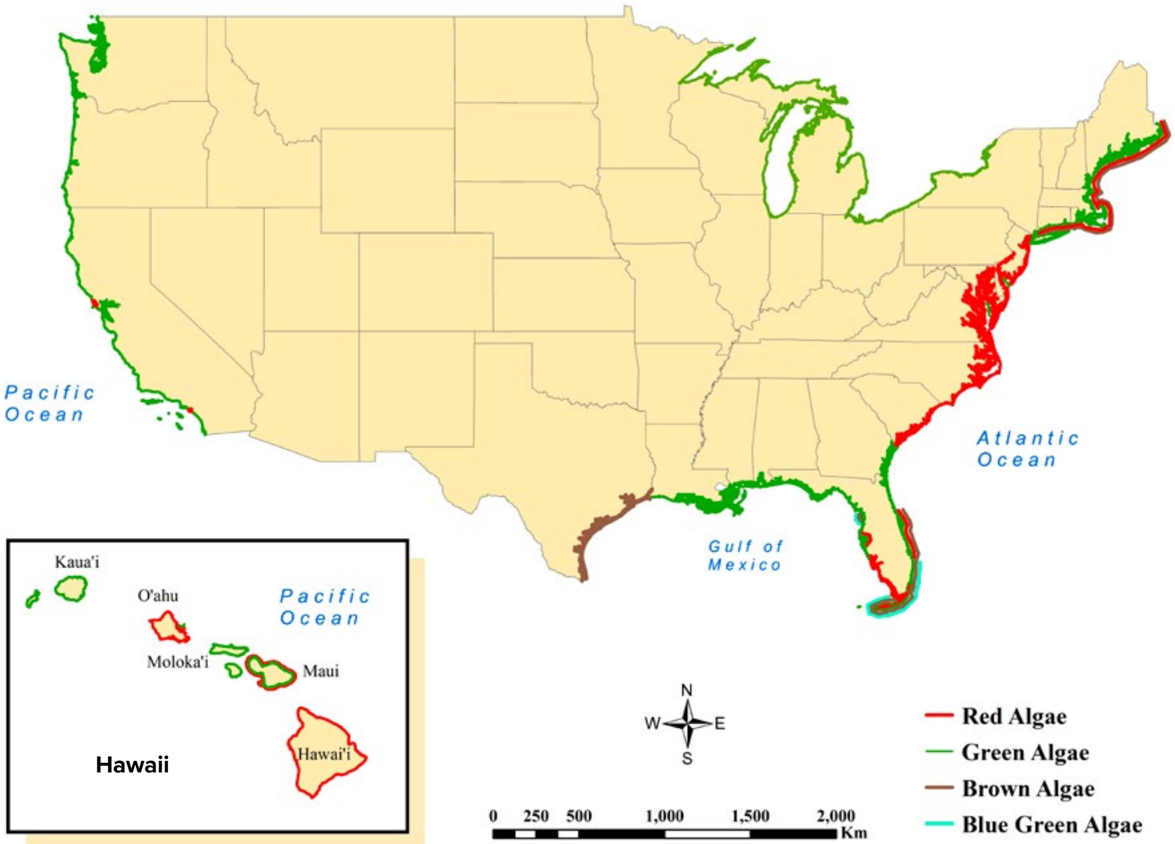


Fig. D. Summary of freshwater HABs and advisories reported in 2021. Note: There are no federal HAB reporting requirements and state monitoring and reporting varies. Source: EPA's Tracking CyanoHABs Story Map. Inset: Peaks represent summer months.

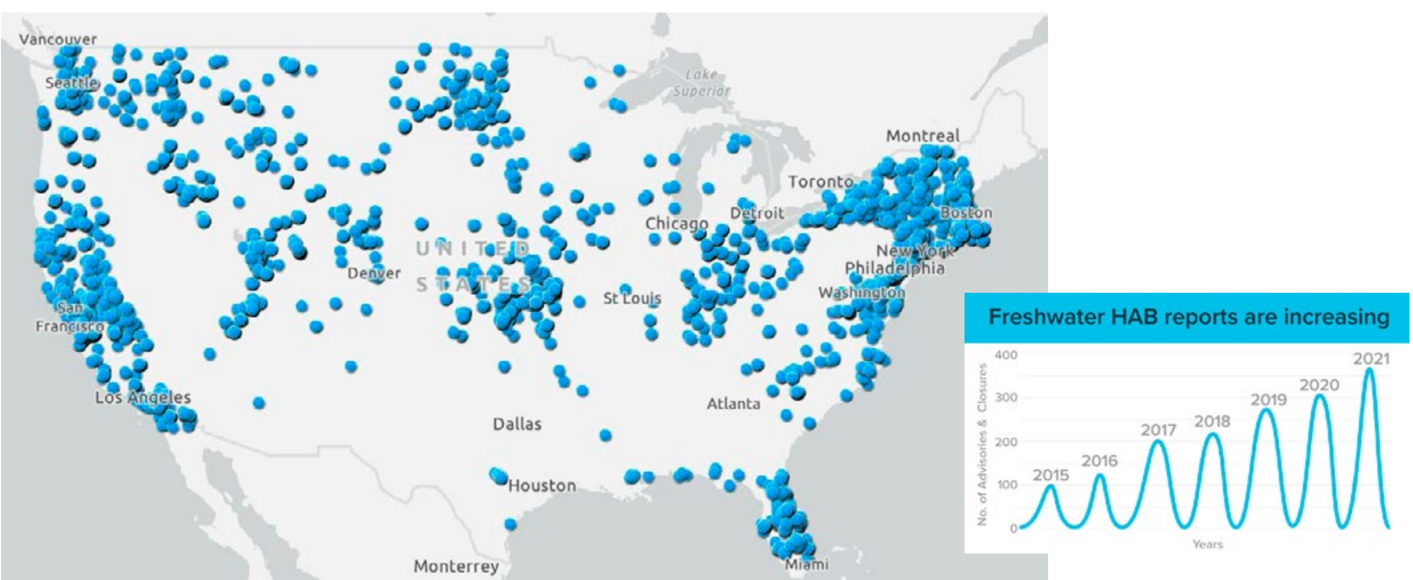


Fig. E. Timeline for HAB legislative activity.

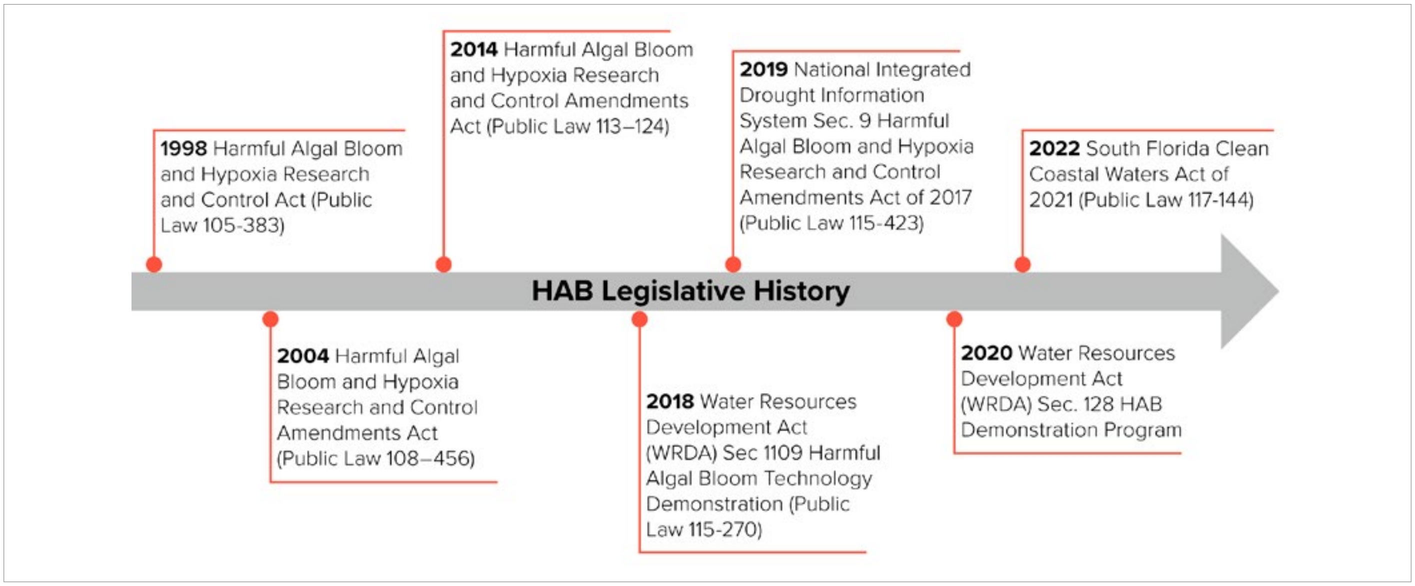
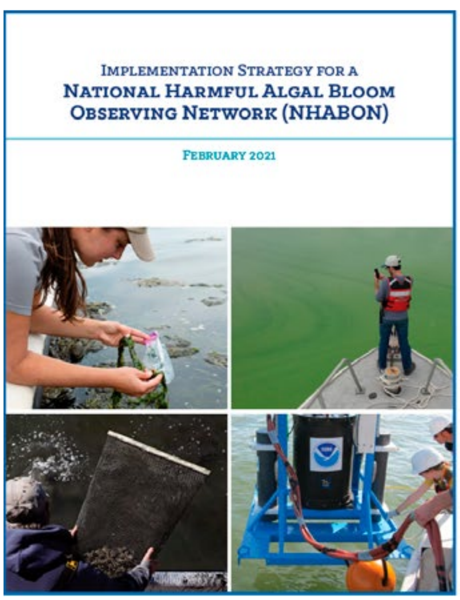
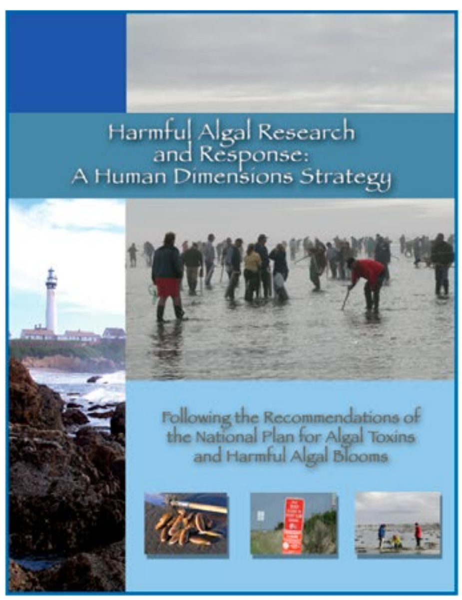


Fig. F. Tally of HAB research programs and HAB reports, with examples of several key reports produced (see Appendix II for a complete list).

Establishment of Programs Solely Devoted to HAB Research and Response 1997-2010 four NOAA programs established 2022 one USACE program established
Reports Submitted to Congress 2000-2020 eight reports submitted
HAB Federal Agency and Community Reports 1993-2022 eighteen reports





Approach

This report was spearheaded by National HAB Committee (NHC) leadership and made possible through a four-year collaborative effort between scientists and managers from a wide base of knowledge and expertise in HABs. This effort included a HAB community webinar (330 participants), a detailed web-based questionnaire (500 comments), and four Core Focus Groups comprising the Scientific Steering Committee (47 participants including External Contributors) (Fig. G) to review and collate information with respect to current understanding and advances, knowledge gaps and opportunities, and future recommendations and paths forward (Fig. H). The Scientific Steering Committee had diverse representation from the academic and management community comprising multiple areas of expertise (including both marine and freshwater HABs), as well as career stage and geographic representation. The NHC, along with advisors from federal and state agencies, and scientists in academic fields and industry contributed to the content and critical review of this document.

The ultimate goal of this contribution is to provide a decadal plan to guide legislation, research, and solutions to the HAB problem, and collaboration and coordination for a broad range of stakeholders (Fig. I). The granular details found in this report can facilitate and support the various regional report preparations tasked to the Interagency Working Group (IWG), as well as the recommendations set forth in the US Governmental Accountability Office's Report (2022) to Congressional Requesters, which include defining a national HAB program, developing a national goal for prevention actions, and the expansion of freshwater monitoring and forecasting.

Fig. G. HARRNESS update process. The update to HARRNESS was initiated by a webinar with over 330 people attending, followed by a web survey to all participants. Four focus groups then began their work on a subset of thematic areas, contacting outside collaborators for input.

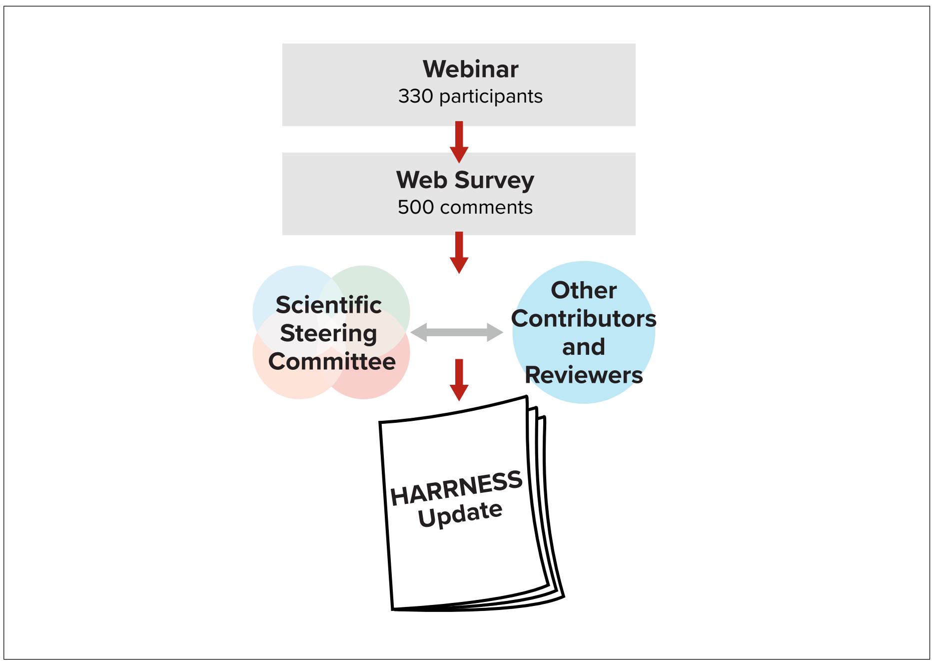


Fig. H. HARRNESS sub-committees. Four sub-committees reviewed and collated information related to key themes and focus areas and made recommendations for paths forward.

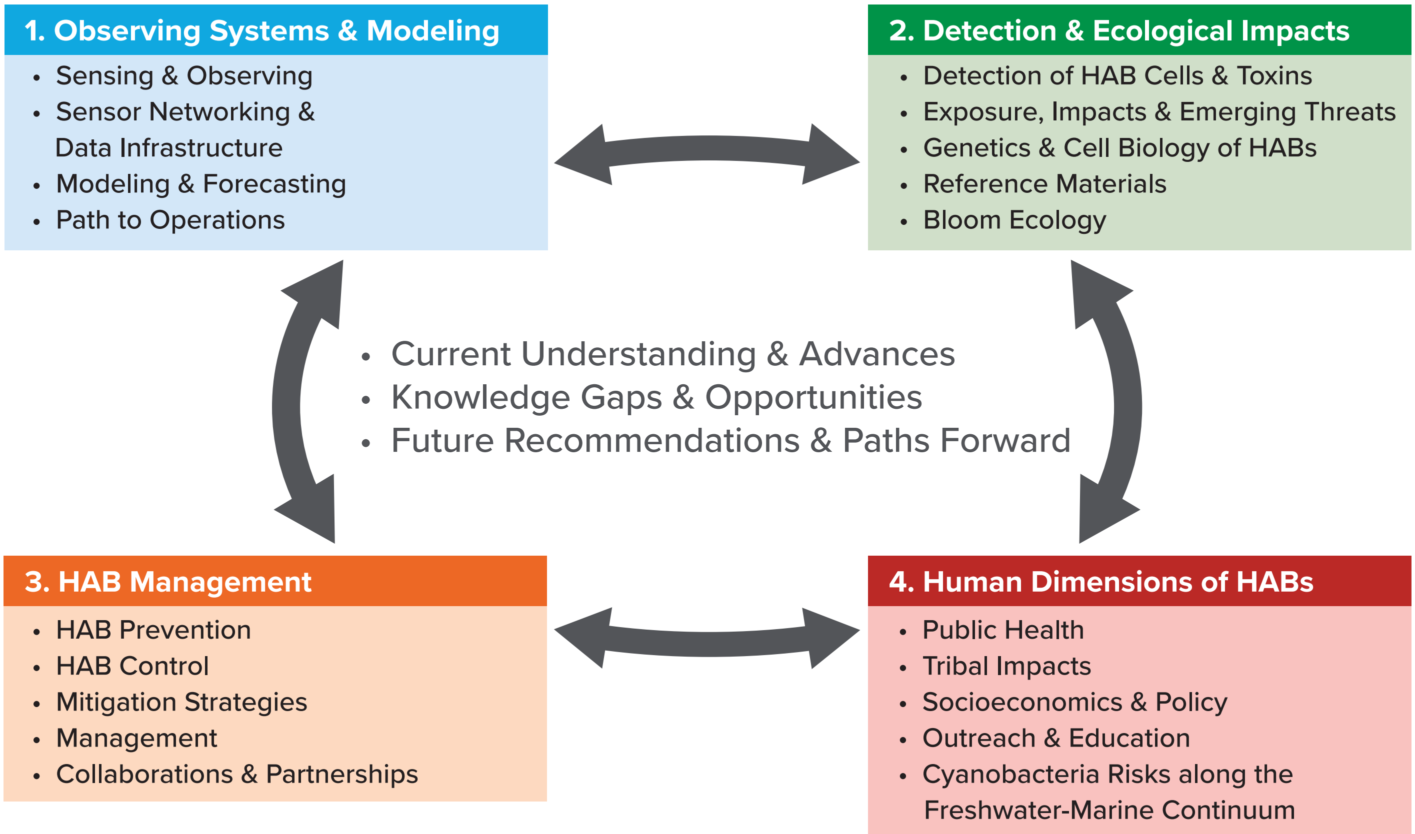


Fig. I. Schematic showing the principal stakeholder groups that represent the audience for HARRNESS.

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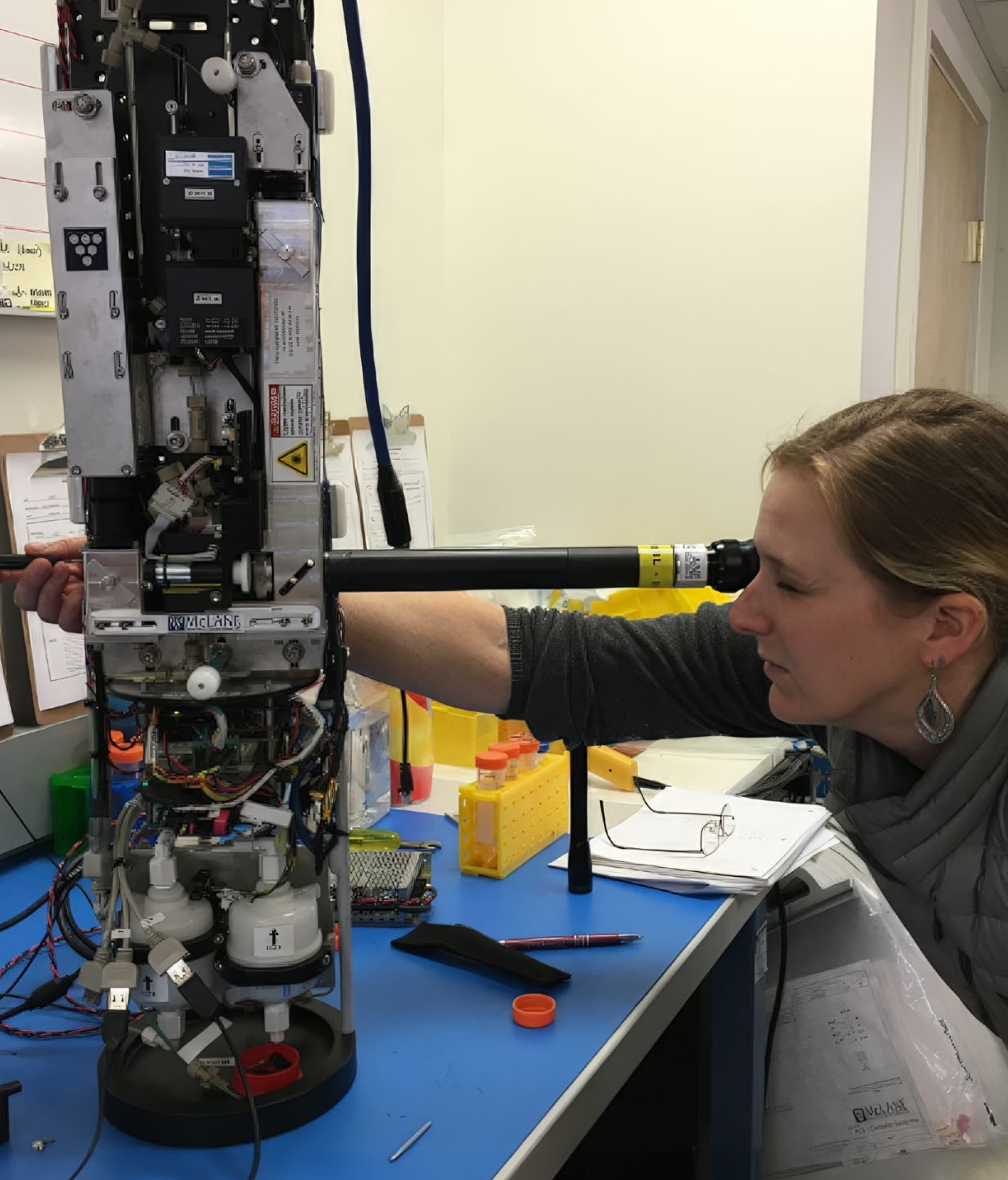

Alignment of the Imaging Flow Cytobot in the laboratory. Credit: R. Kudela, University of California, Santa Cruz.

1 OBSERVING SYSTEMS, MODELING, AND FORECASTING

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Summary

Predicting harmful algal blooms (HABs) requires integrating physical, chemical, and biological data collected from observing networks and then assimilating these data into models, which are used to generate forecasts. In 2005, the Harmful Algal Research and Response: A National Environmental Science Strategy 2005-2015 (HARRNESS, 2005) made recommendations on how to improve HAB modeling and forecasting over the next decade. Key HARRNESS recommendations related to sensing, networking, and modeling HABs included:

- Support the development and validation of new and improved technologies for remote cell and toxin detection, and for modeling and forecasting,
- Improve coordination of monitoring/ and modeling efforts, both at national and regional levels,
- Improve the use of networking technologies for monitoring and modeling efforts,
- Conduct sustained time series measurements of the biotic, chemical, and physical environments impacted by HABs,
- Develop food web models on the ecosystem fate and effects of toxins,

- Develop and improve species-specific models that link to physical-biological models.

Here we review HAB observing, modeling, and forecasting advances and technologies and recommend research and management priorities for the next decade and beyond. Our report encompasses sensing technologies, sensor networking and data management, models and forecasts, and the paths to operationalize forecasts.

Continued improvements of deployable sensors are foundational to improving early warning indicators, models, and forecasts, which are only as good as the underlying data. Sensing technology has advanced considerably in the last decade; for example, more capable fluorometric pigment sensors can track changes in bloom biomass in real-time. Additionally, automated imaging/classifying systems to identify and quantify key harmful algal (HA) taxa are being routinely deployed. However, deployable toxin sensors are available for only some HAB toxins and continue to be identified as a critical need by researchers and managers. As more and improved sensors and technologies become available, the data quality associated with each sensor needs to be assessed. Data quality encompasses the reliability, accuracy, and uncertainty associated with sensor-generated data. These data need to be of known quality so that researchers, managers, and end-users can reliably determine if the information is appropriate for their intended applications. Many of the data quality recommendations from HARRNESS (2005) are still relevant and have been reiterated within the management community. Understanding and documenting data quality, and when applicable, standardizing best practices for sensor use, continue to be recommended.

Sensor observing networks can harness the power of data collected across space and time. Since 2005, information technology advances have increased our ability to develop sensor networks, transmit data in real time, and analyze and manage data. These tasks are not trivial, however, and we face challenges uploading real-time data with high spatial and temporal resolution into databases and then assimilating this information into models, forecasts, and early warning systems. Additionally, standardizing sensor deployment and data processing methods are essential to generating comparable data across a network of multiple end-users. Core infrastructure programs, with shared observing resources and standardized methods to meet these needs, were a central recommendation in the 2008 HAB Research, Development, Demonstration, and Technology Transfer report (HAB RDDTT, 2008). While efforts such as the HAB Observing Network - New England and the Implementation Strategy for a National HAB Observing Network have made progress toward this goal, the recommendation is still relevant, and dedicating resources to expand shared infrastructure to standardize methods, manage data, coordinate observations, and enhance communication would greatly benefit HAB observing networks and forecasting [(NOAA's National Centers for Coastal Ocean Science (NCCOS) and US Integrated Ocean Observing System (IOOS), 2020].

Delivering useful HAB forecasts requires building and validating relevant early warning systems and models, communicating actionable (for example, harvesting or beach closure) results to end-users, and then keeping these forecasts supported and operational (Implementation Strategy for a National HAB Observing Network). Staying focused on "fit for purpose" and end-user needs will allow more efficient use of resources and maximize the relevance of forecasts. Ultimately, models must predict the impact of HABs on the target of interest such as toxins in shellfish or drinking water, algal biomass accrual, or other ecologic and socioeconomic consequences of HABs. Most existing forecasts and models only partly address the final goal of forecasting the societal and economic impacts of HABs. For example, most existing forecasts and models predict bloom biomass, but stakeholders would benefit from predictions of toxin production or the risk to human health, and more mechanistic understanding about toxin production and human health data are needed to reach this goal. If appropriate end points are identified, modelers can apply increasingly available, powerful new modeling methods and computing capacity such as Bayesian models, artificial intelligence (including machine learning), and cloud computing. Models will need to keep up with sensing technology to allow assimilation and use of new types of measurements such as toxin concentrations, which may be readily incorporated into future observing networks.

The capacity to generate operational and sustained HABs forecasts has increased since 2005. However, early warning systems that communicate potential HAB events to relevant stakeholders in a timely manner are rare. Successfully transitioning an indicator or model from research and development to operational early warning systems and forecasting requires a carefully considered transition plan that details the responsibilities of the entities tasked with management and maintenance of the system. Another key element in the transition plan is to identify sustained support. Due to the biological drivers of HABs and timelines associated with bloom development, HAB forecasts and transition plans may deviate from norms associated with forecasting events based on physical processes such as weather or seismic events. Once observational early warning systems, models, and forecasts are operational, regular assessment of their effectiveness would ensure that they are still relevant to end-users and stakeholders and updated accordingly. Research on new modeling methods, occurring in parallel to the current state-of-the-art approaches being employed, would ensure future effectiveness to monitor and address HAB conditions.

Progress has been made towards many of the HARRNESS (2005) and HAB RDDTT (2008) goals, and themes from these foundational reports are echoed in many of our recommendations below. This updated technical report identifies the major advances and pressing HAB knowledge gaps to help prioritize needs for the next decade of HAB research. The future success of HAB research and management will continue to rely on strong collaboration and coordination among researchers, managers, local, state, and federal agencies, and tribes. As these groups adopt similar standards and methods to generate comparable data that are open and readily accessible, the benefits from HAB sensing, networking, and modeling will accelerate accordingly.

This section is organized around three central themes: 1) sensing and observing; 2) sensor networks and data infrastructure; and 3) modeling and forecasting. Within each of these thematic areas the current state of knowledge – including significant advances since HARRNESS (2005), knowledge gaps and underdeveloped subject areas, and paths forward are summarized. This chapter concludes with a section describing paths to operations for each of the three thematic areas.

1.1. Sensing and Observing

1.1.1. CURRENT STATE OF KNOWLEDGE AND SIGNIFICANT ADVANCES

- Fluorometric sensors have improved substantially in the last 15 years. Deployable sensors are now available to discriminate among different algal classes based on their pigment fluorescence signatures. However, there are still data quality and/or specificity challenges with these technologies.

- Sensors for measuring inorganic variables are now widely deployed and include wet chemistry and optical technologies (e.g., nitrate sensors, dissolved oxygen sensors), although many were originally developed for the marine coastal environment and are still being adapted for use in freshwater.

- Recent improvements in field-portable microscopes, field-deployed real-time polymerase chain reaction (qPCR) assays, and rapid test kits to measure algal toxins are adding important advanced measurement capabilities and rapid turnaround time to coastal ocean, estuarine, and freshwater observing networks.

- Autonomous molecular, analytical, imaging, and spectrophotometric instruments (e.g., the Environmental Sample Processor [ESP, Fig. 1.1]), Imaging FlowCytobot (IFCB, Fig. 1.2), Programmable Hyperspectral Seawater Scanner (PHYSS)] are deployed on fixed (in situ or dockside) and mobile platforms (Spanbauer et al., 2020), primarily in coastal marine and estuarine environments and the Laurentian Great Lakes. From these devices, HAB species, biotoxin concentrations, and general phytoplankton community composition data are transmitted in near-real time (e.g., https://habhub.whoi.edu/, http://www.nanoos.org/products/habs/real-time/home.php) and can be used for early warning, nowcasting (prediction of current, and very-near past and future conditions), and forecasting.

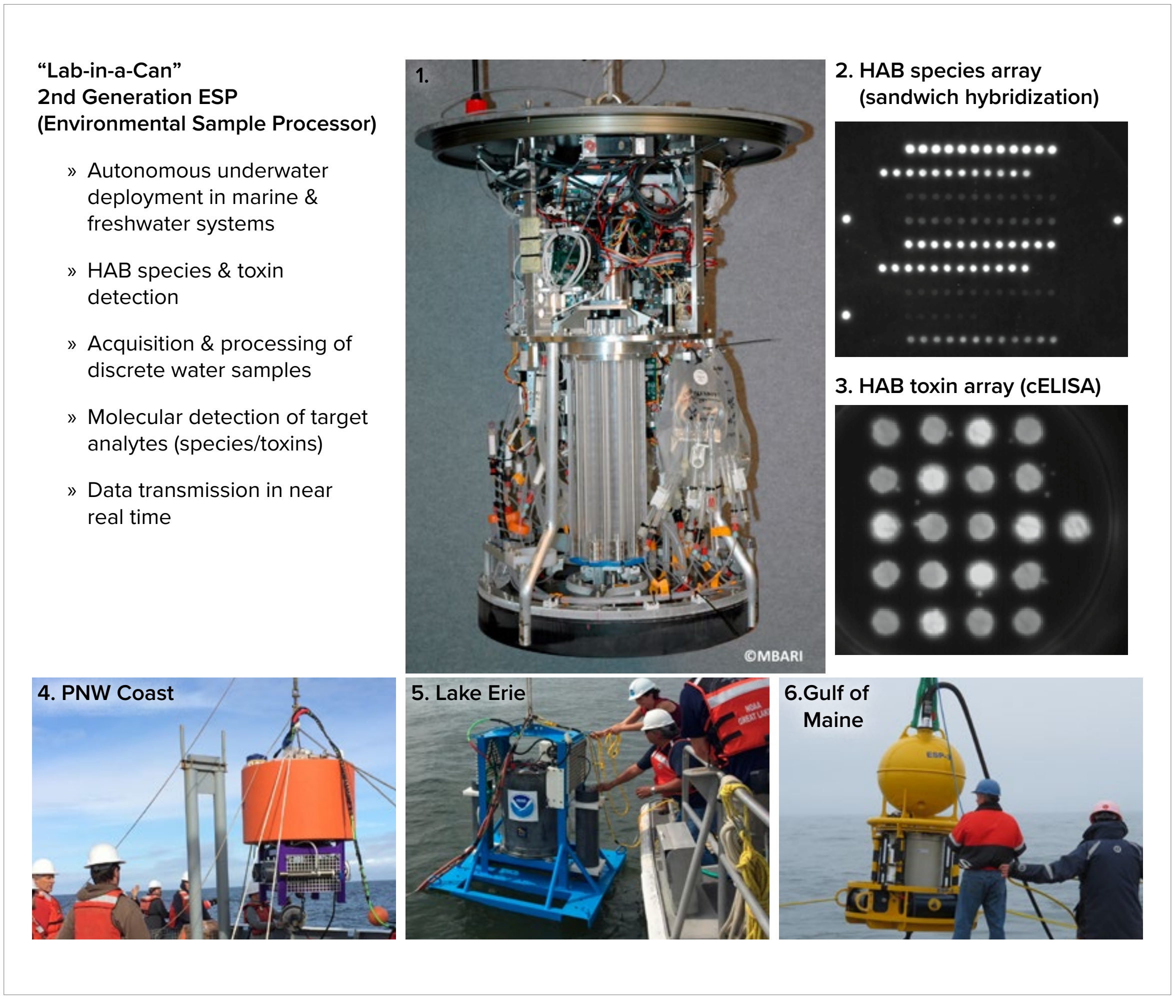
- Unoccupied remotely operated vehicles (ROVs) offer cost-effective platforms and the flexibility for HAB sensor deployment and data collection. Autonomous underwater vehicles (AUVs) are constrained primarily to the marine coastal environment and the Laurentian Great Lakes, whereas shallow-draft, autonomous surface vehicles (ASVs) have wide application in diverse marine and freshwater systems. Unoccupied aerial vehicles (UAVs) have enhanced the ability to collect high-resolution, remotely sensed data at local scales. Autonomous vertical profilers have also expanded the ability to collect vertical profiles for understanding stratification and subsurface dynamics.

- Satellite imagery and algorithms provide large-scale data on HAB biomass and distribution in surface waters (Fig. 1.3). Ocean Land Color Instrument (OLCI) sensors on Sentinel 3 satellites (European Space Agency) have led to improved HAB-related satellite algorithms demonstrated to be useful in freshwater and marine coastal environments. High spatial resolution satellites (e.g., Sentinel-2, Landsat8) do not have spectral bands specific to HAB taxonomic groups; however, they provide useful contextual information such as chlorophyll-*a* concentrations at 10-30 m resolution. These high-resolution sensors are particularly useful for small inland waterbodies in which desired parameters cannot be resolved by lower resolution satellite sensors. Satellite-based sensors facilitate collection of long-term time series used by researchers to analyze decadal data and trends back to the 1980s and 1990s (e.g., Ho et al., 2019).

- Improved satellite remote sensing has been used to identify the Great Atlantic *Sargassum* Belt in the tropical Atlantic Ocean (Wang et al., 2019). This new region of seasonal *Sargassum* biomass development is the source of increasing flux to the Caribbean, Gulf of Mexico, and the east coast of Florida.

- Community science contributions to HAB monitoring (e.g., Cyanoscope for the mapping of cyanobacteria or blue-green microalgae, Phytoplankton Monitoring Network, California-HABMAP), are able to produce high- quality data that are fundamentally improving observing and modeling efforts, and management of human health risk.

Fig. 1.1. **Second-generation (2G) Environmental Sample Processor (ESP).** The ESP enables remote, autonomous water collection and onboard processing/analysis for detection and quantification of harmful algal species using molecular methods and their toxins using competitive ELISA (cELISA). Data are transmitted in real time, processed, and disseminated to inform timely decision making. 1) 2G ESP core instrument for sample acquisition, processing, and analysis. *Credit: MBARI**. 2) Images of HAB species (sandwich hybridization assay; SHA) and 3) toxin (cELISA) membrane-based arrays developed in-situ on 2G ESP. Brightness of target-specific spots on arrays is directly (SHA) or indirectly (cELISA) proportional to the concentration of individual species or toxin present, respectively. *Credits: MBARI, NOAA/ NCCOS*. 2G ESP and mooring field deployments: 4) off the Pacific Northwest (PNW, Washington State) coast for detection of *Pseudo-nitzschia* and domoic acid. *Credit: NOAA/ NWFSC**; 5) with the bottom lander in Lake Erie western basin for detection of microcystin produced by toxic *Microcystis* blooms. Credit: NOAA/ GLERL*; 6) in the Gulf of Maine for detection of *Alexandrium* and saxitoxins. *Credit: WHOI**.



*Monterey Bay Aquarium Research Institute; Northwest Fisheries Science Center; Great Lakes Environmental Research Laboratory; Woods Hole Oceanographic Institute

Fig. 1.2. The Imaging FlowCytobot (IFCB) is an automated, submersible microscope that can continuously monitor coastal waters for several months at a time. Associated machine learning-based analysis software identifies HAB species in near real time and provides HAB early warning **1.** Alignment in the laboratory. *Photo credit: R. Kudela*, *University of California, Santa Cruz.* **2.** Flow Cytobot deployed in seawater in its housing. *Photo credit: K. Bengt, Swedish Meteorological and Hydrological Institute*. An IFCB instrument dashboard enables sharing of HAB cell images **(3)**, metadata, and analysis products available via a webpage. *Reproduced with permission from Sosik and Futrelle (2012).*

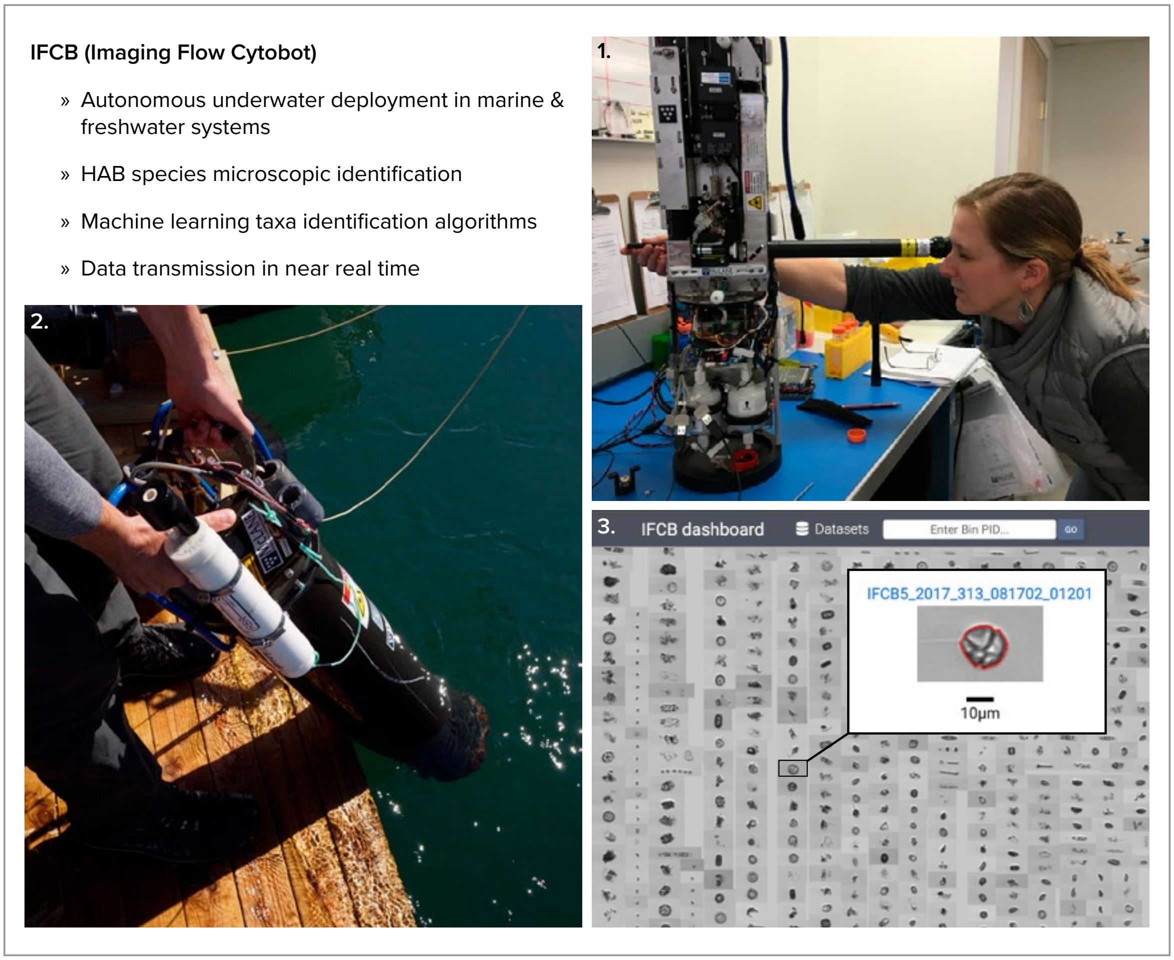
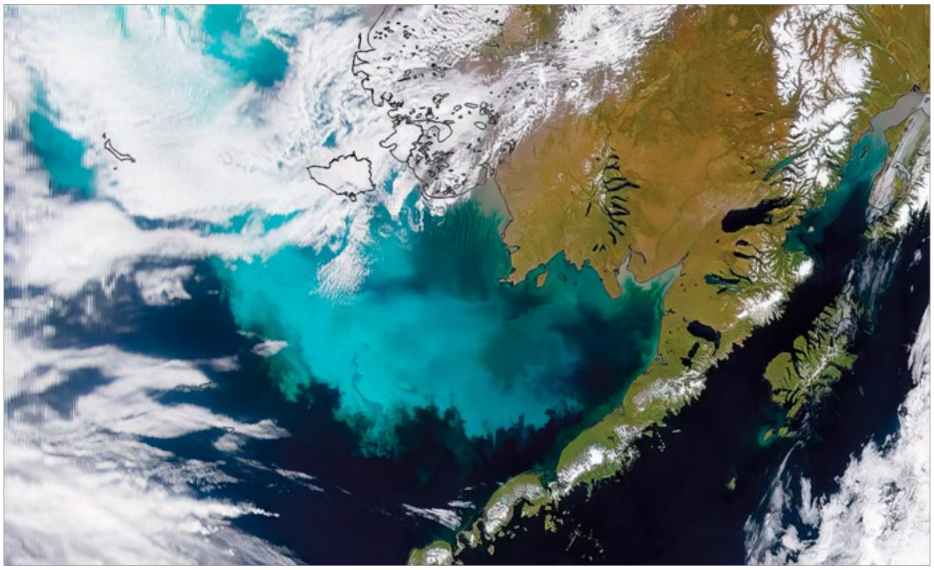


Fig. 1.3. Satellite image of a coccolithophore bloom in the Bering Sea. Over the past decade, this region has experienced massive and geographically widespread blooms of *Alexandrium catenella*, which have been reported in the Bering and Chukchi Seas. See Anderson et al. (2021). *Image provided by the SeaWiFS (Sea-viewing Wide Field-of-viewSensor) Project, NASA/Goddard Space Flight Center, and GeoEye*.



1.1.2. KNOWLEDGE GAPS AND UNDERDEVELOPED CAPABILITIES

- Capital and operational/maintenance costs of many sensors limit their accessibility for use in routine monitoring programs and observing networks. However, relatively low-cost, distributed sensor technology can still have unresolved data quality or system integration limitations that may constrain their usefulness.
- Thorough characterization of the data quality provided by different sensors is needed.
- Because of cost and other limitations associated with sustained operations, many in situ observation networks focus on measurement of physicochemical variables (e.g., temperature and nutrients) and do not yet readily integrate biological sensors, even fluorometric sensors, to assess changes in algal biomass and toxicity.
- There is a continuing need for robust, cost-effective toxin sensors given that public health risks are often closely dependent on toxin levels (although biomagnification of low toxin levels can occur through the food web). This includes toxins present in water, tissues, and aerosols (e.g., some aerosolized cyanotoxins and brevetoxins). Near real-time data on toxin ingestion/assimilation for incorporation into models would greatly enhance the accuracy of early warning systems, forecasts, and predictions of changing toxins and their concentrations. Currently, deployable toxin sensors (e.g., for microcystin and domoic acid) are available only for the ESP, although several relatively low-cost,

field-portable devices (e.g., LightDeck [formerly MBio] Diagnostics Multiplex Test Kit, Scotia Rapid Test, Abraxis Test Strip Kit) are coming online.

- Nutrient measurements are essential for modeling of HABs. Although sensors have advanced substantially over the last decade, several gaps can still be identified. Thus, deployable sensors for phosphorus, silicate, and nitrogen species other than nitrate remain a critical need.

- Autonomous platforms such as the ESP (a sample acquisition, processing and analysis platform that carries species and/or toxin-specific sensors) are being deployed on the Gulf of Maine (https://habhub.whoi.edu), Washington State coast (http://nanoos.org/products/habs/real-time/esp_now/hab_measurements.php), and Lake Erie (https://www.glerl.noaa.gov/res/HABs_and_Hypoxia/esp.html). There is also increasing use of molecular markers for toxin and algal genes, species, and populations in field sampling, but these platforms are generally expensive and are still limited in sample capacity and deployment duration.

- More effort is required to ground truth remote sensing algorithms, and establishing their accuracy for specific water bodies with different HAB species would reduce the uncertainty around satellite-derived algal density or toxin concentration estimates. Validation efforts should integrate AUVs or other vertical profiling, as many but not all HAB species undergo diel vertical migration.

- Sensing of attached benthic algal and cyanobacterial mats remains challenging, although benthic algae and cyanobacteria lead to toxin outbreaks and high biomass issues in many ecosystems. In clear waters, underwater vegetation can be observed with satellites (e.g., mapping of the filamentous macroalga *Cladophora* in the Laurentian Great Lakes [Shuchman et al., 2013] or mapping of coral reefs [Li et al., 2020]), although sensors and spectral algorithms to observe and quantify attached mats are less developed than for phytoplankton.

1.1.3. PATHS FORWARD AND RECOMMENDATIONS FOR THE FUTURE

- Expand the development, use, and validation of unoccupied and field-portable platforms (mobile [aerial, surface, and sub-surface] and fixed) to achieve more flexible and affordable deployment options for various HAB species and toxin sensors (e.g., co-deployments, distributed deployments, imaging below clouds) in marine and freshwater ecosystems. The consistency of time series data is critical, and novel paths to achieve sustainable observations should be evaluated.

- Advance the accessibility and availability of increased spatial resolution satellite-based data to improve estimates of HAB distribution and abundance/biomass and allow more concise tracking of HAB event magnitude, frequency, and duration.

- Increase the linkage of satellite observations to UAV data collection and model simulations. Take advantage of fixed sensors and platforms such as the ocean color component of the Aerosol Robotic Network (AERONET-OC), which has been deployed in the Laurentian Great Lakes for algorithm development and time-series generation.

- Coordinate the spatiotemporal alignment of multiple synchronous data streams (e.g., algal species, biotoxins, nutrients, temperature, wind stress, and other environmental variables). The aim is to optimize the frequency of information input for models underpinning HAB hindcasting (to allow for novel analysis/reanalysis of historical data), early warning systems, nowcasting, and forecasting. Artificial intelligence (AI) and machine learning could be used to improve the data quality of real-time sensors by removing outliers and smoothing the data. Integration of AI and existing citizen science can generate and facilitate processing of large volume datasets for ecological monitoring beyond what is possible with conventional methods useful in modeling of complex ecosystems (McClure et al., 2020).
- Explore novel strategies for sensor deployment and data delivery. These strategies may move costs associated with ownership, operation, and maintenance of the platform to a commercial or centralized entity. This would allow sensor data collected during a mission to be purchased or supported by the user/stakeholder (e.g., current Saildrone "mission-as-a-service" business model).
- Although field fluorometry technologies have advanced considerably, the relationship between pigment diagnostic signatures (e.g., phycocyanin for cyanobacteria or 19'-butanoyloxyfucoxanthin [but-fuco] pigment for *Aureococcus anophagefferens*, the causative agent of brown tides) and potentially harmful taxa are not always robust (Stauffer et al., 2019). Additionally, sensors for many pigments (e.g., phycocyanin) cannot rely on standardized quantitation methods or reference materials. Continued research and evaluation (e.g., Alliance for Coastal Technologies [ACT] evaluations) are needed to inform best practices for use of current fluorometric technology and develop sensors that are able to more accurately characterize algal biomass and community composition at the resolution needed.
- Encourage and guide algorithm development from spectral sensor data to improve our ability to classify key HAB taxa and discern their abundance (biomass) and distribution at fine spatial scales (Paine et al., 2018).
- Develop strategic partnerships with private industry and other stakeholders to enhance innovation and improve cost-effectiveness, robustness, and accessibility of sensor technologies for monitoring of HAB species/biotoxins and forecasting applications that meet manager or stakeholder needs. These efforts could include expanding or building on existing efforts such as the Federal government-wide Small Business Innovation Research/Small Business Technology Transfer (SBIR/SBTT) program, agency-specific (e.g., National Oceanic and Atmospheric Administration [NOAA] initiatives, and private/non-profit innovation challenges [e.g., Schmidt Reimagine challenge, X-Prize competition, Erie Hack Cleveland Water Alliance challenge]).

1.2. Sensor Networking and Data Infrastructure

1.2.1. CURRENT STATE OF KNOWLEDGE AND SIGNIFICANT ADVANCES

- Many advanced platforms and technologies (e.g., IFCB, ESP) have moved from research-only to higher Readiness Levels (RLs), allowing establishment and implementation of networks (e.g., in Texas and New England) with these powerful sensors.
- At a national (US Integrated Ocean Observing System [IOOS]) and international level, core sets of variables, such as the Core Biological Variables (US IOOS) and Essential Ocean Variables (Global Ocean Observing System [GOOS]) (Miloslavich et al., 2018), have been standardized and include HAB-relevant parameters such as phytoplankton species and abundance, nutrient concentrations, and contextual information such as temperature, salinity, pH, and dissolved oxygen.
- Method and parameter standardization have improved substantially. For example, IOOS regional programs and networks are implementing core variables (essential ocean and biodiversity variables) (Muller-Karger et al., 2018) with associated Quality Assurance/Quality Control (QA/QC) protocols, including development of Quality Assurance for Real Time Data Program (QARTOD) documentation. For inland waters, the US Geological Survey (USGS) National Water Quality Network has also made progress standardizing methods and parameters for core water-quality variables.
- Consensus is emerging at multiple levels toward standardizing data management around DarwinCore metadata and Ocean Biodiversity Information System (OBIS) requirements. This represents a key step towards making HAB-relevant data compliant with Findable, Accessible, Interoperable, Reusable (FAIR) standards. Data management and infrastructure technologies have advanced greatly in the last decade.
- Community science and volunteer monitoring networks can now provide rapid data access using local and regional networks (e.g., HABscope for *Karenia brevis* cell counts, Cyanobacteria Monitoring Collective, SoundToxins in Washington State).
- HAB observations have been incorporated into larger data and model systems, in particular the IOOS Regional Associations (RAs), which may also serve to display and disseminate these data to managers and other stakeholders. An Implementation Strategy for a National HAB Observing Network, has been proposed to establish a sustained national network for regional HAB observing, with RAs playing a pivotal role in its execution.

1.2.2. KNOWLEDGE GAPS AND UNDERDEVELOPED CAPABILITIES

- While progress has been made, there is still much work to do in standardizing HAB-relevant data. For example, QARTOD data pipelines have worked well for physical and chemical data but are challenged by the complexity of biological data.
- There is still a lack of national consistency in data processing and reporting. Many of these data are available only to authorized access or remain unutilized. Other data are not always compatible across different databases due to a lack of consistent standards and appropriate metadata. A clear plan should be articulated for long-term data preservation and archiving that conforms to FAIR guiding principles; investment in appropriate infrastructure will likely also be needed to achieve this goal.
- There is concern that standardization of Essential Ocean Variables and Core Biological Variables will not adequately capture the need for algal species and strain-level information, which is critical for understanding HABs. They also may not sufficiently capture key drivers underlying bloom dynamics and toxin levels without additional observations or models.
- Freshwater systems have separate networks, hubs, and repositories (such as the USGS Water Data for the Nation and the Water Quality Portal) from estuarine and marine systems. However, there is a need for standardization of methods and agreed-upon parameters, or creation of data repositories, across freshwater and marine systems, and ultimately it should be possible to seamlessly transition from freshwater through brackish estuaries to marine networks.
- The value of real-time data is in the immediacy of the information, but long-term data collection must be more rigorously assessed for quality and consistency. Real-time HAB data are often underutilized for immediate nowcasting or early warning systems and are rarely used to inform or initialize models.

1.2.3. PATHS FORWARD AND RECOMMENDATIONS FOR THE FUTURE

- The availability of data from field-deployed sensors, community science networks, remotely deployable instrumentation, and satellites has increased exponentially. Effort now needs to be focused on how to best interpret new data streams and integrate these data for use in models, early warning systems, regulatory decisions, and retrospective analysis, and on addressing the critical requirement for establishing sustained HAB observing networks.
- As more real-time data become available, these data streams could be ingested (i.e., captured and stored) and assimilated into early warning systems and predictive models underpinning forecasts, similar to initializing and/or course-correcting weather-targeted applications. Currently, few HAB forecasts are set up for true initialization or data assimilation. The data ingestion and assimilation processes need to be relevant to HAB space and time scales, which can range from short-term to annual and can be localized or span multiple regions. These data integration processes also need to account for the variability

in number of instruments in a region over a certain period and make careful decisions about interpolation and extrapolation accordingly.

- Shared facilities and core regional infrastructure programs (e.g., HAB Research, Development, Demonstration and Technology Transfer [HAB RDDTT], 2008) would help to standardize methods and protocols for sensor use and data translation, interpretation, and presentation, serving as research hubs providing joint ownership of hardware, deployment best practices, standardized data processing, reporting, and archiving. Such programs could also facilitate sharing technology performance assessments to allow for appropriate selection and use of new tools, thus facilitating the development and operation of regional and national sensor and data networks. Such activities would provide datasets of known, documented quality, across the freshwater-to-marine continuum. This is critical not only for routine observations, but also to facilitate coordinated and comprehensive event response efforts.
- Expansion of existing performance verification/certification programs, such as those modeled on the NOAA-funded ACT program (2001-2021), would help instill confidence in the various data streams and sensors. Adoption of these same standards by Federal agencies would increase the ability for inter-agency data comparability (e.g., through IWG-HABHRCA).
- Sensor networks are less common in freshwater than marine systems. Increasing freshwater observation networks (e.g., USGS Next Generation Water Observing System, Global Lake Ecological Observing Network) would be beneficial for multiple end users, especially where regional HAB issues are shared across ecosystems.
- Freshwater scientists and managers should strengthen the development and use of core variables and the standardization of methods, modeled after these efforts in estuarine and marine systems. There are already entities addressing methods standardization (e.g., National Environmental Methods Index and Interstate Technology Regulatory Council [ITRC]). Coordination across entities collecting freshwater data could be strengthened and, when appropriate, extended to standardize with marine methods and variables.

1.3. Modeling and Forecasting

1.3.1. CURRENT STATE OF KNOWLEDGE AND SIGNIFICANT ADVANCES

- Models and forecasts have advanced significantly since HARRNESS (2005). They vary in complexity from primarily empirical/statistical or simple particle-tracking models that lead to short-term forecasts, to more sophisticated dynamic or process-oriented, physical-biological, seasonal and physiology-based models, some with operational forecast systems (Anderson et al., 2019; Rousso et al., 2020).
- Several of these models have moved from primarily research efforts to sustained operations. Examples of these models include:

- Pacific Northwest, weekly short-term bulletin based on state (Washington and Oregon) monitoring data, LiveOcean hydrodynamic model and expert opinion, now disseminated via the Northwest Association of Networked Ocean Observing Systems (NANOOS);
- California, 3-day forecast of toxin (domoic acid) risk based on a statistical model (California Harmful Algae Risk Mapping [C-HARM]) using hydrodynamic and satellite data;
- Lake Erie, seasonal forecast based on nutrient loading and weekly forecasting models based on satellite imagery, hydrodynamics, and weather forecasts;
- Gulf of Maine, seasonal forecast based on cyst maps, dinoflagellate physiological parameters, and a numerical (transport) model (Figs. 1.4A and 1.4B). An experimental weekly Gulf of Maine Alexandrium catenella nowcast/forecast is being produced;
- Gulf of Mexico, short-term *Karenia brevis* bloom trajectory and respiratory irritation forecasts due to aerosolized brevetoxins based on multiple data streams including numerical models, satellites, and direct sampling;
- Near real-time, satellite-based HAB monitoring products (e.g., NOAA's National Centers for Coastal Ocean Science [NCCOS] and Cyanobacteria Assessment Network [CyAN; Fig. 1.5] for bloom detection in selected regions).

Fig. 1.4 A. Life cycle of harmful dinoflagellates of the genus *Alexandrium*. Stages are critical for bloom initiation and termination. Flagellated, **vegetative cells** swim in the water column, photosynthesize, and proliferate to develop a bloom by undergoing asexual cell division. When environmental conditions are stressful, they produce small haploid (n DNA content) **gametes** that fuse to produce a large diploid (2n) **planozygote** (sexual reproduction) indicative of bloom termination. Paired dividing vegetative cells and fusing gametes can be distinguished morphologically. Zygotes mature, cast off their flagella, develop a thick cell wall and form **benthic resting cysts** that fall to bottom sediments and are highly resistant to stress. In response to seasonal cooling and heating, cysts then cycle between dormancy (alive but unable to germinate) and quiescence (able to germinate but waiting for favorable conditions that lead to germination into a vegetative cell) thus repeating the cycle.

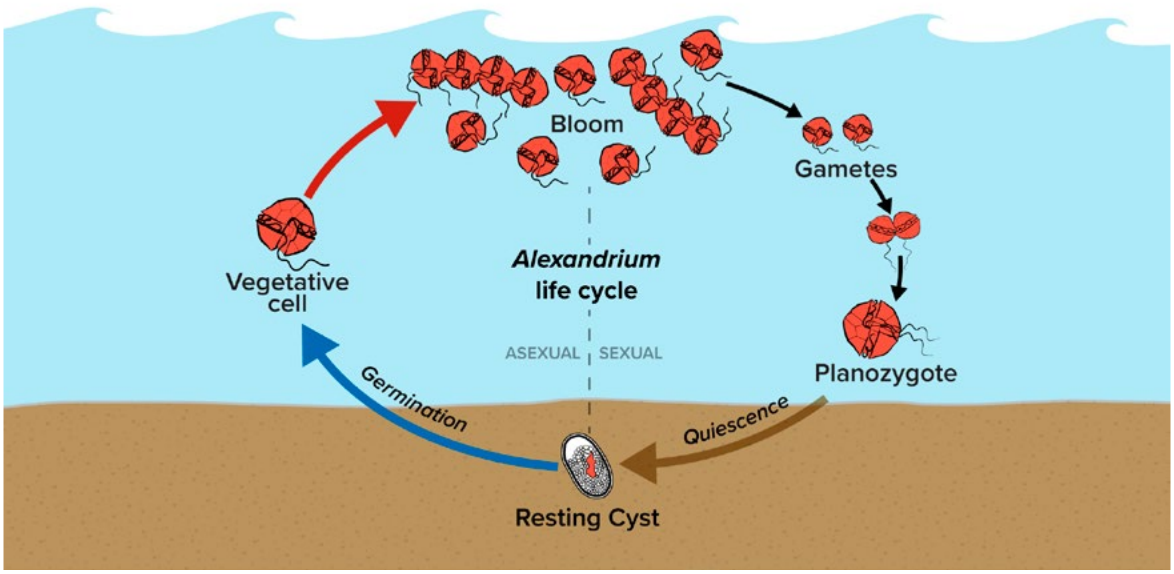


Fig. 1.4 B. Modeling of *Alexandrium catenella* blooms in the Gulf of Maine. The full *Alexandrium* population dynamics model couples hydrodynamics with a biological submodel.

1. Biological submodel input: 1a. Map of *A. catenella* cyst abundance in sediment samples. Inset shows *Alexandrium* life cycle (also see Fig. 1.4A). This is updated each year with data from survey cruises to give the potential inoculum for the next year's bloom; conditions for *A. catenella* cyst germination: an internal clock regulates when germination can occur (1b), with the rate of germination determined by temperature and light (1c). Temperature and salinity (icon not shown) dependence of growth rate of the resulting vegetative motile *A. catenella* cells (1d): cell growth is also dependent on light, i.e., photosynthetically active radiation (PAR). The cells' surface-directed swimming speed is specified. Their "mortality" rate represents the loss of cells due to grazing by zooplankton which increases with temperature, as described by the temperature coefficient Q10 (the change in phytoplankton growth rate that occurs with a 10 degree Celcius temperature change; Mundim et al. 2020).

2. Model output: When the biological submodel is coupled with a hydrodynamic model tied to real-time data on sunlight, river discharge, tides, winds, etc., a simulation of the distribution of *A. catenella* vegetative cell concentrations is generated, as shown here for a major, unprecedented bloom that occurred in 2005 and affected extensive inshore & offshore shellfish beds. *Figures and data reproduced with permission from Solow et al. (2014), Stock et al. (2005) and He et al. (2008).*

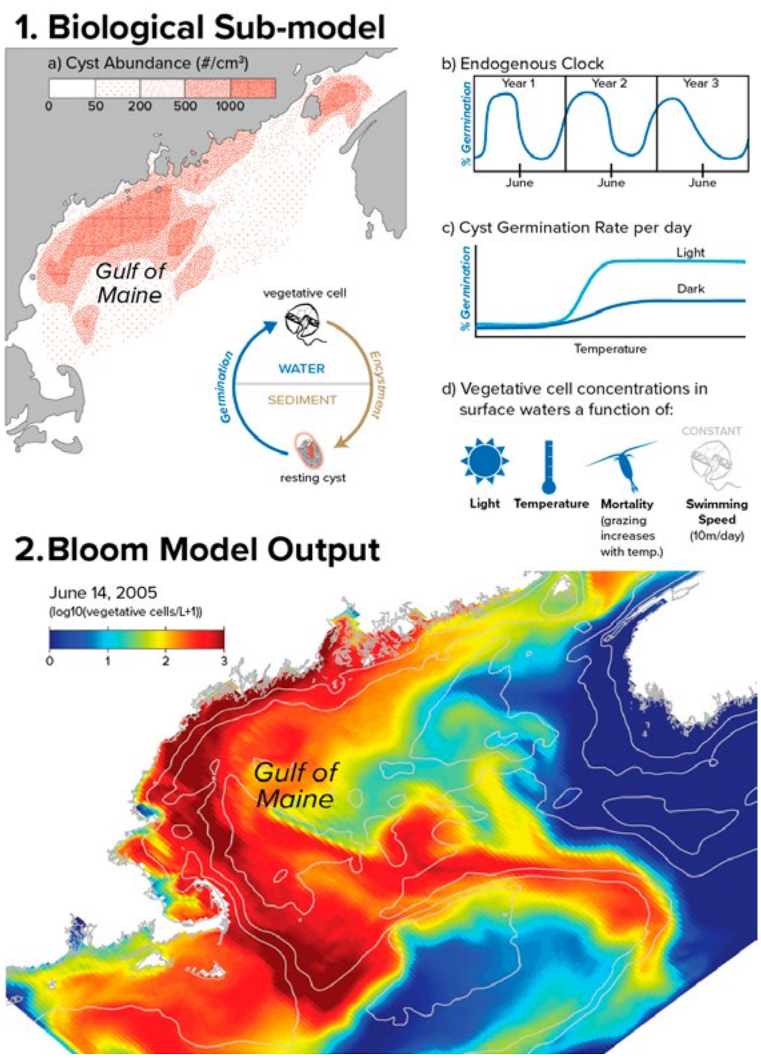
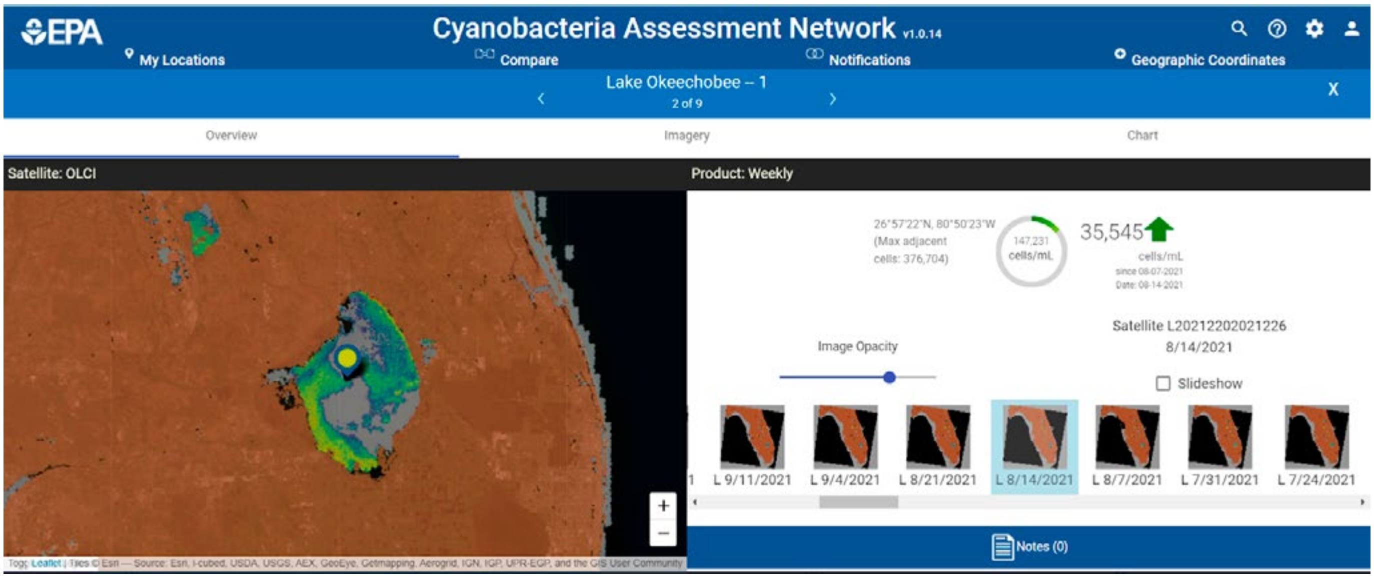


Fig. 1.5. Remote sensing imagery of a cyanobacterial bloom in Lake Okeechobee, southeastern Florida. Satellite data estimating cyanobacterial abundance in over 1,000 lakes across the continental United States is provided by the Cyanobacterial Assessment Network (CyAN), an interagency (US EPA, NOAA, USGS) project to enable the use of satellite imagery to track and monitor cyanobacterial blooms. *Image Credit:* https://www.epa.gov/water-research/cyanobacteria-assessment-network-cyan



- Formal skill assessment, i.e., how well a model predicts future conditions (Stow et al., 2009), has become more common for these modeling systems. Skill assessment provides confidence and interpretability of the model outputs for end users (Anderson et al., 2016).
- Ensemble forecasts, which provide a range of possible scenarios in regions where multiple modeling outputs exist, could improve the accuracy of harmful algal bloom (HAB) predictions. Better integration of multiple models, particularly with expert guidance, would enable end users to simultaneously interpret, or use, outputs from more than one model depending on its context and performance.
- The development of environmental hydrodynamic and numerical models has served multiple end users by addressing challenges that include HABs, hypoxia, oil spills, larval transport, and ocean acidification. For example, marine HAB models such as the California coast domoic acid model (C-HARM), have benefited from the development of Regional Ocean Modeling Systems (ROMS). In freshwater or estuarine systems, hydrodynamic models (e.g., US Army Corps of Engineers [USACE] Adaptive Hydrodynamic Model) could help predict downstream fate and transport of blooms, and also aid in modeling sediment or spill transport.
- Additional HAB taxa such as the brown macroalga Sargassum, have emerged as an ecological or public health threat and are ideally suited for use of remote sensing and numerical transport models; efforts are underway at multiple levels (regional, national, international) to address these emerging issues. Despite differences in life history, there are potential synergies in *Cladophora*

(filamentous green algae) and *Sargassum* research and modeling, including growth and transport modeling.

- While still in their inception, machine learning methods are rapidly gaining acceptance within agencies (e.g., National Oceanic and Atmospheric Administration [NOAA], USGS), and benefit from the rapidly increasing volume of observational data. These models can also be used to identify high-value data streams (Reichstein et al., 2019) that may otherwise be unrecognized as important for forecasting HABs. Bayesian statistical methods have enhanced the ability to model complex environmental systems.
  - Artificial Intelligence is now proving to be useful in identifying patterns in toxin data that can lead to highly accurate forecasts of paralytic shellfish poisoning (PSP) toxicity in the Gulf of Maine (Grasso et al., 2019).

1.3.2. KNOWLEDGE GAPS AND UNDERDEVELOPED CAPABILITIES

- With a few exceptions (e.g., Lake Erie), integrated modeling and forecasting have not advanced as rapidly for lakes and inland waters compared to marine systems (Janssen et al., 2019; Rousso et al., 2020). Inland waters may be better suited for regional modeling efforts and use of models that can be adapted/calibrated at the local level.
- Population dynamics models are lacking for several key HAB species/regions. For example, *Alexandrium* spp. blooms on the west coast and *Pseudo-nitzschia* blooms in the northeast may not be fully modeled based on knowledge of blooms of these species on the east and west coasts, respectively. These are likely to represent distinct populations that necessitate regional-scale observations of bloom dynamics to inform models.
- Although sensors, sensor networks, models, and forecasting have advanced substantially since HARRNESS (2005), early warning systems that rapidly communicate changing environmental conditions indicative of potential HAB development to relevant stakeholders are rare. However, monitoring of some algal toxins to protect public health has been successfully implemented at the state level for decades (NSSP 2019; Appendix 2, Shumway et al. 2018).
- For the most part, HAB abundance models spanning the freshwater-to-marine continuum (Paerl et al., 2018) are lacking, as are watershed-scale models focusing on HABs. Nonetheless, recent federal initiatives (e.g., NOAA Water Initiative; USGS Next Generation Water Observing System) could possibly be leveraged to facilitate advances in this area.
- Many existing models focus on short-term (weather-scale) predictions; seasonal forecasts exist (e.g., for Lake Erie and the Gulf of Maine) but are less common, and are challenged by inherent difficulties in forecasting beyond the scale of weather events (days to a few weeks).

- Using historical observations and current conditions to predict how HABs will respond to decadal and climate-scale changes is difficult (e.g., Ralston and Moore, 2020; Wells et al., 2021).
- It is unclear whether existing models could be scaled up or applied to other regions, particularly those based on statistical relationships. These models may provide a template for development of similar models for other systems, but will not necessarily reduce the data, time, and effort requirements to transfer the modeling approach to new regions or water bodies (e.g., Graham et al., 2017; Francy et al., 2020).
- Available information from 'omics' and physiological and biochemical studies has increased greatly, but it is still not clear how best to integrate this information into models that would be useful for HAB monitoring and prediction, even though some examples exist (e.g., Lake Erie [Rowe et al., 2016]).
- Development of models to predict ciguatoxin concentrations in marine organisms is complicated by the numerous parameters that influence the fate and dynamics of these toxins produced by benthic microalgae (e.g., substrate type, body weight of vectors, highly variable toxicity of microalgae [>1000-fold in *Gambierdiscus* spp., Litaker et al., 2010]). Modeling is also complicated by the long (months) and variable lag time between the maximum cell abundance of *Gambierdiscus* cells and toxin detection in fish (Clausing et al., 2016).

1.3.3. PATHS FORWARD AND RECOMMENDATIONS FOR THE FUTURE

- As models of all types mature, the potential for forecasting at all timescales should be capitalized upon. Transitioning these modeling efforts to sustained products builds on substantial investment in research and monitoring that provides the basis for the ability to forecast.
- Indicators of algal activity (e.g., rapid increases in overall algal biomass, metabolic responses of key species of interest, extreme diurnal variability in dissolved oxygen and pH, bloom development in upstream source areas) should be developed to allow the establishment of critical thresholds. These could be applied in sensor networks to establish tiered early warning systems that rapidly communicate changing conditions indicative of potential HAB development to relevant stakeholders (e.g., Texas Observatory for Algal Succession Time Series [TOAST] Network, USGS WaterAlert), followed by acquisition of more HAB-specific observations.
- Observations, early-warning systems, models, and forecasts should be better integrated spatially, i.e., from regional to watershed to waterbody, as well as across the freshwater-to-marine continuum.
- HABs are often driven by local conditions (e.g., wind is an important factor for many nearshore and inland HABs [Liu et al., 2019]) and it is unlikely that one modeling solution will work for most regions. When expanding modeling efforts, emphasis should be placed on building upon existing modeling approaches and applying best practices and lessons learned.

- HABs and HAB toxins must be included in ecosystem and food web models (HARRNESS, 2005) such as Atlantis, Ecopath with Ecosim, to more seamlessly link physical and chemical parameters to HAB dynamics and to tissue toxin bioaccumulation in higher trophic levels (e.g., Gray DiLeone and Ainsworth, 2019). These should be modules of larger integration towards ecological forecast systems with a holistic approach to ecosystem prediction. Trait-based data sets (e.g., IFCB) will be crucial for improving ecosystem model parameterization.

- The volume and specificity of molecular 'omics' data have increased rapidly (see sec. 2.3) but are underutilized in models and forecasting. Are there unrecognized applications for molecular data, and how can these be incorporated effectively into existing modeling frameworks? For example, can toxin biosynthesis models be nested within physiological models with environmental forcing to forecast bloom toxicity?

- Models are only as good as the underlying data; there is still a lack of real-time data that follow FAIR principles. Models and data products could be strengthened by developing partnerships with other entities collecting HAB-related parameters (e.g., drinking water districts, aquaculture companies, public health organizations).

- Conduct rigorous skill assessments and valuation studies for HAB observations and the early warning systems, models, and forecasts they support to allow critical evaluation of the associated cost-benefit relationships. Cloud computing offers potentially powerful emerging computational power to compare models and assess cross-regional model applications.

- To develop, validate, and maintain these models and their data products, it is important to continue supporting the research and monitoring that they are built upon. In many cases this requires years to decades of commitment in all aspects - personnel, computation, and interpretation - to support and sustain these efforts.

1.4. Path to Operations

1.4.1. SENSING AND OBSERVING

- Sensors must be transitioned from Research & Development (R&D) to operations, applications, and/or production/commercialization. Requirements for these endpoints depend, in large part, on the sector involved (i.e., government, industry, or academia). Each sector will generally have its own mechanism for moving new technologies to "operations" (National Oceanic and Atmospheric Administration [NOAA], National Aeronautics and Space Administration [NASA]), which may present challenges to coordinated efforts.

- The transition from a prototype to an operational product (so-called 'Valley of Death') is a well-documented barrier to transitioning an R&D product to its targeted endpoint (Murphy and Edwards, 2003; Harmful Algal Bloom [HAB] Research, Development, Demonstration and Technology Transfer [RDDTT], 2008). Therefore, identifying these barriers and the ideal 'path to operations' during very early stages of sensor R&D projects is essential to facilitating a successful transition to the desired endpoint.

- There are existing mechanisms by which more than one sector can work together or leverage common objectives/goals to realize an operational endpoint (Hulla et al., 2020). The use of common cloud computing infrastructure is one example, and these opportunities could be pursued to operationalize advances in sensing and observing technologies.

1.4.2. SENSOR NETWORKING AND DATA INFRASTRUCTURE

- At a level above the development and transition to operations of individual sensor technologies, observing networks are integrating these and other observational components into regional systems and must be viewed as critical elements along the "path to operations."
  - Efforts are underway to develop a Framework and Implementation Strategy for a US National HAB Observing Network (i.e., a system of regional subsystems) for US coastal waters and the Great Lakes NCCOS and US Integrated Ocean Observing System Program [IOOS], 2020).
  - Other examples exist (e.g., Hudson River Environmental Conditions Observing System) that engage multiple partners (local, state, and federal agencies, and universities) in the operation of continuous water quality stations using a harmonized protocol. These kinds of observing systems can be leveraged to more fully realize a US National HAB Observing Network across the freshwater-to-marine continuum.
- Establishing data infrastructure and management are critical foundational elements for an observing network, and are essential components to provide accurate, actionable (for example, harvesting or beach closure), and timely data/information to managers, public health officials, and other users in support of decision-making. There is a need for a centralized system containing regional nodes.
- A strategy to develop, validate/demonstrate, and deploy data infrastructure and management components included in any plan to transition an observing network to operations (e.g., US National HAB Observing Network Framework and Implementation Strategy) would greatly improve outcomes.

1.4.3. MODELING AND FORECASTING

- HAB-related forecasts differ from NOAA's operational weather-related end products and forecasts, which generally require continuous support (i.e., 24 hours a day, 7 days a week, 365 days a year) and built-in redundancy. A sustained delivery framework may be more appropriate for HAB forecasts due to the seasonal and episodic nature of regional HAB events.

- A key requirement for development of effective, sustained, and integrated early warning systems, models, and forecasts is to acknowledge that there are at least four components that require personnel and committed support:
    - research supporting the development of these modeling systems needs to be in place,
    - resources for sustained observations to inform the models must be available,
    - modeling needs to be supported, including updates of the model as necessary, and skill assessment if end users are to trust the output,
    - end users are unlikely to use raw model output, so personnel to contextualize and interpret the model and underlying data, as well as to develop tools and products accessible to users, must be included in the support system.
- The deployment of formal, operational or sustained forecasts for weather, HABs, or other environmental conditions (e.g., hypoxia or pathogens) is a core mission for some agencies. For example, to accomplish this goal, NOAA's forecast development process generally includes preparation of a formal, yet dynamic or fluid, 'transition plan' (or research to operations plan) during the R&D stage, with changes made as needed across the various Technology Readiness Levels (1-9). A transition plan should be used to guide use and implementation of a HAB forecast.
- Initial and continued stakeholder input is essential to ensure the utility of forecasts. Identifying an "operator" (i.e., an entity that will receive, operate, and disseminate the forecast product) is also a critical requirement.
- Identifying and establishing the resources (funding, infrastructure, personnel) required to support sustained delivery of forecast products and services is essential and may take many different forms including local, state, tribal, and federal resources.
- Modeling groups and funding agencies should take advantage of synergistic opportunities and promote shared resources. In many cases the same model framework (e.g., a numerical model with a biogeochemistry component) supports many potential applications including, but not limited to, HABs.
- Sustained monitoring and modeling should be assessed frequently to ensure that the data and outputs continue to meet the needs of end users and stakeholders. A plan should be in place to upgrade, preempt, or even discontinue systems that are no longer effective or relevant. This assessment planning should ideally be part of the formal transition plan to operations referred to above. In the absence of such a plan, it is still important to conduct relevant (formal or informal) assessments by the operators and stakeholders to address these issues.

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Karenia brevis fish kill at Venice Beach Florida, August 2018. Photo credit: R. Currier.

2 HAB CELLS AND THEIR TOXINS IN THE ENVIRONMENT: DETECTION, ECOLOGICAL IMPACTS AND DRIVERS

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Summary

The effects of harmful algal bloom (HAB) cells, and their toxins and metabolites, on ecosystems vary widely and include devastating events like large die-offs of fish, shellfish, and other invertebrates, and mortality/stranding events of turtles, seabirds, cetaceans, and other marine mammals, e.g., manatees, seals, and sea otters. Societal impacts can derive from contamination of seafood and drinking water, and closures of fisheries, subsistence harvesting and aquatic-based recreational activities. Impacts to freshwater and marine benthic communities (including corals) also occur but are often poorly quantified. Aquaculture operations are particularly vulnerable to HABs because of the challenges or inability to move or protect stocks during a bloom. Adverse effects on commercial species (immunological impacts; reduced recruitment, growth, and reproduction; mass mortalities) can lead to significant losses in harvests or spoiled or contaminated products resulting in substantial economic losses and adverse consumer health consequences. Methods for the detection and quantification of HAB cells and their toxins, including "omics" approaches, underpin a holistic approach to understanding these events and assessing their ecological impacts. Tools are developed and implemented with the goals of characterizing exposure, uncovering emerging threats, and identifying

markers for HAB response to environmental drivers. The complex intersection and synergy of natural and anthropogenically derived environmental factors supporting bloom events (e.g., salinity, temperature, irradiance, pH, carbon dioxide, nutrients [including rates, types, and ratios], and biological interactions such as algal competition, and grazing) creates a very challenging landscape for HAB research. Furthermore, the aspects of potential bloom control mechanisms related to the co-occurrence of bacterial and viral pathogens remain elusive. Nevertheless, the HAB community has made tremendous strides in expanding our knowledge base in these focus areas since the release of the previous HARRNESS.

Major technological advances over the past two decades have dramatically improved the way in which cells and toxins are detected and quantified. Traditionally, microscopy was the sole means for cell identification and enumeration; however, results were easily confounded by morphologically similar species. We also now know that cell toxicity (even within isolates of the same species) can vary widely, and that cell numbers do not always correlate linearly with toxin concentrations. Therefore, toxin bioassays are an important part of the research and monitoring framework. Historically, whole animal models (typically mouse or rat) were used, whereas today new toxins and metabolites are discovered and monitored mainly using advanced instrumentation such as mass spectrometry. Many regulatory agencies globally and in the US have adopted or are moving towards the routine use of these methods for management purposes. While detection assays have vastly improved, they still require the findings of ongoing basic research to capture additional key species and strains (e.g., previously unknown, geographically separated isolates), and toxin congeners to ensure assays are highly specific, robust, and cost-effective to allow their transition to routine monitoring programs. One key related initiative (also highlighted in the last HARRNESS) that has remained largely unfulfilled is the development of reference material repositories for curated toxins and genetic material (including standards, calibration solutions, matrices, and quality control materials). This would be a significant advancement for the HAB field yet requires sustained funding to develop and support a community of experts, physical and virtual infrastructure, and long-term operations.

Ecosystem-level impacts of HABs and their toxins ultimately begin at the individual cellular and subcellular levels. Despite advances over the past decade in our understanding of the molecular targets/mode of action for different HAB toxin groups, their integrated cellular or system-level effects, and specific mechanisms of susceptibility require additional study. This is due, in part, to the myriad factors involved and the interactions that occur between organism-level toxin exposure responses (i.e., ion channels, receptors, enzymes, etc.) and the subsequent symptoms/responses throughout an ecosystem. For example, involvement of multiple organ systems may lead to chronic diseases affecting animal health. Additionally, toxins may affect natural signaling processes leading to obvious (i.e., pain perception) as well as less obvious effects (i.e., synaptic plasticity [modification of transmission across synapses], that may lead to neurological disorders).

Although some progress in understanding ecological-level impacts has been made, additional animal models and biomarkers of exposure are needed to study susceptible populations, based upon exposure history, sex, inherited genetic traits, developmental stage, and disease stage. Continued research on the routes, rates of transfer and depuration, fates, and effects of HAB toxins from the molecular and cellular, to the organismal and population levels is required to better understand their integrated negative ecosystem effects. Moreover, much remains to be learned about the transfer (including the movement of cyanobacterial toxins from freshwater to marine environments), pervasiveness, and persistence of HAB toxins in food webs and how trophic structure and dynamics are ultimately impacted.

The application of collective "omics" tools has grown exponentially and can greatly support efforts to uncover the interactive individual to ecosystem-level aspects of HAB ecology. These techniques include genomics (the study of cellular genes), transcriptomics (a measure of gene activity or expression), and metagenomics (large scale dataset analysis of genes present from the entire community). Advances in proteomics and metabolomics (the study of cellular proteins and metabolites, respectively), have been slower but both contribute to a more holistic assessment of cellular biology, including toxin production and responses to both natural and anthropogenic environmental factors. These trends will likely continue and may address some of the challenges in deriving more complex cellular level information, e.g., gene[s] and signaling molecules related to processes such as algal toxin production and encystment/excystment, whole community response of natural assemblages, and single cell biological information. Indeed, since the last HARRNESS faster and lower cost methodologies have allowed the research community to increase the number of isolates studied, generate whole cell genomic data, and identify genes related to toxicity and physiological responses to environmental conditions.

The vast amount of data that can now be generated using "omics" approaches will continue to support research in systems with inherently complex conditions, which are extremely challenging to study synergistically in the laboratory (beyond one to three variables). Moving forward, HAB research will continue to benefit greatly from multivariate experiments conducted across wider spatial and temporal scales, using a combination of detection methods and techniques that generate large datasets from organismal to population levels.

2.1. Detection of HAB Cells and Toxins

2.1.1. CURRENT STATE OF KNOWLEDGE AND SIGNIFICANT ADVANCES

Since the writing of the last decadal national research plan (HARRNESS, 2005) there have been significant advances:

- A harmful microalgae taxonomy course offering for US Harmful Algal Bloom (HAB) scientists and managers. Previously, these courses were only available at international venues. This effort supports the renewed demand for organism taxonomic identification using traditional techniques (largely morphological features via microscopy), so that new findings on species diversity based on biogeography, genetic analysis, and toxicity can be placed in an appropriate historical context.

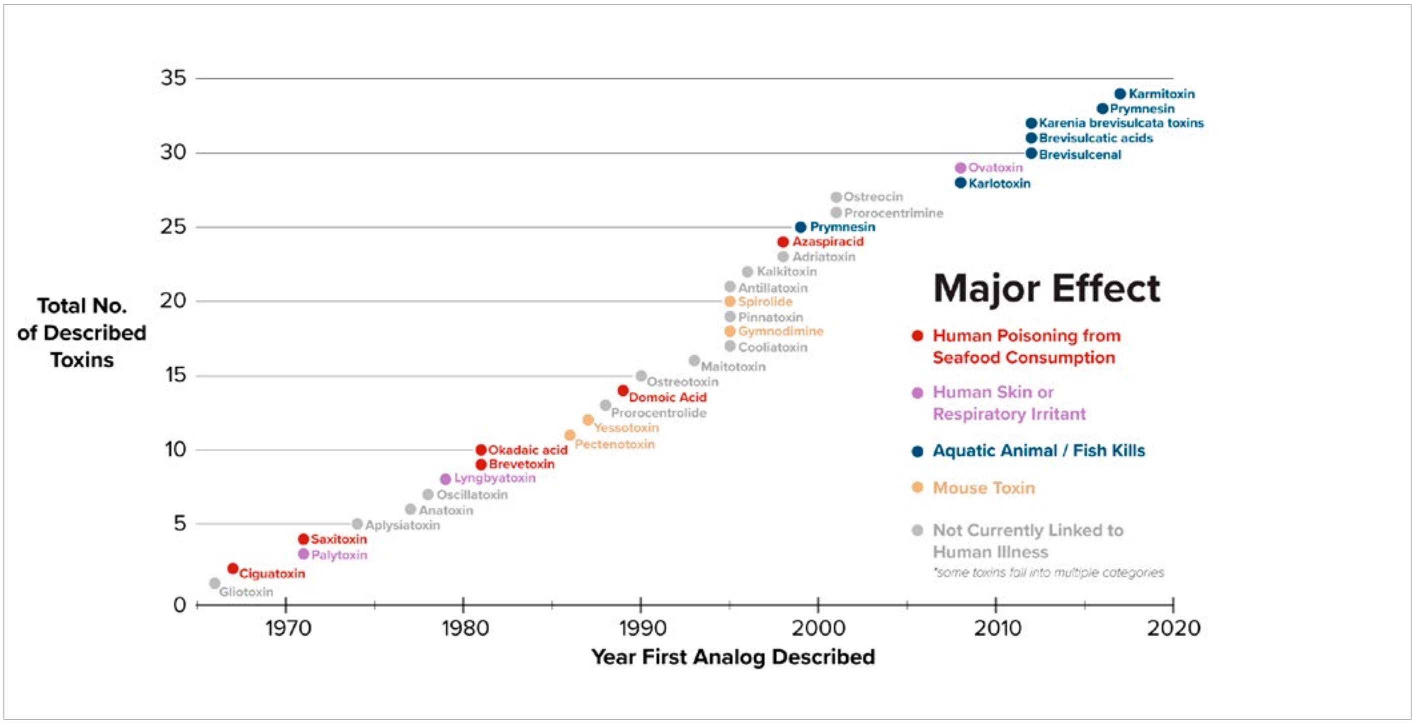
- Expanded development of species-specific genetic/molecular detection assays based on quantitative polymerase chain reaction (qPCR), sandwich hybridization (SHA), fluorescence in situ hybridization (FISH), etc., particularly for species that are morphologically similar/indistinguishable via microscopy (Al-Tebrineh et al., 2012; Howard et al., 2012; Vandersea et al., 2012, 2017; Eckford-Soper and Daugbjerg, 2015; Darius et al., 2018; Ruvindy et al., 2018; Murray et al., 2019) (Table S3 in Lu et al., 2020; reviewed in Penna and Galluzzi, 2013).

- Access to mobile devices and techniques for cell and/or toxin analyses in the field such as qPCR (reviewed in Martin, 2019), DNA sequencing (Hatfield et al., 2020), and solid phase adsorption toxin tracking (SPATT) (MacKenzie et al., 2004).
- In situ imaging capabilities for monitoring and early warning of HAB cells (Doucette and Kudela, 2017), including development of deep learning algorithms for identification (González et al., 2019).
- HAB monitoring via citizen scientist programs (e.g., in Florida and Washington State, NOAA Phytoplankton Monitoring Network).
- Use of remote sensing and satellite imagery for the detection of HABs through cellular photosynthetic pigmentation (Li et al., 2020; Klemas, 2012).
- Development and commercialization of both screening and confirmatory analyses for HAB toxins in the environment and in food for human consumption. These take advantage of advances in both the development of analytical recognition elements (antibodies, aptamers, etc.), known modes of action (receptor binding, enzyme inhibition, etc.), as well as advanced analytical instrumentation (liquid chromatography-tandem mass spectrometry [LC-MS/MS], high resolution-mass spectrometry [HRMS]) (Reverte et al., 2014; Zendong et al., 2015).
- Development of methods for confirming exposure of humans and aquatic fauna (i.e., validated for use in clinical samples, biomarkers of previous exposure, etc.) to select marine and freshwater HAB toxins including domoic acid (DA), saxitoxins (STXs) and microcystins (MCs) (Wharton et al., 2017, 2018, 2019; Bragg et al., 2015); DeGrasse et al., 2014; Lefebvre et al., 2012, 2019).
- Identification of additional congeners and metabolites, often with unknown potency or lacking toxicity equivalency factors (TEFs), within several of the toxin groups currently managed in seafood in the US (i.e., with potential to cause human illness). These include: azaspiracids (AZTs), brevetoxins (BTXs), ciguatoxins (CTXs), DA, okadaic acid/dinophysistoxins (OA/DTXs), and STXs; the causative agents of azaspiracid shellfish poisoning (AZP), neurotoxic shellfish poisoning (NSP), ciguatera poisoning (CP), amnesic shellfish poisoning (ASP), diarrhetic shellfish poisoning (DSP) and paralytic shellfish poisoning (PSP), respectively (listed in red in Fig. 2.1) (Deeds et al., 2020; Kryuchkov et al., 2020; Krock et al., 2019; Abraham et al., 2015).
- Identification of new toxin groups, as well as identification of additional congeners and metabolites with unknown potency or undetermined TEFs, within previously described toxin groups (Fig. 2.1) responsible for negative environmental or other human and non-human animal health effects (i.e., fish

kills, animal mortalities, genotoxicity, skin and respiratory irritation) such as: anabaenopeptins, anatoxins, amphidinols, brevisulcenals, cylindrospermopsins, gymnocins, gymnodimines, karlotoxins, maitotoxins, microcystins, ovatoxins, palytoxins, pectenotoxins, pinnatoxins, spirolides, yessotoxins (e.g., Bacchiocchi et al., 2020; Boente-Juncal et al., 2019; Bouaïcha et al., 2019; Hamamoto et al., 2012; Krock et al., 2017; Mazzola et al., 2019; Pavaux et al., 2020) (examples, not an exhaustive list).

- Incorporation of toxin and molecular assays on in situ sampling platforms (Greenfield et al., 2006, 2008; Scholin et al., 2009; Birch et al., 2016; Bowers et al., 2018) (see also sec. 1) and into several state monitoring programs (e.g., states of California, Ohio).
- Use of eDNA (environmental DNA) to address issues such as biosecurity and invasive species (Sepulveda et al., 2020; Bowers et al., 2021), ecosystem assessment (Pawlowski et al., 2018), biodiversity (Cristescu et al., 2019), monitoring (Thalinger et al., 2020), and management of aquatic systems (Darling et al., 2011).

Fig. 2.1. Cumulative progression of microalgal toxin discovery since 1965. In many cases we have yet to fully understand the inherent complexity of toxin synthesis pathways and their associated genetic control (see also sec. 2.3). This has hampered progress in developing species-specific genetic assays targeting toxin-related genes. For the few examples we have, there have been long lags between these elucidations: cyanotoxins in the early 2000s (reviewed in Pearson et al., 2010), followed by saxitoxins in dinoflagellates (Stüken et al., 2011), and more recently domoic acid in *Pseudo-nitzschia* (Brunson et al., 2018). Additional toxin pathways need to be resolved to develop relevant genetic assays for detection and monitoring. Note: the cyanotoxin class, microcystins, was first discovered in the 1950s (Bishop et al. 1959). *Reproduced with permission from Hess (2018).*



2.1.2. KNOWLEDGE GAPS AND UNDERDEVELOPED CAPABILITIES

- There is a limited number of classically trained HAB taxonomists in the US with the expertise required to accurately identify HAB species based on morphology, and many of these individuals are nearing retirement. A new generation of HAB taxonomists is required to maintain the critical bridge between morphology- and molecular-based species identification.
- Much of our historical knowledge of HAB toxins in seafood is based on total toxicity using in vivo animal bioassays. As we move towards the routine use of analytical recognition element-based screening tests (e.g., enzyme-linked immunosorbent assays [ELISAs], biosensors) and specific chemical confirmatory analyses (e.g., high-performance liquid chromatography with ultraviolet, fluorescence, or mass-based detection [HPLC-UV/FLD], LC with tandem mass spectrometry [LC MS/MS], high-resolution mass spectrometry [HRMS]) knowledge of regional toxin profiles and individual toxicity equivalency factors (TEFs), particularly based on oral exposure as opposed to exposure by traditional intraperitoneal (i.p.) injection, is lacking for many toxins. This information is necessary to equate either integrated ELISA responses or specific toxin

profiles to integrated toxicity values (i.e., toxin equivalents) as required for regulatory use (Botana et al., 2017).

- Historically, toxin chemists have largely focused on the parent molecules of select toxin classes. However, numerous derivatives of these, produced by toxigenic HAB species and/or via transformation of toxins in food webs, play an important role in determining overall toxicity. Additional methods of analysis that include both the parent toxins and transformed toxins (metabolites) are needed (e.g., Abraham et al., 2015).
- In some cases, such as brown tides of *Aureococcus anophagefferens*, although the HAB species was discovered more than 30 years ago, the chemical structure of the toxin produced remains unknown, and therefore its detection relies on bioassays. It has been established that *A. anophagefferens* produces a toxin that elicits a dopamine-mimetic action, inhibits the gill lateral cilia of many adult bivalves on contact with brown tide cells, and is contained in the exopolymer (EPS) cell layer (Gainey and Shumway, 1991), but it has yet to be chemically characterized.
- In many cases we have yet to fully understand the inherent complexity of toxin synthesis pathways and their associated genetic control (see also sec. 2.3). This has hampered progress in developing species-specific genetic assays targeting toxin-related genes. For the few examples we have, there have been long lags between these elucidations: cyanotoxins in the early 2000s (reviewed in Pearson et al., 2010), followed by STX in dinoflagellates (Stüken et al., 2011), and more recently DA in *Pseudo-nitzschia* (Brunson et al., 2018) (Fig. 2.1). Additional toxin pathways need to be resolved to develop relevant genetic assays for detection and monitoring.
- Although progress has been made for some toxin groups (e.g., DA, STXs, and MCs), thorough assessment of the role most HAB toxins play in illnesses and mortalities of higher vertebrates is hindered by the lack of tools and techniques for accurate verification of toxins in tissues and other biological samples.
- Except for the guidelines established under the National Shellfish Sanitation Program (NSSP), which only focuses on HAB toxins that accumulate in molluscan shellfish and pose a potential human health risk (listed in red in Fig. 2.1), there is a general lack of standardization for toxin analysis methods as well as sampling and sample preparation procedures to ensure comparability of analytical data during responses to many HAB events.
- Confirmatory methods for toxin analysis (e.g., HPLC-UV/FLD, LC-MS/MS) require the use of reference standards. There is a need for methods that can accurately detect and measure the concentration of new HAB toxins and congeners for which analytical standards are not yet available (Zendong et al., 2017).
- Most state monitoring programs for seafood safety focus on the regulation of commercial harvesting. There is a need for affordable, easy to use, and rapid toxin test kits that can be used to provide information for recreational or

subsistence seafood harvesters in remote/rural locations where routine monitoring is not provided or impractical (Trainer et al., 2014).

- Most routine phytoplankton monitoring programs sample either from surface water or at discrete depths. Standard practices to include the contribution of benthic or epiphytic HABs or those that form large floating mats (e.g., *Phaeocystis*) to monitor toxic events need to be developed.
- There is a need for rapid methods to distinguish toxigenic from non-toxigenic species that are morphologically similar or otherwise difficult to identify using microscopy.
- Classification software for automated cell identification, necessary for autonomous platforms based on cell imaging technologies, must continue to be deployed in various geographical locations to validate species-specific algorithms for local populations. These algorithms can be challenged by several factors including cell orientation, cell physiology, life history stage, chain-formation, and morphologically similar species. In addition, there is a need to collocate "omics" measurements with imaging sensors.
- Further experimentation is needed to assess the effects from inter- and inintraspecific genetic variation, and cell growth and physiological states on genomic targets used in molecular-based assays (see also sec. 2.3).
- Genetic-based methods beyond traditional polymerase chain reaction (PCR) chemistry and its more modern counterpart quantitative real-time PCR (qPCR) remain largely underexplored (e.g., loop-mediated isothermal amplification [LAMP], robotic process automation [RPA]; [Lobato and O'Sullivan, 2018; Notomi, 2000]).
- Most of our existing knowledge on relative toxin congener and metabolite potencies, needed to set regulatory guidance levels, is based on intraperitoneal injection data in a mammalian model, typically mice. There is a need to re-assess much of these data with more appropriate routes of exposure (e.g., oral potency) to assess human risk (e.g., Abal et al., 2018).
- There is a need for additional in vitro assays to assess total toxic potential both as a bridge between specific chemical analyses and in vivo animal data, and to assess individual toxin potency compared to the parent compound.
- Some reference materials and technologies, including commercial test kits, were developed abroad, and are not easily obtained in the US.
- Widespread adoption of eDNA techniques is limited by a lack of standard operating procedures (SOPs), robust and reproducible data collection, bioinformatics tools, reporting strategies, appropriate use of data for management decision-making, and infrastructure for shared databases.

2.1.3. PATHS FORWARD AND RECOMMENDATIONS FOR THE FUTURE

- Build a US community of expert taxonomists through training and career development opportunities, who can identify HAB species using classical and molecular techniques.
- Enhance the capabilities of expert chemists in the US to identify structures for emerging HAB toxins and their metabolites and align with similar international efforts.
- Engage expert toxicologists, both in the US and abroad, to determine the potency for appropriate routes of exposure for the evaluation of human risk for new toxins and metabolites relative to existing, managed toxins (i.e., TEFs).
- Establish a national database for algal toxins and their metabolites in both seafood and in exposed higher vertebrates, with attention to regional profiles, and align with similar international efforts.
- Establish best practices such as regional/national interlaboratory SOPs for sample preparation (including field DNA extraction protocols) and toxin analysis in different types of species, tissues, or fluids. Standardize methods used to quantify HAB species and toxins in situ, onboard ships, and at field monitoring sites including remote locations and aquaculture farms.
- Establishing guidelines to produce and develop a stable system for the storage/supply of vetted genomic DNA would be a major benefit to this effort. Increased access to these materials would support faster development and validation of molecular assays (see also sec. 2.4 on Reference Materials).
- Dovetail existing efforts in genetic detection with the fast-emerging eDNA community.
- Develop and/or improve the sensitivity of detection methods for determination of toxins and toxin metabolites in preferred clinical samples and non-human animals of management concern.
- Develop and improve multiplex technologies for simultaneous screening or detection of groups of species and toxins.
- Explore and integrate new detection platforms that often debut in the medical field and assess their feasibility for use in HAB monitoring programs.
- Develop additional in vitro screening tools based on the known mode of action of different toxin groups both to account for undescribed toxin variants and to act as a bridge between in vivo and chemical confirmatory methods.
- Develop cost-effective, rapid test kits for toxins that pose a threat to food safety, particularly those that are field deployable, and are available to those who provide information to recreational and subsistence seafood harvesters.

- Advance/upgrade deployable technologies that allow for an expanded suite of cell and toxin detection and image capture (including a way to archive material for later retrieval for further analysis [e.g., capture of additional species/toxins]).
- Support of basic research initiatives to conduct whole genome sequencing and further elucidate toxin pathways and their associated genes, such that more targeted genetic assays can be developed and added to in situ technologies (see also sec. 2.3).
- Support technology advancements that reduce sampling intervals, thereby moving towards real-time/near real-time results.
- Streamline the process for acquiring critical materials such as reference standards and commercial test kits developed abroad and that are not currently distributed in the US.
- Encourage partnerships among researchers, commercial entities, and managers, both domestically and abroad, to achieve technological advances that lead to rapid, robust, and real-time results that allow timely management decision-making.

2.2. Exposure, Impacts, and Emerging Threats of HAB Toxins

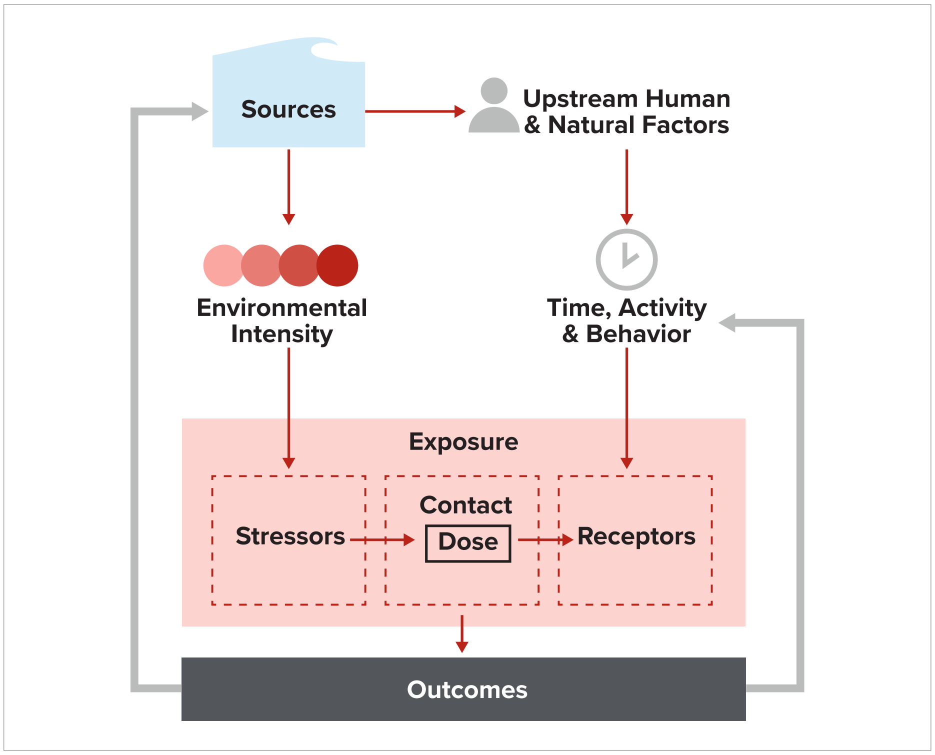
2.2.1. CURRENT STATE OF KNOWLEDGE AND SIGNIFICANT ADVANCES

A. *Exposure*

Historically, most research related to harmful algal bloom (HAB) toxin exposure focused on the vectors of acute algal toxin exposure (National Research Council, 2012). The goals were to safeguard human health, ensure safe consumption of seafood and determine the cause of domestic animal mortalities and mass mortalities of marine life. Recognizing the need to advance exposure science to study how humans and ecosystems interact with stressors in their environment, the National Academies Exposure Science in the 21st Century put forward a concept to integrate environmental phenomena such as HABs and human exposure through creation of an exposure narrative that includes the prediction of biologically relevant human and ecological exposures, and the generation of improved exposure information for making informed decisions on human and ecosystem health protection. Additional advances in this area since the writing of the last decadal national research plan (HARRNESS, 2005) include:

- A glossary of exposure science terms to harmonize the use of exposure and toxicity terminology across multiple disciplines (National Resource Council, 2012).
- A new conceptual framework to connect environmental sources to exposure (see Fig. 2.2) to better understand algal toxins.

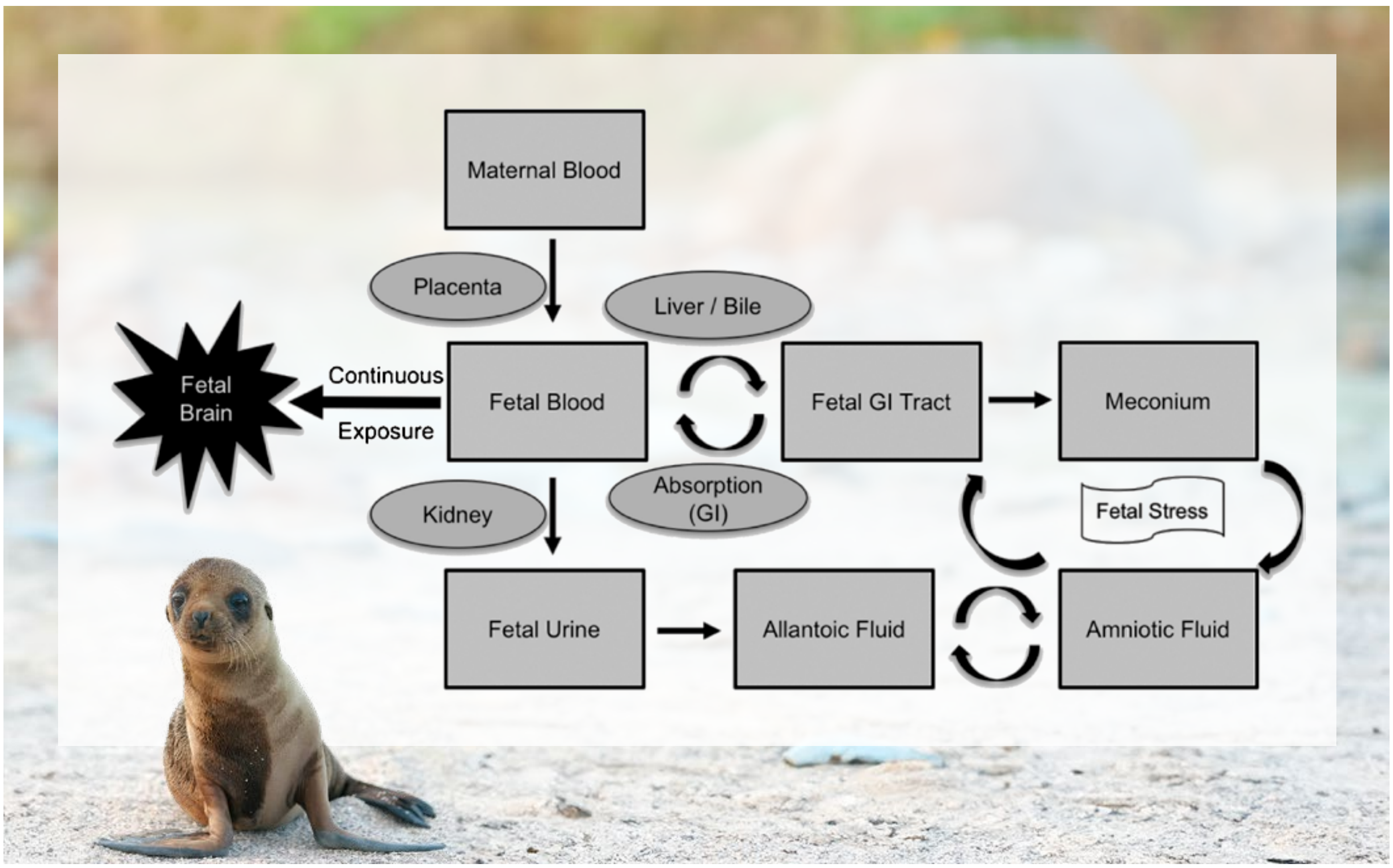
Fig. 2.2. Core elements of toxin exposure science (developed by the National Research Council Committee on Exposure Science), adapted as a framework for evaluating and modeling exposure of humans, wildlife, and ecosystems to HAB toxins. *Figure adapted with permission from National Research Council (2012).*



- A concept to measure the totality of exposure over a lifetime and its corresponding effect on health, referred to as the exposome (Rappaport and Smith, 2010).
    - The exposome is defined as a complementary concept to the genome, i.e., the totality of exposures to stressors over a lifetime, which predispose and predict health effects in an individual. This assumes that exposure begins in utero, encompasses environmental (including occupational) sources of injuries, irritations, and other stressors including lifestyle and diet, and is dependent upon characteristics of the individual. The exposome is thus the record of all exposures, both internal and external, received over a lifetime.
- Identification of new or previously unrecognized exposure routes, including toxin transport from freshwater to marine waters (Gibble et al., 2016; Paerl et al., 2018), new examples of airborne transmission (e.g., MCs; Schaefer et al, 2020), and more recently recognized toxin vectors (e.g., carnivorous/scavenging gastropods) (Shumway, 1995; Darius et al., 2018).
- New studies on cognitive developmental effects after HAB toxin exposure (e.g., to DA) (Grant et al., 2019).

- Development of a model to predict the outcome of fetal poisoning in relation to the specific timing of HAB events in major sea lion rookeries; (Ramsdell and Zabka, 2008; also see Fig. 2.3 on mechanisms of DA exposure in fetal sea lions).

Fig. 2.3. High susceptibility of the mammalian fetus to domoic acid (DA). California sea lion fetuses can be at high risk of developing lasting neurobehavioral impairment as pups due to continued exposure to domoic acid (DA) in utero. Pregnant females ingest food contaminated with low levels of DA, which may not cause acute symptoms in the adult. As shown in the schematic, DA is then transferred from maternal blood to the fetus, excreted and recirculated through fetal fluids (amniotic and allantoic) leading to continued DA exposure of the fetal brain (Lefebvre et al., 2018). This prenatal high susceptibility to DA has also been shown in rodents in the laboratory (Ramsdell & Zabka, 2008). *Figure reproduced with permission from Lefebvre et al. (2018).* Photo credit: D. Peak © by 2.0 Sea Lion Pup.

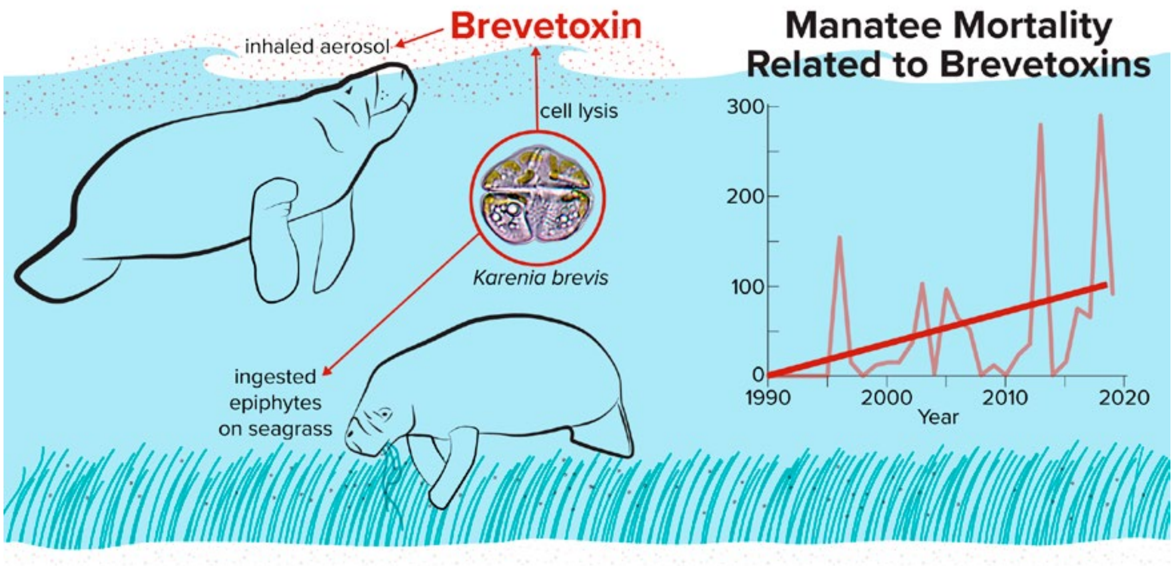


- Demonstration of differential mode of action and vulnerability to HAB exposure of various life history stages of aquatic fauna (e.g., high susceptibility of postlarvae/early juveniles of soft-shell clams to PSP-producing dinoflagellates and lack of exposure/effects in their planktonic larvae [Bricelj et al., 2010]).
- Initial studies have documented the potential for simultaneous exposure and synergistic effects of multiple algal toxins in wildlife. Examples include DA and STX in Alaskan waters (Lefebvre, 2016; Fig. 2.4), MCs and DA in coastal waters of California (Gibble and Kudela, 2014), DA, MCs and BTXs in coastal Florida (Metcalf et al., 2020) and freshwaters where multiple cyanotoxins can co-occur (Metcalf and Codd, 2020).

- Identification of new potential vectors of HAB exposure in food webs, including lionfish (ciguatera poisoning) (Robertson et al., 2013; Hardison et al., 2018), menhaden (Del Rio et al., 2010), and blue crabs (cyanotoxins) (Garcia et al., 2010), and transfer of BTXs from epiphytic algae on seagrasses to manatees (Flewelling et al., 2005, Fig. 2.5).
    - Seagrass die-off from the recurring brown tides in the Indian River Lagoon (Florida) are resulting in starvation and mortality of threatened manatees (Lapointe et al., 2020).
- Vectors of trophic transfer of algal toxins have been mapped through aquatic food webs across multiple trophic levels for select toxin groups (Yang et al., 2016).

Fig. 2.4. Increasing threat of HAB toxins in Alaskan coastal waters. Locations where domoic acid (DA) and saxitoxin (STX) were detected in stranded and harvested marine mammals (2004-2013). Red and blue indicate species positive for DA and STX, respectively. The greatest prevalence of DA was found in bowhead whales, and that of STX in humpback whales. The number and wide geographic range of affected species illustrate the increasing threat of HAB toxins in this region experiencing warming ocean temperatures and loss of ice cover. This threat was confirmed by reports of extensive, exceptionally dense beds of *Alexandrium catenella* cysts in the Alaskan Arctic, associated with a higher risk of temperature-dependent cyst germination and conditions more favorable for the earlier development and more extended duration of *A. catenella* blooms (Anderson et al., 2021). *Figure reproduced with permission from Lefebvre, 2016.*

Fig. 2.5. Mortalities of endangered manatees in southwest Florida are caused by brevetoxins (BTXs) produced by the dinoflagellate *Karenia brevis*, 1990-2020 (from Anderson et al., 2021). Manatees inhale aerosolized BTXs at the air-water interface where cells are readily lysed by turbulent wave action. They also ingest epiphytes containing BTXs that are attached to local seagrasses, even when no *K. brevis* cells are detectable in the water column, a toxin food web pathway discovered by Flewelling et al. (2005). *Mortality plot from Anderson et al., 2021*.



B. *Impacts*

Health risks of HABs have traditionally been understood in terms of case investigations of human exposures, replication in laboratory animals, and extension to zoonotic events. For select toxin groups, these health risks have been examined in terms of acute toxicity, developmental toxicity, and progression to disease or death.

A systematic scoping literature review for marine toxic/harmful algal blooms and observed acute and chronic health effects (Young et al., 2020) covered studies published between 1985 and 2019 with the following observations:

- The number of published studies on health effects of marine toxins more than doubled between the first (2005-2015) and second (2024-2034) National Plans.
- Ciguatera was the most published syndrome (58%) with 131 case reports, 73 surveillance studies, 8 epidemiological studies and 6 studies on biological or genetic markers.
- Neurotoxic shellfish poisoning (NSP), diarrhetic shellfish poisoning (DSP) and amnesic shellfish poisoning (ASP) comprised a total of 88 health studies.

A similar systematic scoping literature review for acute and chronic impacts for freshwater/cyanobacteria HABs is lacking. Additional examples of advances in our understanding of the impacts of HABs and their toxins include:

- Impacts of HABs on benthic communities are increasingly recognized (Landsberg 2002; Bauman et al., 2010) leading to complex shifts in the food web (Fig. 2.6).

- Repeated and long-term exposure investigations in experimental aquatic animals have been published for several algal toxins. Findings include documentation of neurological impairments and cognitive deficits (Hiolski et al., 2014; Lefebvre et al., 2017, 2019), and the accumulation, biotransformation, and depuration of toxins (e.g., Plakas et al., 2002; Bricelj et al., 2014; Clausing et al., 2018; Loeffler et al., 2018).
- Advances in understanding how chronic exposure to the neurotoxin domoic acid (DA) affects cognitive capabilities in marine mammals and the potential impacts to humans via laboratory model studies in mammals (Lefebvre et al., 2017).
- A case definition has been established for DA epileptic disease in sea lions (Ramsdell and Gulland, 2014):
  - Domoic acid acute poisoning was documented to progress through a silent period of months before manifesting as epileptic disease in sea lions.
  - Damage to the secondary olfactory cortex affects the ability of these animals to recognize members of their social group and leads to conspecific aggression.
- Guidelines have been established for domestic animal protection due to mortalities caused by exposure to HAB events.
- Intraspecific differential impacts of STXs (on burrowing capacity, toxin uptake, growth, and mortalities) in Atlantic US soft-shell clam populations were explained by a single point mutation in the sodium channel of this bivalve; intense STX-producing blooms acted as a natural selection agent leading to rapid evolution of STX nerve resistance (Bricelj et al., 2005; Connell et al., 2007, Fig. 2.7).
- HABs and their toxins are known to adversely affect the immunological response (largely cellular immune response provided by hemocytes) of many bivalves (reviewed in Lassudrie et al., 2020), but immunological effects on other aquatic invertebrates and the effects of HABs on the more complex immune response of vertebrates are poorly understood. The linkage between HAB-induced immune suppression and disease is often not clearly established.
- Macroalgal blooms have broad impacts on human activities, from physically limiting recreational and commercial shore-based activities (e.g., fisheries, aquaculture, swimming, boat operations, irrigation systems, desalination plants, tourism; Lyons et al., 2014 and references within). They also have varied effects on organisms within the local ecosystem (e.g., light attenuation, reduction in biodiversity through competition with native species, suffocation and oxygen depletion, food web changes, allelopathy (see sec 2.5.1.B) (reviewed in Lapointe et al., 2018), and threats to human and marine mammal health through harboring of pathogens (Ishii et al., 2006, Vijayavel et al., 2013) and decay-related metabolites (Smetacek and Zingone, 2013; Resiere et al., 2019).

Fig. 2.6. **Complex marine food web showing multiple pelagic (left) and benthic (right) pathways of biotoxin contamination via harmful algae.** Herbivorous zooplankton and benthic suspension-feeding bivalves can transfer toxins to secondary consumers, e.g., planktivorous marine mammals, carnivorous gastropods and crabs, sea otters and mollusk- and fish-consuming seabirds. Benthic harmful algae can also be consumed by deposit-feeders or by suspension-feeders following resuspension. Many new pathways have been discovered both in marine and freshwater in past decades. *Figure adapted with permission from Shumway, Burkholder & Morton, eds. (2018).*

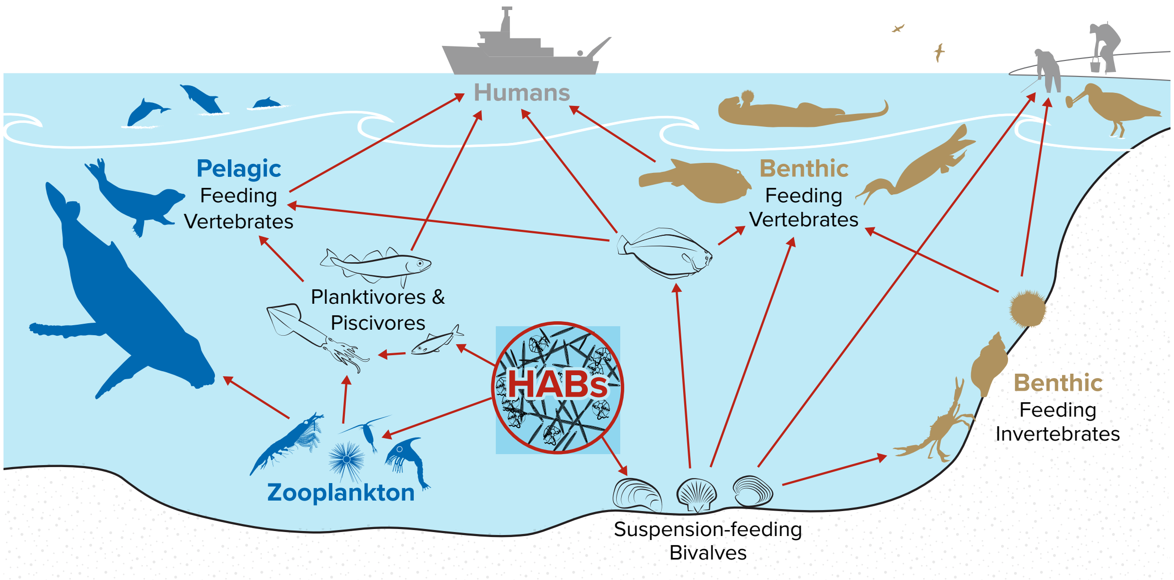
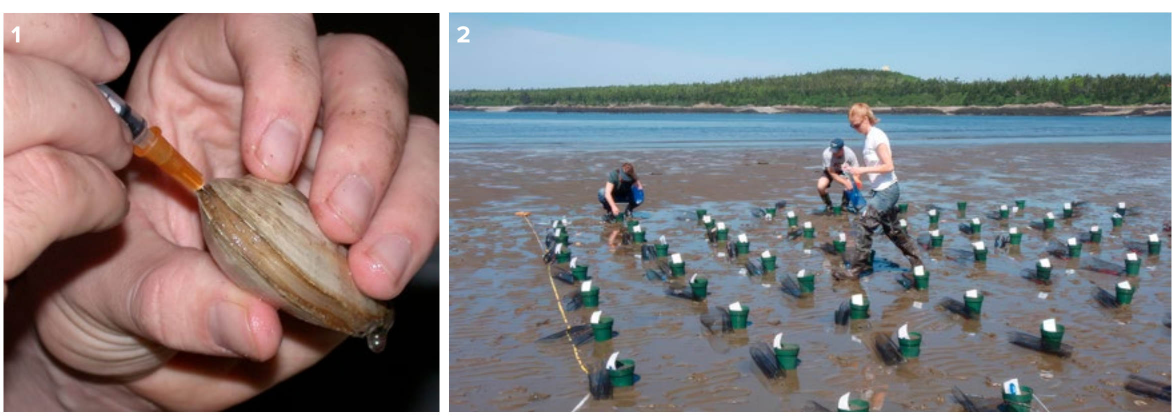


Fig. 2.7. Field experiments conducted in coastal eastern Maine demonstrated that toxic blooms of *Alexandrium catenella* select for genetically based resistance to paralytic shellfish toxins (PSTs) in populations of the soft-shell clam, *Mya arenaria*. (1) Large adult clams can be genotyped non-destructively by determining the sequence of the sodium channel protein at the site of the resistant mutation from extracted hemolymph (Hamilton and Connell, 2009). **(2)** Offspring bred from known genotypes (clams sensitive or resistant to PSTs) were deployed in the intertidal in pots protected from predators, prior to the seasonal bloom of *A. catenella.* They were recovered at the end of the red tide season to determine clam recovery, a proxy for survival, and individual shell growth rate as a function of genotype (Bricelj et al., 2023). *Photos reproduced with permission from L. Connell, University of Maine.*



C. *Emerging Threats*

The continuing globalization of economic activity (trade and related shipping) and increasing impacts from changes related to climate pose fundamental threats to environmental health. These drivers may also influence the impacts of HAB species (Burford et al., 2020; Wells et al., 2020). The HAB community has made significant advances to address such emerging threats, including:

- The role of large-scale oceanographic processes in controlling the origin and progression of HAB events has been documented. For example, the 2015 "warm Blob" in the northeastern Pacific and *Pseudo-nitzschia* blooms (Zhu et al., 2017), causing a simultaneous shellfishery closure across three states (WA, OR, CA) (McCabe et al., 2016); the 2014 Toledo, Ohio, water crisis, where a dense, toxic *Microcystis*-dominated bloom was transported from Maumee Bay towards the city water intake playing a major role in a two-day drinking water ban (Steffen et al., 2017; Alliance for the Great Lakes, 2019); and the 2018 *K. brevis* bloom that ultimately impacted Florida's panhandle, panhandle, and southwest and east coasts (Weisberg et al., 2019).

- The role of viruses in the transfer of cyanotoxins (e.g., MCs) from intracellular to extracellular pools may increase the risk of exposure to the public by delivering a pool of dissolved toxin directly into water treatment utilities (McKindles et al., 2020).

- The expansion in HAB ranges, frequencies, and intensities has been documented in many regions. Examples include the Gulf of Maine, Rhode Island, and Florida's Gulf of Mexico coast (*Pseudo-nitzschia* spp.) (Fernandes et al., 2014, Bates et al., 2018, Sterling et al., 2022); Chesapeake Bay (*Alexandrium monilatum* and *Margalefidinium* [formerly *Cochlodinium polykrikoides*]) (Robison, 2019); the northern Gulf of Mexico (*Gambierdiscus* spp.) (Tester et al., 2014); Lake Okeechobee and tributaries (*Microcystis* spp.) (Kramer et al., 2018); Washington State waters (*Azadinium* spp.) (Adams et al., 2020); Alaska State waters and the Gulf of Maine (*Karenia mikimotoi*) (Vandersea et al., 2020; Record et al., 2021). The knowledge base for climate-driven changes and environmental parameters (e.g., nutrient concentrations and ratios, temperature, salinity, and pH) and the role they play in toxin production continues to expand (Botana, 2016).

- The above expansion and intensification of HABs poses an increasing threat to aquaculture in the US by, e.g., affecting the development of mariculture in offshore waters (Mizuta and Wikfors, 2020). There is also increasing awareness of the adverse effects of HABs on mariculture either directly (e.g., Pitcher et al., 2019; King et al., 2021) or through more subtle effects such as loss of habitat (e.g., submerged aquatic vegetation) that affects recruitment of marine species (Brown et al., 2020).

- Increased attention is now given to benthic HAB species and new technologies and protocols that can identify and distinguish among several extremely toxic species of the benthic dinoflagellate, *Gambierdiscus*, the organism responsible for ciguatera poisoning (Fig. 2.8A and 2.8B), as well as to monitoring techniques for benthic HABs (Tester et al., 2014; Hardison et al., 2016; Nishimura et al., 2016; Parsons et al., 2021; Pitz et al., 2021).

- The impacts of discharge of freshwater HABs (cyanobacteria) into estuarine and coastal environments have been documented (Gibble et al., 2016), and the topic was one of the major themes of the 10th US HAB Symposium in 2017.
- Drinking water for humans and other terrestrial animals is adversely affected by cyanobacterial HABs and their toxins throughout much of the US (Backer et al., 2015; Wood, 2016; see sec. 4.1).
- The presence of cyanotoxins in freshwater poses an increasing threat to pets, livestock, and large marine mammals (Roberts et al., 2020; see sec. 4.1). Many cyanobacterial genera produce toxins, and some common HAB-forming genera include *Anabaena (Dolichospermum)*, *Aphanizomenon*, *Microcystis*, *Cylindrospermopsis*, *Planktothrix*, *Microseira*, and *Moorea*.

Fig. 2.8 A. *Gambierdiscus* species, producers of ciguatoxins, are benthic (= bottom-dwelling) dinoflagellates that attach to macroalgae, seagrasses, and coral habitat (1) in US tropical and subtropical waters: Florida Keys, Hawai'i, Puerto Rico, Gulf of Mexico, and the Caribbean. (2) Scanning electron micrograph of *Gambierdiscus carolinianus*. *Photo credits:* 1. *P. Tester, NOAA; 2. M. Faust, Dept. of Botany, Smithsonian Institution (retired).* Bottom: *Gambierdiscus* cells attached by mucus to fiberglass window screen. *Photo credit: S. Kibler, NOAA.* Increasing ocean temperatures associated with global warming may promote the geographic range extension of *Gambierdiscus* to higher latitudes not presently affected by ciguatera poisoning (CP) (e.g., Kibler et al., 2015).

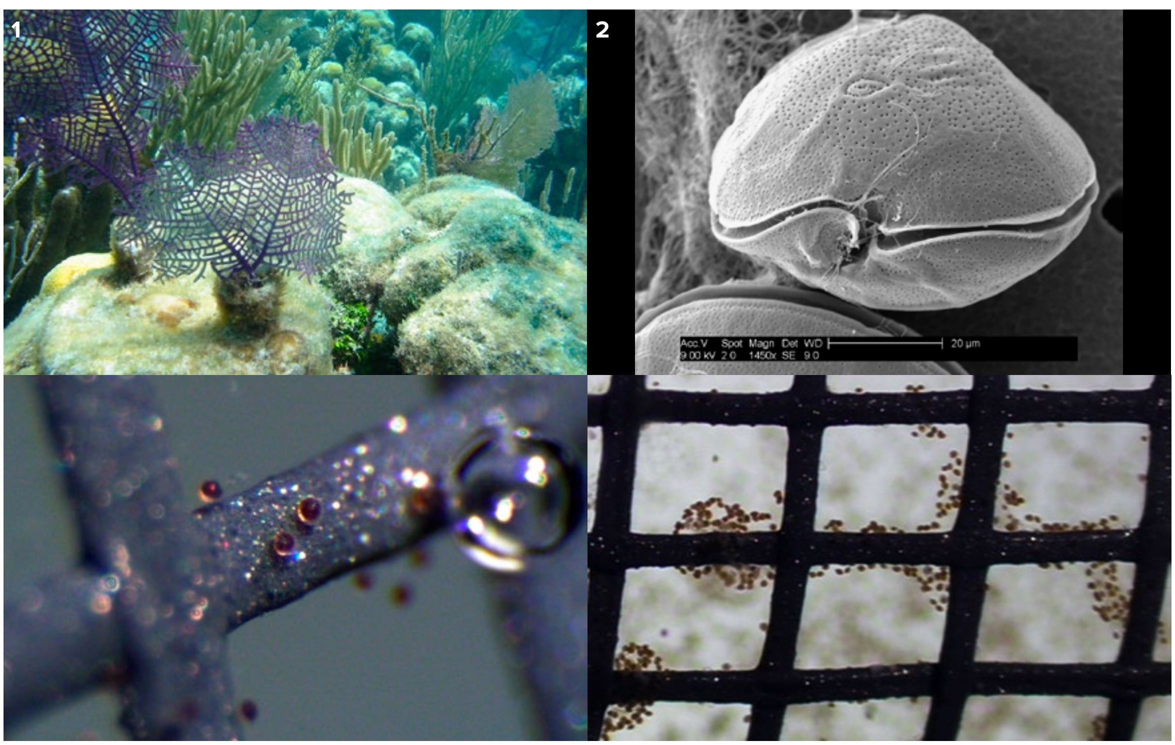
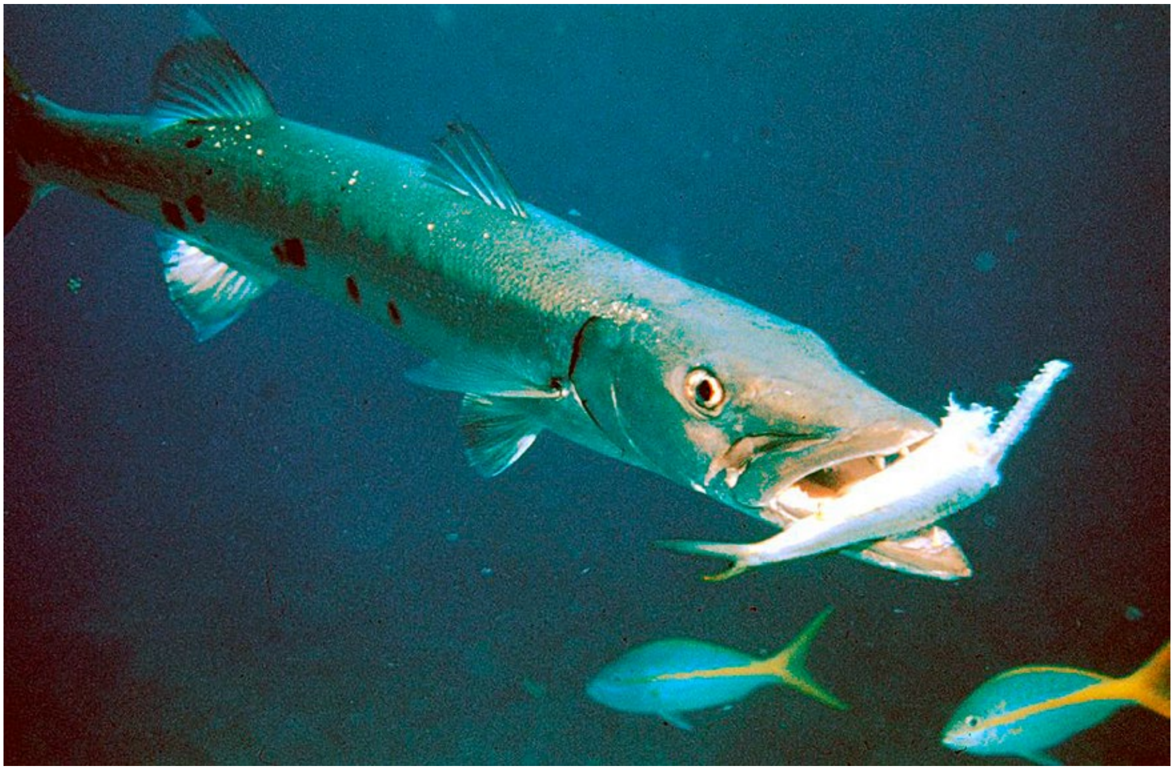


Fig. 2.8 B. *Gambierdiscus* cells are grazed by herbivorous fish and invertebrates, and toxins concentrate in carnivorous reef fish, such as barracuda, *Sphyraena* spp. (shown), grouper, and snapper causing ciguatera poisoning (CP) when consumed by humans. *Photo credit: Florida Keys National Marine Sanctuary.*



2.2.2. KNOWLEDGE GAPS AND UNDERDEVELOPED CAPABILITIES

A. *Exposure*

- Of 380 studies published during 1985-2019 on the acute and chronic effects of exposure to HAB toxins (Young et al., 2020), the most studied route of exposure was ingestion via a food vector (93.7% of studies). Other routes of exposure, including inhalation and direct contact with seawater, require further study.
- It is recognized that harmful algae (HA) and their toxins can influence ecosystems from the top-down (i.e., affecting predators and influencing grazing), and from the bottom-up (i.e., affecting planktonic and benthic HA communities). There is little knowledge, however, about how these factors influence the structure, dynamics and stability of major fisheries and populations of critically endangered species. The impacts of HAB toxins upon natural resources, their transfer and pervasiveness in the food web and the sedimentary environment, and their influence on trophic structure (size and composition) require additional study.
- There is a lack of data on the exposure risk of lakefront communities to aerosolized cyanotoxins, especially near large lakes including but not limited

to western Lake Erie, Green Bay and Lake Michigan, and Lake Okeechobee, Florida (Plaas and Paerl, 2021).

- Limited data exist on cyanotoxin accumulation in both marine and freshwater bivalves and other seafood.
- More information is needed on the risk of exposure to cyanotoxins from freshwater algae and cyanobacteria consumed directly as food or as dietary supplements.
- The full extent of the impacts of cyanotoxins is still poorly understood, including: 1) severe neuro-, cyto- and hepatotoxicity in a variety of animals including pets, livestock, and large terrestrial mammals (e.g., elephants); 2) transport and fate through riparian food webs when biomass accumulates on the shoreline; 3) transfer across the freshwater-to-marine continuum; 4) chronic transfer and sublethal impacts (vs. generally well documented acute events); 5) the fate of non-microcystin cyanotoxins in the food web; and 6) whether protein-bound microcystins (MCs) are a health risk to animals or humans.
- Additional efforts should be considered to examine the potential for cyanotoxin accumulation in terrestrial crops irrigated with contaminated source waters.
- The movement (and biotransformation) of toxins and the rates of toxin transfer through multiple trophic levels are still poorly understood for several HAB toxin groups. For example, the lag times for ciguatoxins (CTXs) to enter the food web and cause ciguatera poisoning is especially problematic when trying to relate increased cell abundances to toxic events. Increasing knowledge about susceptible fishery species will lead to improved predictions for community vulnerabilities.
- Limited information exists about the chronic, sublethal effects of bioaccumulated or biomagnified algal toxins, the routes of exposure, and whether such effects render organisms more susceptible to disease by pathogens (bacterial or viral) or parasitism.
- The basis (genetic or other) of the species-specific susceptibility to HAB toxins within given affected taxa is often unknown.

B. *Impacts*

- Of the 380 published studies referenced in Young et al. (2020):
    - Exposure to toxins was classified as an acute event (hours to days of single exposure) for most studies (89.5%), with only four studies reporting chronic exposure (weeks to months or recurrent).
    - Case reports and anecdotal accounts dominate the literature (almost two-thirds of studies) whereas there are few formal epidemiological studies. Of these nearly 50% relate to brevetoxin exposure in North America.

- Notable gaps in the evidence base include a lack of surveillance and epidemiological studies, inadequate methods of exposure assessment and diagnosis, and a paucity of studies of chronic exposure.

- Development of additional guidelines for assessment of the impacts of benthic HABs (both freshwater and marine) is needed.
- The synergistic effects among different algal toxin groups, in addition to other environmental pollutants (e.g., microplastics), are still poorly understood (Wang et al., 2019; Nava and Leoni, 2021).
- Chronic impacts of algal toxin exposure (including cyanotoxins) to human and animal health and fitness are poorly understood and may place certain populations at increased risk.
- Synergistic immunological effects of HABs and their toxins and the development of pathogenic diseases have been largely studied in the laboratory and in bivalves. Field studies demonstrating a link between a suppressed immune response due to HAB toxins and disease are required.
- Advances in the last decade in photobioreactor technology for mass microalgal culture and its application for the culture of HAB/toxic species (e.g., Jauffrais et al., 2012) has great potential to support research on the dynamics of toxin production, toxicology and impacts on aquatic organisms which require longer term studies and a high algal biomass.
- The role of lipophilic shellfish toxins such as yessotoxins and pectenotoxins in aquatic animal mortality events needs to be better understood. Both have been previously researched for their effects on humans from consuming contaminated seafood but an awareness of their potential impacts on aquaculture is only beginning (Pitcher et al., 2019; Gaillard et al., 2020; King et al., 2021).

C. *Emerging Threats*

- Effects of ocean/lake acidification, increasing sea surface temperatures, and loss of sea ice on HABs, their toxin production, and trophodynamics require further study.
- Risk assessment of HABs in Arctic/subarctic regions is warranted. This is where the most rapid rates of ocean warming are occurring and associated food web contamination and toxin impacts in wildlife and ecosystems are becoming of greater concern (Anderson et al., 2019), including freshwater systems (Rosen and St. Amand, 2015).
- Exposure impacts on human health from aerosolized marine and freshwater toxins (Plaas and Paerl, 2021) need to be further investigated.

2.2.3. PATHS FORWARD AND RECOMMENDATIONS FOR THE FUTURE

Moving forward, we need to better translate garnered knowledge into managerial implementation and continue research on emerging issues. Specifically, as top-level priorities we need to focus future research efforts on:

- A plan to integrate movement of toxins through the food web, including determination of rates of toxin transfer and depuration with a focus on understanding metabolism of toxin precursors to more active forms in progenitor and vector species,
- A plan to better understand biotic and abiotic sinks for HAB toxins (e.g., degradation rates of cyanotoxins in natural waters),
- Documentation of risks of exposure to algal toxins of greatest public health concern is needed. This information is required for the development of guidelines for potential exposure via seafood, drinking water, air, and recreational water use.
- Determination of the true burden of human and other animal disease, following acute and chronic exposure to HABs, and including impacts on well-being, using an interdisciplinary approach. This is required to provide a baseline that will facilitate the measurement and understanding of variations in response to current and predicted climate-related variables and other environmental change.
- A focused plan is needed to document the impacts of climate changes on the occurrence and severity of HABs and the toxins they produce.

2.2.4. SPECIFIC SUB-TOPIC RECOMMENDATIONS

A. *Exposure*

- The HAB research and scientific community would benefit by aligning priorities and approaches with the National Academy of Science's guidelines on Exposure Science in the 21st Century to connect environmental sources to human exposure and harmful outcomes (National Research Council, 2012).
- Integrate laboratory animal model data and wildlife exposure information with human exposures and disease. Development of cross-disciplinary research among toxicologists will provide important information about toxic effects. Improved coordination among scientists, veterinarians, physicians, and public health and wildlife/fishery managers is essential to achieve this goal (see sec. 4.1.1; CDC's One Health Harmful Algal Bloom System, OHHABS).
- Continue to develop toxin-specific biomarkers of exposure and understanding of effects for assessing sublethal and chronic exposure. Animals can be exposed to multiple toxins from several HAB species and synergisms are expected. Therefore, toxin-specific biomarkers can aid in recognizing and discriminating among these stressors.

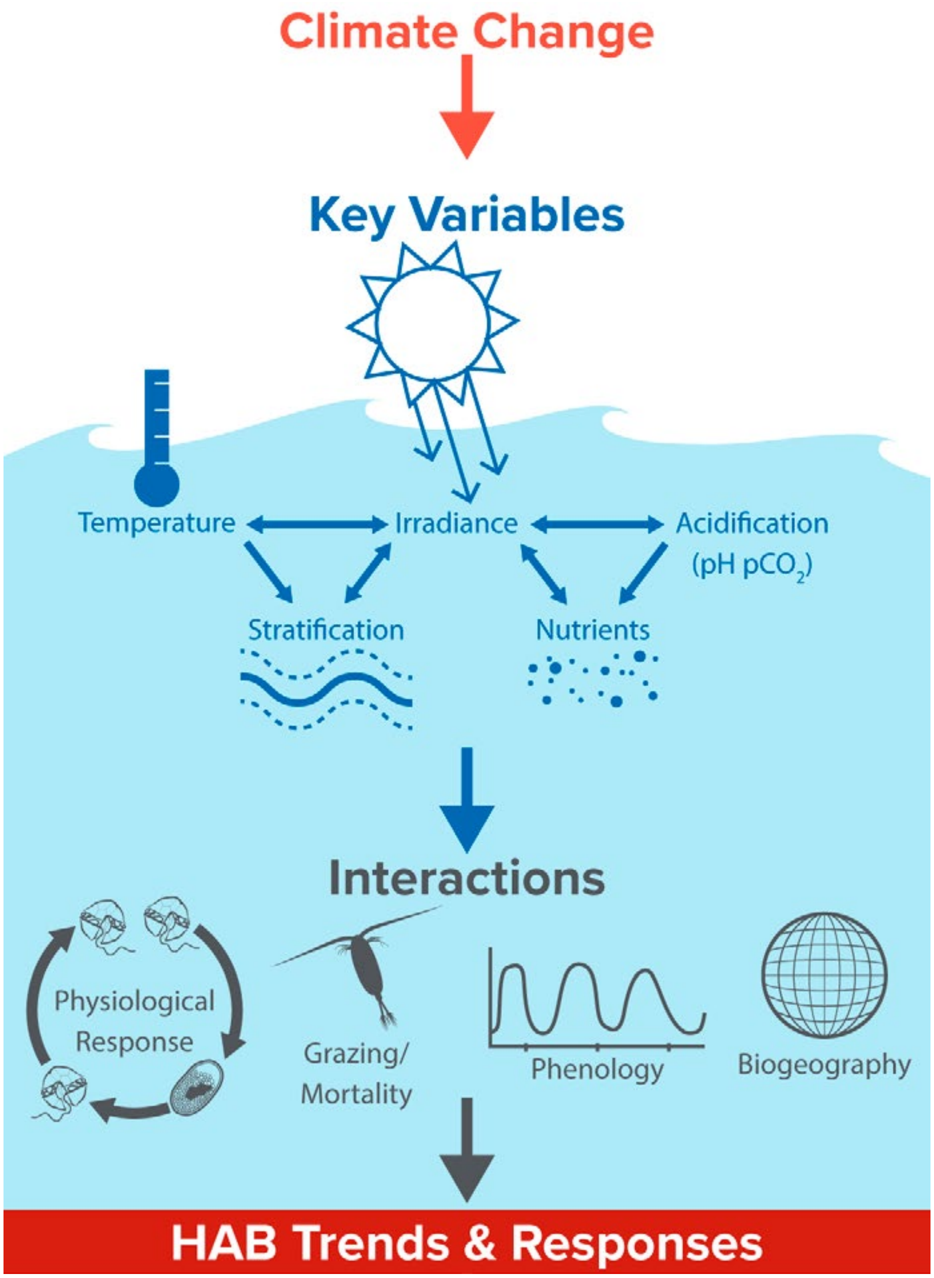
B. *Impacts*

- Assess acute, and especially sublethal and chronic impacts of HABs on various life history stages of affected aquatic species. The limited existing data suggest differential susceptibility by stage.
- Assess the effects of chronic and recurrent exposure to HABs on food webs and economically and ecologically relevant species at the population level. Some toxin groups have seen significant advances in the past decade (e.g., DA) whereas others are still lacking (e.g., azaspiracids [AZTs]). Special attention should be paid to toxin groups that are known tumor promoters (i.e., okadaic acid [OA] and MCs).
- Improve the characterization of the effects of chronic exposure to HAB toxins on both humans and other animals. The primary site of action for many toxins is well known at the biochemical and/or molecular level. What is not well known, however, is how these primary effects translate into long-term adverse health effects such as cancer, cardiovascular disease, developmental defects, and neurobehavioral illnesses.
- Continue to define mechanisms of increased human susceptibility. Studies need to be directed to identify special risk groups such as the very old, the very young, and those with compromised health.
- The vector-specific thresholds for cell concentration and toxicity that cause various impacts in marine organisms are poorly defined in each region and need to be established for many toxic algae.
- Improve our understanding of HABs and HAB toxins that are negatively impacting aquaculture.

C. *Emerging Threats*

- The impacts of climate changes on HABs (Fig. 2.9) need to be assessed on a state and national level, including the subsequent fate of algal toxins in the environment.
- Newly identified HAB toxins may pose a threat, especially if their specific modes of action have yet to be determined. Better understanding is needed on the routes, fate, and effects of these emergent toxins.
- The synergistic impacts of algal toxins and other toxic compounds, as well as additional environmental stressors, need to be assessed. Traditionally, HAB impact studies have focused on a single algal species. Few data exist on synergism with other co-occurring HAB species, or with environmental stressors such as contaminants and infectious disease agents.

Fig. 2.9. **Climate change related variables and HAB interactions and resulting responses.** *Redrawn with permission from Burford, et al. (2020), adapted from Wells et al. (2015).*



2.3. Genetics and Cell Biology of HABs

2.3.1. CURRENT STATE OF KNOWLEDGE AND SIGNIFICANT ADVANCES

- Since the writing of the last decadal national research plan (HARRNESS, 2005), which predicted increased usefulness of algal molecular identification, more than 400 US/international publications have used molecular methods to distinguish >1,000 HAB species representing >205 genera (Ott et al., 2022). The genetic information derived has allowed development of species-specific

PCR, including qPCR, capabilities and other molecular methods for rapid identification (ID) and quantification of HAB species. These methods are now widely available and represent a significant advance in detection and enumeration techniques and their integration into HAB monitoring protocols (highlighted in sec. 2.1).

  - Multi-gene characterization (vs. reliance on one or two genes) has led to improved species ID and detection, often allowing for reconciling molecular identifications with more traditional methods of algal ID, and has contributed to the large international body of available genetic data (https://www.ncbi.nlm.nih.gov/genbank/; e.g., Lundholm et al., 2012; Ji et al., 2015; Meyer et al., 2017).

- The number of isolates used to derive genetic data for detection assay development and associated laboratory physiology studies has risen dramatically since studies revealed that strains of the same species can vary greatly with respect to genetics and toxin production on small (within a bloom) to large (regional; seasonal) scales (e.g., Wilson et al., 2005; Calbet et al., 2011; Trainer et al., 2012; Park et al., 2014; Bowers et al., 2018; Willis et al., 2018).

- In cyanobacterial research, "omics" technology (as depicted for dinoflagellates in Fig. 2.10) has played an important role in toxicological assessment.

  - Genomic technologies have promoted the development of identification of toxin biomarkers and allowed for the prediction of compounds' toxicity and classification (Gatzidou et al., 2007).

  - Transcriptomics has revealed deeper underlying relationships between gene expression and biological processes to generate more direct information of functional genes and specific pathways related to toxicity.

  - Due to their smaller genome sizes, several cyanobacterial HAB species have been fully sequenced (e.g., Shih et al., 2013).

- Complex laboratory-based physiology studies, many supported by genomic methods, have afforded insight into how HAB cells respond in terms of growth, toxin production, etc., to various environmental parameters such as ultraviolet (UV) radiation, nutrients, pH, carbon dioxide (CO_2) related to ocean acidification, salinity, etc., that mimic natural and anthropogenic changes on short to long-term time scales (reviewed extensively in Fu et al., 2012; Wells et al., 2015; Table 1 in Hennon and Dyhrman, 2020).

  - Much of the work on freshwater species has focused on anthropogenic nutrients such as nitrogen (N) (Gobler et al., 2016) and phosphorus (P), as well as factors associated with changes in climate including increased CO_2 concentrations and temperature (Visser et al., 2016). Cyanobacteria have exhibited higher growth rates at increased temperatures compared to dinoflagellates and diatoms and exhibit a more flexible response to environmental conditions (reviewed in Burford et al., 2020).

- Rapid advances in high throughput, low-cost sequencing technologies and related analytical software has greatly expanded the amount of data generated for revealing community structure, elucidating whole individual genomes, and discovering gene(s) related to toxin production and physiological responses to external stimuli (transcriptomics).
  - A variety of next-generation sequencing methodologies (e.g., metabarcoding, microsatellite analysis, automated ribosomal intergenic spacer analysis [ARISA]) have related community structure to ecological parameters (e.g., Steffen et al., 2012; Cooper et al., 2014; Hubbard et al., 2014; Sassenhagen et al., 2018; Shang et al., 2019).
  - Elucidation of whole (or nearly complete) genomes across HAB taxa has opened possibilities for holistic study of cells and their physiological responses, including insights into gene map structure (Ponmani et al., 2016), life cycles (Basu et al., 2017), bloom dynamics (Gobler et al., 2011), and bacterial associations (Ponmani et al., 2016). Furthermore, knowledge of gene maps can be used to complement transcriptomic, proteomic, and metabolomics studies (reviewed in Harke et al., 2016a).
  - Toxin gene(s) discovery has allowed development of molecular assays targeted to key gene(s), thereby moving beyond detection at just the species level (reviewed by Pearson et al., 2016; Neilan et al., 2008; Hackett et al., 2013; Brunson et al., 2018).
  - Transcriptomics, the expression profiling of genes (types and abundance) responding under specific conditions (as defined in a controlled laboratory setting or in the natural environment) (Fig. 2.11), has been used to gain insights on a variety of HAB cell physiology processes (reviewed in Lin, 2011; McLean, 2013; Caron et al., 2017; Hennon and Dyhrman, 2020). A few examples in the use of this technique include: uncovering putative genes related to toxin production (e.g., Boissonneault et al., 2013; Pawlowiez et al., 2014; Brunson et al., 2018), assessing cell response to nitrogen and/or phosphorus concentrations (e.g., Erdner and Anderson, 2006; Morey et al., 2011; Bender et al., 2014; Harke et al., 2016a; Liu et al., 2015; Wurch et al., 2019), and uncovering community level interactions during a bloom (e.g., Cooper et al., 2014; Penn et al., 2014) and during elevated CO_2 levels (e.g., Hennon et al., 2017, 2019).
- Advances have been made in toxicogenomics, which examines the molecular mechanisms involved in the expression of toxicity, and tries to derive molecular expression patterns (i.e., molecular biomarkers) that predict toxicity or the genetic susceptibility to toxins. This approach has been used to address various toxins, including microcystins (MCs) (Hudder et al., 2007; Ma et al., 2021), brevetoxins (BTXs) (Walsh et al., 2003), and domoic acid (DA) (Brunson et al., 2018).
- Metabolomics has grown in popularity as an "omics" technique over the last decade (Hennon and Dyhrman, 2020, Fig. 2.11). It can be used to evaluate cellular responses to changing environments, e.g., salinity, nutrients (Wurch et al.,

2011a, 2011b; Kujawinski et al., 2017; Gaillard et al., 2021), or reveal signaling between bacteria and HAB species (Amin et al., 2015) and among competing algae (Poulson-Ellestad et al., 2014; Song et al., 2017; Poulin et al., 2018).

- Molecular Networking (MN) is a computational strategy introduced in 2012 aiding in the interpretation of complex data arising from tandem mass spectrometry (MS/MS) spectra of unknown but related compounds. More recently this dereplication approach has been applied to investigating the chemical diversity of harmful algae (HA), e.g., *Microcystis aeruginosa* (Briand et al., 2016), *Pseudo-nitzschia multistriata* (Fiorini et al., 2020), *Dinophysis* spp. (Sibat et al., 2021), and *Prorocentrum lima* (Wu et al., 2020). New toxic analogues have been discovered using this cutting-edge tool.
- The utility of proteomics has advanced over the last decade with the increasing availability of complementary transcriptome and genome sequence data. In concert with other "omics" techniques, changes in protein abundance can be quantified to reflect the physiological condition of a HAB or its response to environmental change, e.g., brown tides of *Aureococcus anophagefferens* (Wurch et al., 2011a, 2011b) and *Microcystis* (Steffen et al., 2014) (Fig. 2.11).

Fig. 2.10. **Application of "omics" technologies for dinoflagellate research**. Omics technologies allow understanding of some of the unusual features of dinoflagellate genomes and molecular mechanisms relevant to their biology, including the mechanism of harmful algal bloom (HAB) formation, toxin biosynthesis, symbiosis, lipid biosynthesis, as well as species identification and evolution. These tools can be useful for comparable studies in other non-dinoflagellate HAB forming species. *Figure reproduced with permission from Bi et al. (2019).*

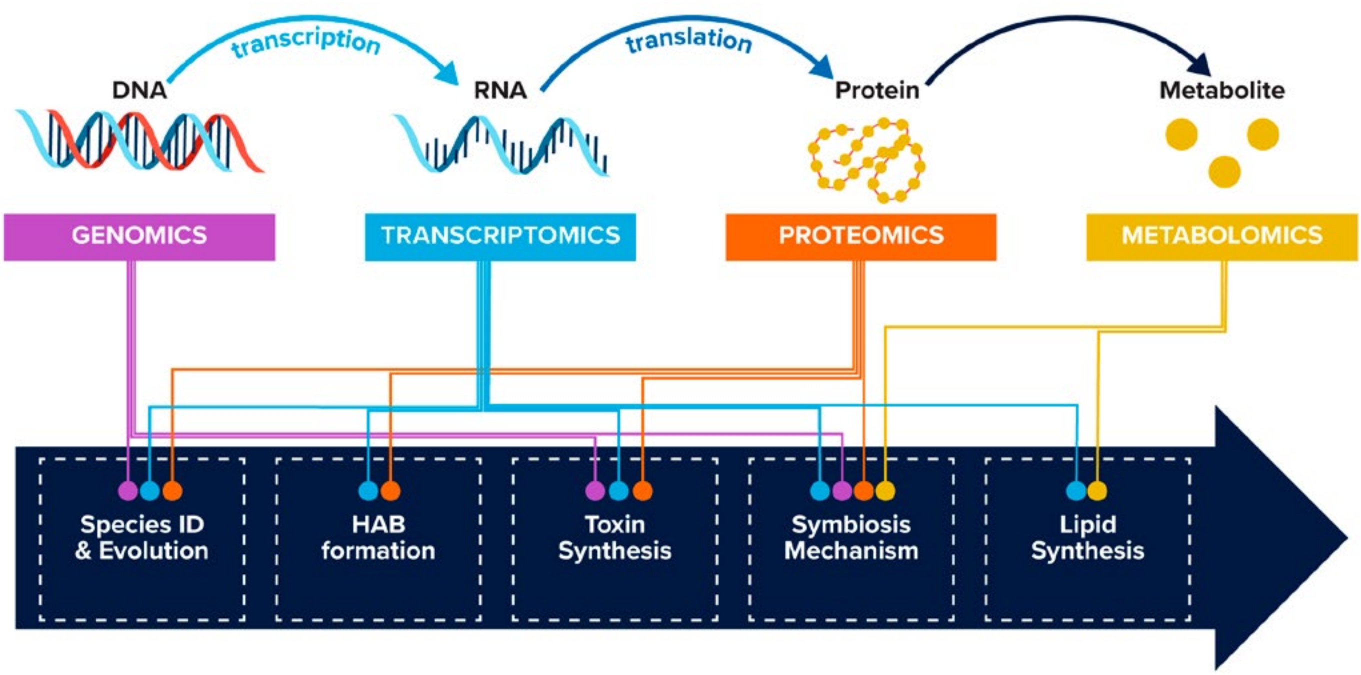
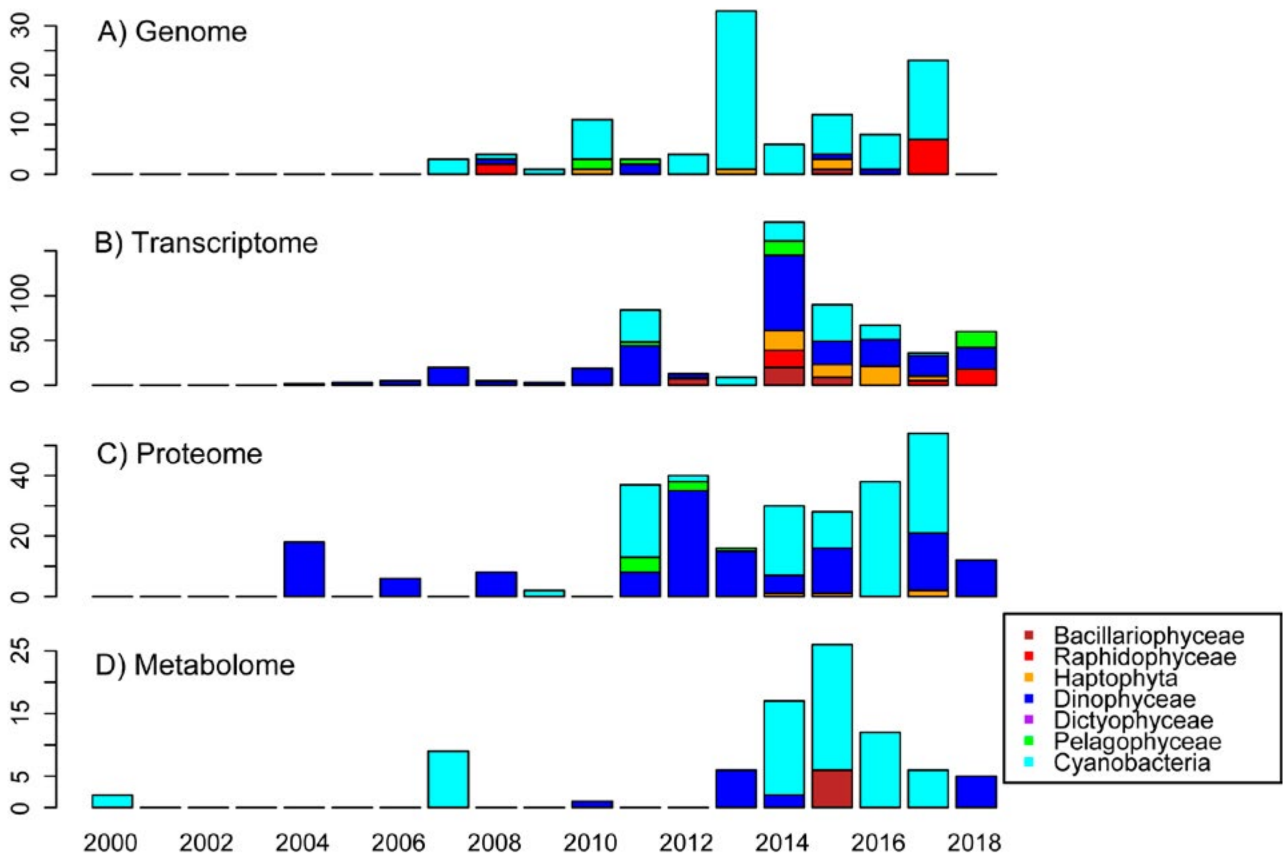


Fig 2.11. **Survey of published and publicly available "omics" datasets for HAB families/taxa.** *Figure reproduced with permission from Hennon and Dyhrman (2020).*



2.3.2. KNOWLEDGE GAPS AND UNDERDEVELOPED CAPABILITIES

- There is limited knowledge of if/how intraspecific genetic diversity (cryptic species, ribotypes, polymorphisms) relates to toxicity and bloom dynamics (initiation, development, maintenance, termination), especially given the fact that variable toxicity has been well documented for strains of the same species (Burkholder and Glibert, 2006; Lelong et al., 2012; Trainer et al., 2012, Briand et al., 2016; Willis et al., 2016; Litaker et al., 2017).
    - Intraspecific diversity indicates that species-wide results from physiological experiments cannot be gleaned from the use of just one or a few isolates. Differences in growth and/or toxin production can also be due to inter-laboratory variability (e.g., in growth chamber characteristics, media seawater source, culture methodology [Lakeman et al., 2009]), and how isolates perform in a controlled laboratory setting vs the natural environment (i.e., samples can lose toxicity in culture over time).
    - Diverse genotypes have been demonstrated in cyst beds and linked to adaptation of cells to environmental changes (Kremp et al., 2016). With

shifts occurring in water temperature, nutrients, and pH on local to global scales, it is important to investigate the responses of these strain assemblages.

- With new species continually being discovered globally (e.g., Rhodes et al., 2017; Huang et al., 2019), there is a need to expand multi-gene (and multi-strain) characterizations to build on the international body of genetic data.
- While advances have been made towards elucidating whole genomes, this area of basic research remains slow in its progress particularly for dinoflagellates, which harbor large, complex genomes (Lin et al., 2011; Casabianca et al., 2017). It is noteworthy that information gleaned for one species cannot be extrapolated to all species within or outside the genus.
- Transcriptomic studies have not been fully exploited to uncover genetic-level HAB response in the natural environment related to location, species composition and/or unique perturbations (e.g., hurricanes, extreme weather events), and the multitude of associated environmental factors (e.g., nutrients, changes in pH and temperature, ultraviolet radiation [UV], circulation patterns). Use of this genetic approach to understand cellular level gene activities is in its early stages. It is noteworthy that dinoflagellates exhibit physiological responses at the translational level (i.e., protein level [reviewed in Lin et al., 2011]), which need further exploration in the natural environment.
- There are many toxin pathways yet to be elucidated (see sec. 2.1), and this effort would move us closer to networking these data with downstream signaling pathways, understanding broad variability in toxin quotas among strains of the same species, and developing more robust field detection assays.
- There is scant knowledge of the complex parasitic (e.g., Hanic et al., 2009; Gleason et al., 2015), bacterial (e.g., Mayali and Doucette, 2002; Kodama et al., 2006; Jones et al., 2010; Sison-Mangus, 2016) and/or viral (e.g., Carlson et al., 2016; Moniruzzaman et al., 2016, reviewed in Coy et al., 2018) interactions and potential control of HAB species throughout various bloom stages (see sec. 2.5.1B).
- Certain HAB species, such as *Microcystis* spp. and *Phaeocystis* spp., form colonies in nature and ongoing research is beginning to explore the genetic mechanisms that underpin morphology and toxin production in these natural populations (e.g., Otten and Paerl, 2011; Davis et al., 2014; Pound and Wilhelm, 2020). However, we lack comprehensive insight into genetic variability within a colony and how that may or may not influence bloom dynamics and toxin production. Similarly, little is known about the variability in secretion of the exopolymer layer that appears to play an important role in the toxicity and grazing deterrence of the picoplanktonic pelagophytes *Aureococcus anophagefferens* and *Aureoumbra lagunensis* (Gainey and Shumway, 1991; Liu and Buskey, 2000).
- Logistical constraints make it very challenging to fully test the synergistic effects of multiple environmental stressors (e.g., UV radiation, nutrients, pH,

CO_2, salinity) on individual species and communities (including growth, rates of encystment/excystment, and toxin production and its fate [intra- vs. extracellular]). Most studies have incorporated only one to two drivers (see references in Hutchins and Fu, 2017).

- The use of metabolomics and proteomics in investigations of HAB ecology, physiology, and toxicology is currently restricted by access to specialized instrumentation and skilled technicians required to conduct these cutting-edge analyses. While many HAB researchers are interested in such approaches, cost of instrumentation limits advancement.
- The generation of large genetic datasets has grown faster than the infrastructure to process, store, and share the information. Databases generated for organism/bloom/regional information are often maintained at the local level and distribution can be difficult without the needed infrastructure for curating the data and allowing for searchability.
- Funding for basic research is still sorely needed, as there are numerous fundamental questions that still need to be addressed as outlined above.

2.3.3. PATHS FORWARD AND RECOMMENDATIONS FOR THE FUTURE

- Continue large-scale holistic sequencing efforts (e.g., elucidation of genomes and toxin-related genes and biosynthetic pathways, in situ phytoplankton community structure including strain diversity, transcriptional studies to understand mechanisms modulating cell growth and toxicity, informed by quantitative gene expression and exploration of microRNAs and other silencing RNAs, associated microbiomes and viromes, multiple single cell/colony sequencing). These should be aimed towards increased understanding of species' responses to changing environmental factors (e.g., salinity, temperature, pH, macro and micronutrients, UV radiation) before, during and after bloom events, which in turn will aid in the development of predictive models and management tools (e.g., species-specific assays for monitoring programs).
  - Deposition of DNA from species and strains to a central repository would greatly increase the available material for DNA-based studies such as whole genome sequencing and screening of target genes (e.g., those involved in toxin production; see sec. 2.4 on Reference Materials).
  - Build out direct complementarity between molecular methods and other advanced detection platforms such as the Imaging Flow Cytobot (IFCB).
- Increase efforts for multivariate studies (e.g., Boyd et al., 2015; Griffith and Gobler, 2020), on a range of scales, from laboratory-based experiments to larger field efforts, to assess synergistic relationships between environmental factors and HAB physiological responses (including competition within and among species), in turn measured via use of transcriptomics, proteomics, and metabolomics.

- Consult the fields of agriculture and carbonate chemistry for guidelines in experimental setup and analyses to support long-standing protocols in measuring outcomes such as cell growth and toxin production (Callao et al., 2014).
- Convene a formal discussion group to develop bioinformatic guidelines and identify infrastructure to share large genomic datasets among researchers towards creating a robust, long-standing resource for detection assay development and physiological studies.
- Explore collaboration with research groups/agencies generating large datasets of environmental DNA (eDNA) signatures from aquatic (marine and freshwater) locations. This field is growing exponentially in response to management needs for invasive and threatened species and offers an opportunity to mine HAB genetic signatures.
- Consult the eDNA community and medical technologies for advances that can be integrated into field protocols (e.g., DNA extraction) for faster, lower-cost, more robust detection of HAB species.
    - Employ advanced cell sorting technologies to address the "unculturable" nature of some HAB species, including partitioning of associated viral and bacterial populations for further analyses.
- Increased access to technology and skilled users to fully utilize metabolomics and proteomics in the next decade requires:
    - Fostering and leveraging support for new collaborations with medical facilities and/or pharmaceutical groups, as extramural costs will increase, to accommodate this multidisciplinary effort. A small number of private contract laboratories are available in the US, that are associated with academic institutions and list variable pricing based on the amount of preparatory and post-analysis work. Alternatively, refurbished instrumentation can be purchased, or older models obtained via donation from national laboratories.
    - Skilled technicians will be required to maintain and operate the above instrumentation, and service contracts are needed to support aging equipment, again leading to increased research costs. Workshops should be conducted to develop metabolomics and proteomics skills among current and future HAB scientists.
    - Standardized techniques should be developed, and public databases created to store data and facilitate meta-analysis of "omics" data.
- Diverse research funding opportunities that include funding high risk/high reward efforts and and flexibility for basic research at the cellular level would provide baseline information about HAB biology that can complement and support funding to research HAB events.

2.4. Reference Materials

2.4.1. CURRENT STATE OF KNOWLEDGE AND SIGNIFICANT ADVANCES

A. *Toxin Reference Materials*

While the National Research Council (NRC) Canada produces a number of toxin Certified Reference Materials (CRMs) that meet some of the needs of US users, many other available standards (particularly those that are not CRMs) are of unknown or questionable quality, limiting their usefulness when highly accurate results are needed, e.g., in setting regulatory drinking water limits to ensure public safety. A long-standing problem with reference materials is that the scientific requirements are not widely known outside the disciplines of metrology and analytical chemistry, yet they are needed for effective HAB research and management. Accordingly, communication within the community on the need for reference materials has been an important area of focus. Additionally, the last decadal national research plan (HARRNESS, 2005) recommended the establishment of an information database for the characterization and identification of toxins and metabolites, which was initiated in 2019.

- A subgroup of the CRM HABHRCA Interagency Working Group (IWG) met between 2016 and 2019 and produced several products including a CRM one-pager to inform users. It was distributed at the 2017 US HAB symposium.
- The US HAB Symposium provided special sessions in 2017 and 2019 on the science-based need for reference materials. The 2019 special session, titled "Reference Material Priorities for the US HAB community", was held to identify gaps and recommendations (see below).
- A web-based tool for cross-linking knowledge of HAB organisms and toxins has completed the design phase through support from the International Oceanographic Data and Information Exchange (IODE) of the Intergovernmental Oceanographic Commission (IOC). The toxin database will link to the Taxonomic Reference List of Harmful Microalgae. The database is envisioned to be analytically rigorous with information on exact masses, confirmation sequences, nuclear magnetic resonance (NMR) confirmation, and reference material availability. It will have a foundational link to the World Register of Marine Species, allowing connection to both the toxin producing algal species and the vector species that produce many of the metabolites (congeners). Further, these databases will be cross-linked to the Harmful Algae Event Database, which provides records of over 8,000 HAB events worldwide and includes a global mapping function. Work continues to finish incorporating data and finalize the web-platform.

B. *Algal Reference Materials*

Researchers in the HAB community who seek to use molecular methods lack a comprehensive central repository for sourcing genetic material (DNA) from target and non-target species needed for development and validation of detection assays used for biotoxin management and HAB research. Having one or more repositories for genetic material would increase the number of species available for assay validation, and thereby strengthen the confidence in specificity. Further, assays that incorporate species from broad geographic scales have increased utility across regions. DNA is far less expensive to obtain and maintain than whole cultures, which require long-term maintenance (e.g., media, personnel time) by culture collections or individual researchers.

- There are three US-based algal culture collections: the Provasoli-Guillard National Center for Marine Algae and Microbiota (NMCA), the Culture Collection of Algae at the University of Texas at Austin (UTEX), and the Algal Resources Collection at the University of North Carolina Wilmington (UNCW-ARC).
- Many HAB species are extremely difficult to culture, (e.g., *Dinophysis* spp. require an intermediary prey species [Park et al., 2006)]) or "crash" after being in culture for an extended time and once they reach a minimum threshold size (e.g., *Pseudo-nitzschia* spp.). Given these challenges, it is not economically feasible for national culture collections to maintain species that fall into these categories, unless they can be cryopreserved. A DNA repository would provide genetic material long past a culture's expiration.
- For researchers to generate their own material, it typically takes a few months to establish cultures from single cell isolations to derive species identity (detailed microscopy and DNA sequencing). It would be much more cost-effective and expedient to order a panel of extracted DNA from various species than to go through the rigorous isolation process, source material from colleagues, and/or obtain live cultures at a cost of USD $50-250 each.
- At present, communication among HAB researchers and the basic infrastructure are in place to provide vetted DNA material and distribute it on request through culture collection centers once agreements can be formalized.

2.4.2. KNOWLEDGE GAPS AND UNDERDEVELOPED CAPABILITIES

A. *Toxin Reference Materials*

Knowledge gaps were identified by Hess et al. (2007) and discussed by M. Quilliam at the 2016 HABHRCA IWG meeting, and by P. McCarron at the 2019 US HAB symposium. The gaps according to these experts are summarized as follows:

- There is a dearth of both pure calibration standards and matrix reference materials.
- Worldwide there are very few independent bodies that produce CRMs for algal toxins. Currently the main National Metrology Institutes (NMIs) producing toxin materials are the NRC Canada, the Japanese Food Research Laboratory, and the US National Institute for Standards and Technology. There are also a small number of commercial suppliers.
- Availability of contaminated shellfish and algae is limited, as well as the time and knowledge necessary to produce adequate reference materials. This leads to

only limited editions of CRMs and even more limited production of in-house reference materials.

- The restricted availability of in-house quality controlled materials promotes the rapid use of the above limited CRMs, which in turn hampers the production of a broader suite of materials required globally for complete protection of public health.

B. *Algal Reference Materials*

- HAB researchers have been discussing the utility of DNA repositories for two decades; however, the lack of sustained funding for such an initiative has precluded moving forward with implementation.
  - Many molecular HAB researchers have archives of DNA but no easy way to centrally "advertise"' these collections to other researchers who may benefit from their use.
- There has been no comprehensive "wish list" developed by molecular researchers outlining needs, nor a complementary list providing infrastructure requirements for repository sites.

2.4.3. PATHS FORWARD AND RECOMMENDATIONS FOR THE FUTURE

A. *Toxin Reference Materials*

Recommendations for reference materials for the US HAB community were developed at a special evening session of the 2019 HAB Symposium attended by 24 meeting delegates. Recommendations were documented by J. Ramsdell and P. McCarron, sent to participants for vetting, and distilled under the following headings:

Take a different/smarter approach in providing reference materials for the HAB community

- Tiers of reference materials would be valuable; high-level CRMs are not required for all applications.
- A mechanism to summarize and track community reference material is needed. A list of material needs should be generated by the community.
- Best practices for toxin reference materials, including material grades, impurities, and adjustment for mass and purity need to be developed. This can leverage resources from other fora (e.g., Association of Official Agricultural Chemists [AOAC], International and North American Chemical Residue Workshop [NRCW]).
- Determine if representative compounds can be used for multiple analog classes (i.e., use the most common form as representative for others); include studies to establish relative molar response factors.
- Provide mixtures of toxins in both solvent and matrix form.

- Develop the potential for surrogate molecules in the absence of authentic compounds/internal standards.
- Share profiled/confirmed samples as reference quality control (QC) samples among the HAB community (create a database of materials).
- Given that the ISSC method validation framework requires large amounts of reference materials, determine if the community can propose alternative approaches to validation/approval that places less demand on CRM use/costs.
- Identify reference material priorities based upon human health needs (e.g., for ciguatoxins).
- Encourage the use and development of photobioreactors for high-biomass culture of harmful algae (HA) to allow production of HAB metabolites and algal toxins of interest in pharmacology, neurobiology as well as the production of pure toxins for use as analytical toxin standards.
- Add to the Taxonomic Reference List of Harmful Microalgae a list of strains available in worldwide public collections for each toxic species. Provide information in the Harmful Algae Event Database for strains that were isolated from HAB events and are now available in public and private research collections to foster collaborations for strain characterization.

Communities of users, information sharing, and training initiatives.

- Offer analytical workshops for users at US HAB meetings similar to the phytoplankton ID workshops.
- Provide learning and information sharing opportunities on an ongoing basis (e.g., webinars). This would allow for a focus on specific topics at different US HAB meetings. Suggested topics include:
    - Proper selection and use of reference materials,
    - Certificates of analysis, intended use statements, periods of validity.
- Provide resources to the community that have already been prepared in other fora. Examples include reference material communities at AOAC and NRCW. A variety of reference documents already exist that could be used.
- User groups could combine resources to make materials available (purchasing, provision of raw materials, funding production, etc.).

Achieve better understanding of materials available in the market.

- Designate one place (open shared database) for a current listing of toxin reference material suppliers for all standards, which has means/metrics to compare existing materials.
- Define appropriate materials for specific applications.
- Ensure consistency and share experience/information on available materials. This is important given the variability in analytical results that can have negative impacts on HAB community efforts.

- Ensure producers provide data on the characterization of reference materials.
- Make reference material available and toxin information accessible in a database.

B. *Algal Reference Materials*

While a shared database of archived material within molecular research laboratories and a set of standard quality assurance/quality control (QA/QC) procedures would facilitate sharing of genetic material, without central repositories there will always be inter-laboratory variability (e.g., in the sensitivities of quantitative methods used to quantify material). A path forward towards more centralized repositories would standardize these requirements and shift the financial burden (personnel time and supplies) away from research laboratories. Recommendations include:

- Build upon established infrastructures at the three US-based culture collections (NMCA, UTEX, UNCW-ARC) for an expanded initiative to archive and supply curated DNA material from HAB species outside those currently available in-house. All existing centers are very interested in moving forward with this effort (personal communications: D. Nobles, Curator & Director of the UTEX Culture Collection of Algae; M. Lomas, Director, NCMA; C. Alves de Souza, Director, UNCW-ARC).
- Establish a working group of expert HAB molecular researchers and representatives from the three culture collections to develop guidelines for QA/QC documentation of material for submission to the repositories. This group would serve as the liaison for guideline distribution to the community at large during US HAB meetings. This expert panel could meet quarterly during the early stages of this initiative, and thereafter scale back to an annual meeting to ensure the needs of the community and requirements of the collections continue to be addressed.
- Identify and obtain initial 'seed' funding (for initial stocking of inventory), followed with a sustained revenue stream (partly generated from both US and international orders) to address operational requirements such as:
    - Housing a bank of liquid nitrogen dewars and scientific-grade freezers connected to a back-up generator system,
    - Fostering further development of microalgal cryopreservation methods in parallel with DNA archiving, given that certain live cultures lose toxicity over time,
    - Providing support for curators and staff to maintain records with set metadata parameters (ensuring origin of species and genetic ID are complete), fill orders, catalog species information (including changes in species/strain names and locale of isolation). Disperse small funds to HAB researchers for harvesting an adequate amount of DNA from cultures for repository deposition (thereby avoiding duplication of cost and time efforts),

- Develop a streamlined online ordering and fulfillment system that can be accommodated using the website and ordering system already in place for algal cultures at these sites.

2.5. Bloom Ecology

"The success of HABs lies at the intersection of the physiological adaptations of the harmful algal species and/or strain (population), the environmental conditions, including the right nutrient proportions, interaction with co-occurring organisms, and physical dynamics that alter abiotic conditions and/or aggregate or disperse cells (or can alter abiotic conditions in a favorable or unfavorable manner), in turn promoting or inhibiting their growth" (Glibert and Burford, 2017).

2.5.1. CURRENT STATE OF KNOWLEDGE AND SIGNIFICANT ADVANCES

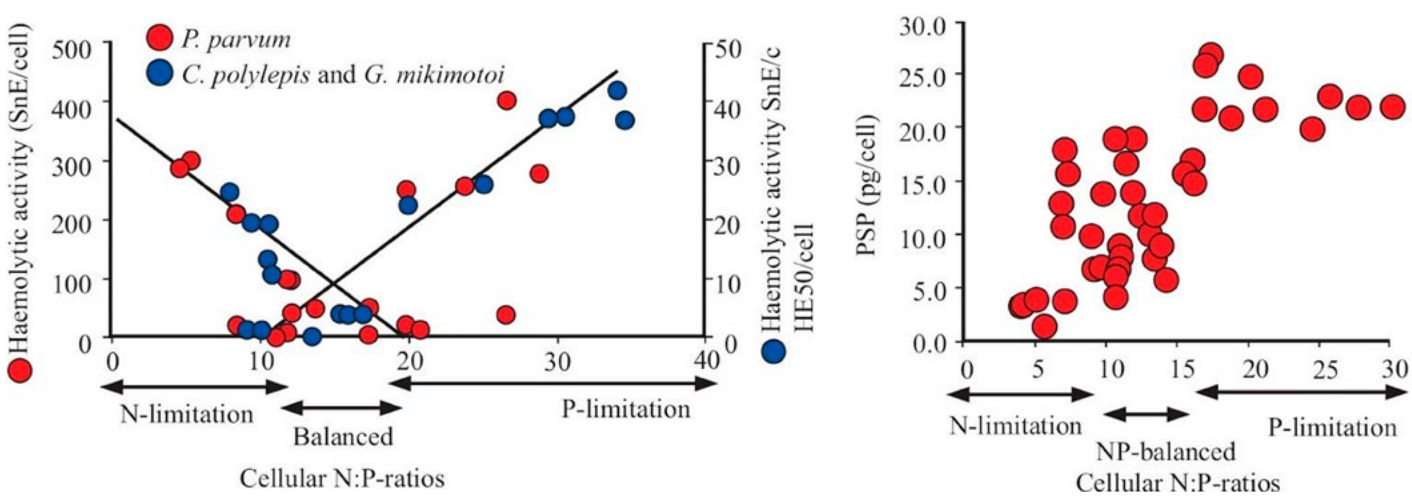
- A number of regional projects have begun to elucidate the complex dynamics of large-scale marine HABs like those of *Alexandrium catenella* in the Gulf of Maine (McGillicuddy et al., 2005), *Karenia brevis* in the Gulf of Mexico (Steidinger 2009), *Pseudo nitzschi*a spp. on the west coast (Moore et al., 2021), *Dinophysis* on both coasts of the USA (Hattenrath-Lehmann et al., 2013; Trainer et al., 2013; Wolny et al., 2020), and *Microcystis* in Lake Erie, (Verhamme et al., 2016; Del Giudice et al., 2021).
    - Life history stages of some HAB species have been mapped in bottom sediments and physiologically characterized, including detailed understanding of the role of temperature and other factors in controlling dormancy and quiescence (e.g., Brosnahan et al., 2020; Anderson et al., 2021a) as well as cyst germination (Moore et al., 2015; Fischer et al., 2018).
        - Understanding the biology of *Alexandrium* spp. from the factors triggering encystment to the causes of proliferation of populations of motile cells, coupled with the influence of physical factors in the transport and retention of cysts, has allowed for the continued development of forecasting models (see Fig 1.4B).
- Smaller-scale targeted studies have provided some level of detailed ecological understanding for marine species like *Aureococcus anophagefferens* (Gobler et al., 2011), *Margalefidinium polykrikoides* (Qin et al., 2021), *Heterosigma akashiwo* (Ikeda et al., 2016; Mehdizadeh Allaf and Trick, 2019), *Karlodinium veneficum* (Lin et al., 2018a), *Prorocentrum minimum* (Zhang et al., 2021), and freshwater cyanobacteria (Harke et al., 2016b; Wilhelm et al., 2020).

A. *Role of physicochemical factors*

- Temperature, salinity, and irradiance are fundamental factors that impact bloom ecology, and genera/species can exhibit a variety of tolerance ranges (e.g., Sullivan and Andersen 2001; Strom et al., 2013; Tester et al., 2020). Fronts, stratification, and eddies can create gradients of these parameters that impact algal retention and/or growth (e.g., McManus et al., 2008; Trainer et al., 2009; Ryan et al., 2011) and can influence vertical cell migration.

- Laboratory based experiments and regional dataset modeling (reviewed in Ralston and Moore, 2020) indicate that changes in sea surface temperature can result in shifts in bloom characteristics, including species distributions (e.g., Tester et al., 2020), toxin production (Bradenburg et al., 2019), and seasonality (e.g., Jacobs et al., 2015).
- Toxin production has been associated with changes in salinity (e.g., Adolf et al., 2009; Errera and Campbell, 2011), macro- and micronutrients. For example, high cellular content of nitrogen-rich paralytic shellfish toxins in *Alexandrium* spp. and thus high bloom toxicity has been generally associated with phosphorus limitation (Fig. 2.12; Anderson et al., 1990; Brandenburg et al., 2020). Iron is a micronutrient that can support the production of toxin in some species of *Pseudo-nitzschia* (Sobrinho et al., 2017). Temperature and salinity also impact domoic acid production by *Pseudo-nitzschia* (Bates et al., 2018).
- In freshwaters, warm temperatures and stratification promote cyanobacterial blooms (Huisman et al., 2004). Weak mixing and stratification can also result in the formation of cyanobacterial surface scums (Hozumi, 2020).

Fig 2.12. Relationship between cell toxicity of harmful algae and nitrogen to phosphorus ratio (N:P). Left panel: for algal species toxic to fish, i.e., *Prymnesium parvum*, *Chrysochromulina polylepis* and *Gymnodinium mikimotoi*; Right panel: for *Alexandrium* species that produce paralytic shellfish poisoning (PSP) toxins. *(Figure reproduced with permission from Glibert and Burkholder, 2011).* The N:P ratio of algal cells reflects the nutrient composition of their external environment as well as their physiology and often deviates from the classical 16:1 Redfield ratio associated with optimal phytoplankton growth.



- Advection of cells (e.g., by wind, currents, ballast water), and local hydrography (which can dictate residence times) work in conjunction with nutrients and other abiotic factors (temperature, salinity, irradiance, pH) to drive bloom dynamics by aggregating or dispersing cells.
  - Recent major blooms of the dinoflagellate *Akashiwo sanguinea* along the west coast have followed a similar trajectory whereby upwelled waters produced favorable growing conditions, and transport to the nearshore coastline exposed the population to wave action which caused cell lysis (Jones et al., 2017). This led to the release of massive amounts of surfactant-like proteins that coated the feathers of seabirds, resulting in loss of waterproofing and thermal insulation capabilities, leading ultimately to hypothermia and death. Several notable events have been documented (Cloern et al., 2005; Jessup et al., 2009; Phillips et al., 2011; Jones et al., 2017).
  - Some areas (referred to as "hotspots") experience recurrent blooms in response to the synergism of parameters, while new hotspots can arise in response to extreme events (Trainer et al., 2020a).
- Algae respond to nutrients derived from a variety of sources, including atmospheric deposition (due to human activities and animal production), groundwater pollution, agricultural fertilizers, animal waste and human sewage, and consumer products (Glibert et al., 2020 and references therein). Inherently, aquatic systems receive varying inputs based on myriad factors (land use, hydrography, local regulations, precipitation).
  - Nutrients (e.g., nitrogen [N], phosphorus [P], silicate) can exist in a complexity of different ratios of organic and inorganic forms. Further, the availability of these attributes must support the specific needs and physiology of the species/strains present to support growth. Moreover, nutrients and their ratios interplay with other factors (environmental parameters, trophic interactions, cell physiology, water column structure) to determine if a bloom will develop (reviewed in Glibert and Burkholder, 2006, 2011).
  - Freshwater *Microcystis* is very effective at storing and scavenging inorganic P, enabling it to continue to bloom in waters with low inorganic P concentrations (Gobler et al., 2016; Harke et al., 2016b, Wan et al., 2019).
  - Changing nutrient load composition has been associated with shifts from diatom- to dinoflagellate-dominated communities (Derolez et al., 2020; Fischer et al., 2020).
  - Different phytoplankton taxa are known to vary in their preference and capacity to take up and assimilate nutrients. For example, brown tides of *Aureococcus anophagefferens* and *Aeroumbra lagunensis* develop when inorganic nutrient levels are low due to their superior ability to use organic forms of carbon (C), N, and P (Gobler et al., 2011).

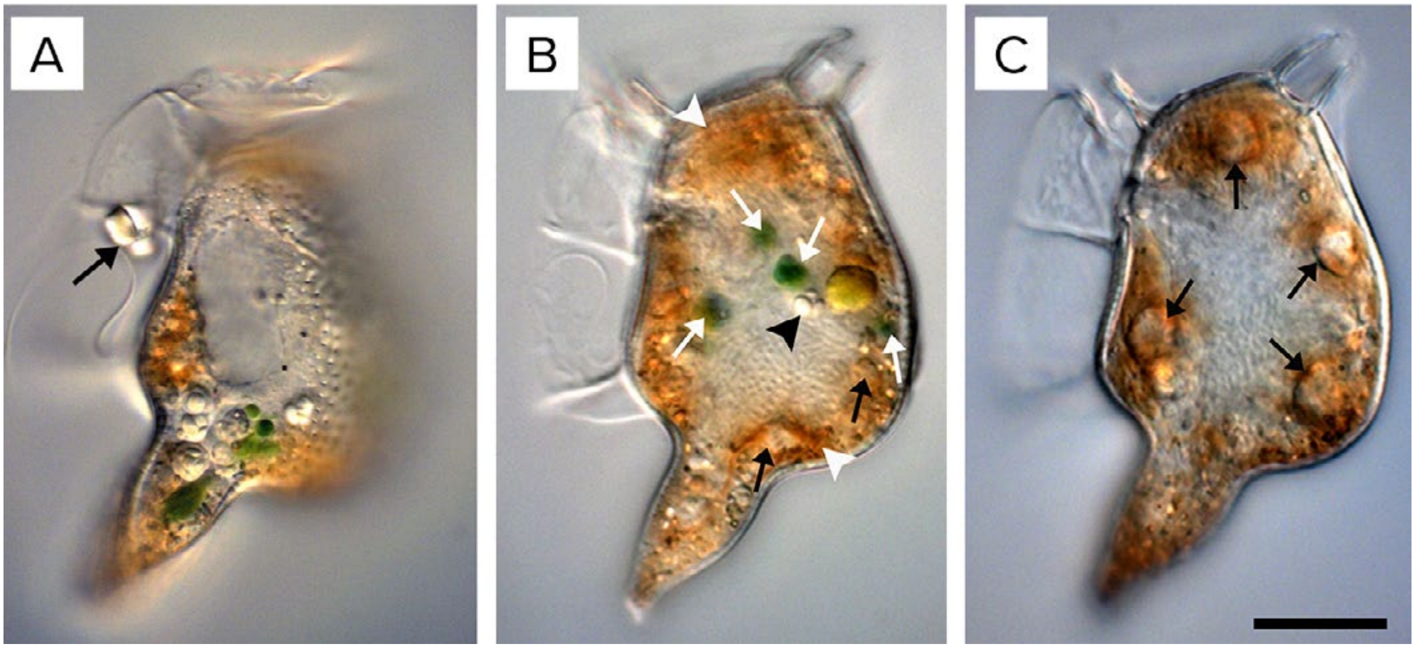
- It is well documented that nutrient loading from point and non-point sources correlates with macroalgal blooms (Lapointe et al., 2018 and references within). Several studies conducted in the US have used stable isotopic analysis to identify nutrient sources (e.g., Lapointe et al., 2018 and references within).
    - *Sargassum* proliferation reached a recent (ca. 2011) historical tipping point with the documentation of the "Great Atlantic *Sargassum* Belt" stretching from the Gulf of Mexico to West Africa (Gower and King, 2011; Wang et al., 2019). This broadly distributed bloom is presumably supported by numerous nutrient discharges, including those of the Congo, Amazon and Mississippi rivers, physical processes (upwelling and vertical mixing), and atmospheric deposition (Lapointe et al., 2021).

- Sources of organic and inorganic nutrients (in particulate or dissolved form) can be quite complex (Osburn et al., 2016; Paerl et al., 2020). They include cultural eutrophication (reviewed in Anderson et al., 2008), N fixation and regeneration (Mulholland et al., 2014), upwelling (Kudela et al., 2010), remineralization of biomass including zooplankton excretion (Vargo et al., 2008), benthic sources (Dixon et al., 2014), watershed geology (Bunnell et al., 2020), and atmospheric sediment fluxes (Vargo et al., 2008). These sources can vary temporally and seasonally and in response to anthropogenic activity (e.g., urban and industrial development, aquaculture, channelization) (Glibert et al., 2020).

- Harmful macroalgae are found in coastal marine and freshwater environments in a variety of forms, including those that are free-floating or benthic/sessile, and are subjected to different transport mechanisms. They can provide habitat and food for a variety of aquatic organisms and function as a sink for carbon, excess nutrients, and contaminants, such as heavy metals and organic pollutants. They can also proliferate in response to eutrophication and form extensive benthic or floating mats (reviewed in Lapointe et al., 2018).

- Past research has revealed that HAB species can acquire nutrition using a variety of methods: phototrophy (use of light for photosynthesis), heterotrophy (ingestion of organic matter, including other organisms), and mixotrophy (ingestion of organic matter as well as photosynthetic capabilities) (Fig. 2.13). Some strategies are quite complex, including the acquisition of symbiotic algal cells/organelles in dinoflagellates that provides photosynthetic benefits (reviewed in Reguera et al., 2012), and correlations of prey abundance with growth and toxicity of harmful algae (e.g., Adolf et al., 2008). However, in freshwater, HABs are usually caused by cyanobacteria, which are limited to phototrophy.

Fig. 2.13. Micrographs showing feeding on ciliate prey (*Mesodinium*) by the mixotrophic dinoflagellate *Dinophysis caudata*. A: a single *Mesodinium* ciliate (black arrow) caught by *Dinophysis* using its peduncle (feeding tube that connects it with its prey and allows it to pierce it and extract its cell contents). **B**: ingested green plastids derived from the ciliate prey (indicated by white arrows), which were in turn derived by *Mesodinium* from cryptophyte algae they feed on. **C**: food vacuoles (indicated by the black arrows) ~ 1 day after feeding (Kim et al., 2015). These "stolen" plastids (organelles only found in plant and algal cells), or so-called kleptoplastids, can be used by *Dinophysis* to photosynthesize but must eventually be replenished via consumption of more prey. Scale bar = 20 µm. *Photos adapted with permission from Kim et al. (2015).*



B. *Biological interactions*

- The differential tolerance and adaptation to physicochemical parameters can often explain the proliferation, maintenance, and demise of HABs of a given species (stages shown in Fig. 2.14). Harmful algal species are also subject to biotic interactions with other co-occurring organisms that influence bloom dynamics: predator-prey relationships (e.g., as prey via grazing or as predator via heterotrophy), release of nutrients back into the environment following bacterial decomposition and viral cell lysis, competition with other algae via allelopathy, and the effects of microbial pathogens.
    - Bacteria have been associated with a variety of HAB species (Amin et al., 2015; Sison-Mangus et al., 2016). These can be mutualistic relationships or algicidal in nature, which has implications for bloom control and management (Inaba et al., 2019; Pokrzywinski et al., 2017). In turn, cyanobacterial HABs can lead to shifts in co-occurring non-cyanobacterial species (Berry et al., 2017). A distinct bacterial community was shown to be associated with freshwater *Microcystis* blooms (Tromas et al., 2017; Cook et al., 2020).
    - Viruses have been linked to algal cell physiology via growth suppression, induction of spore formation, and lysis (Onji et al., 2003; Gastrich et al.,

2004; Pelusi et al., 2021) (Fig. 2.15). Infection in the natural environment can change phytoplankton communities by shifting species composition, leading to algal succession, and affecting the distribution of organic matter within an ecosystem (reviewed in Coy et al., 2018). In turn, phytoplankton can harbor endogenous genetic machinery providing defense against viral attack, and these processes may be linked to nutrient availability (Papoulis et al., 2021).

- Viruses are known to play a critical role in the demise of HABs. So-called giant double-stranded DNA viruses have caused major changes in host gene expression, leading to the collapse of *Aureococcus anophagefferens* brown tides (Moniruzzaman et al., 2016).
- Phages have also been implicated in the collapse of *Microcystis* blooms in Lake Erie (Steffen et al., 2017).

Fig. 2.14. **Algal Bloom succession.**

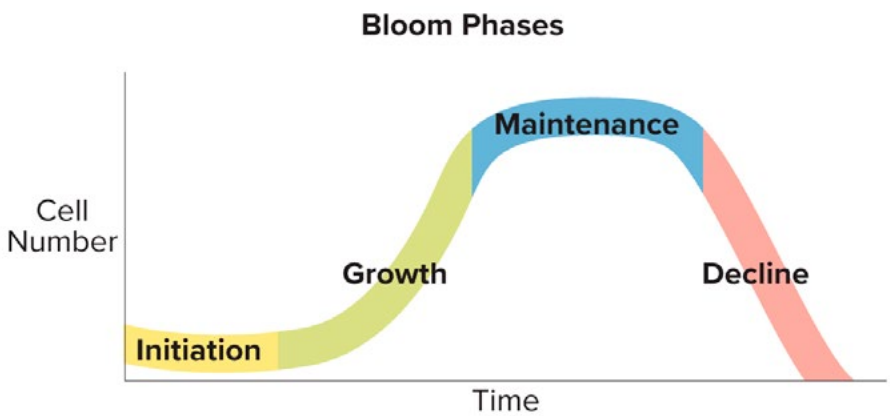
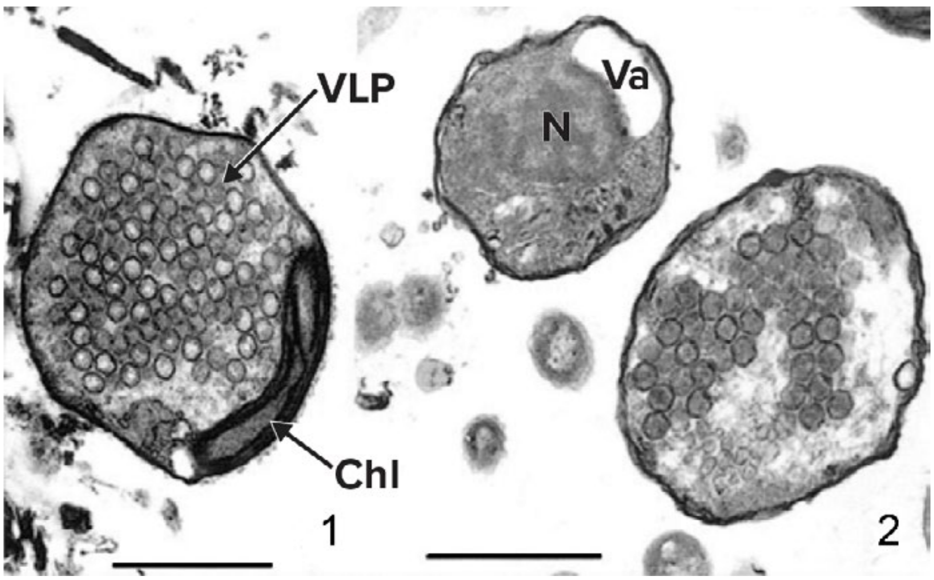


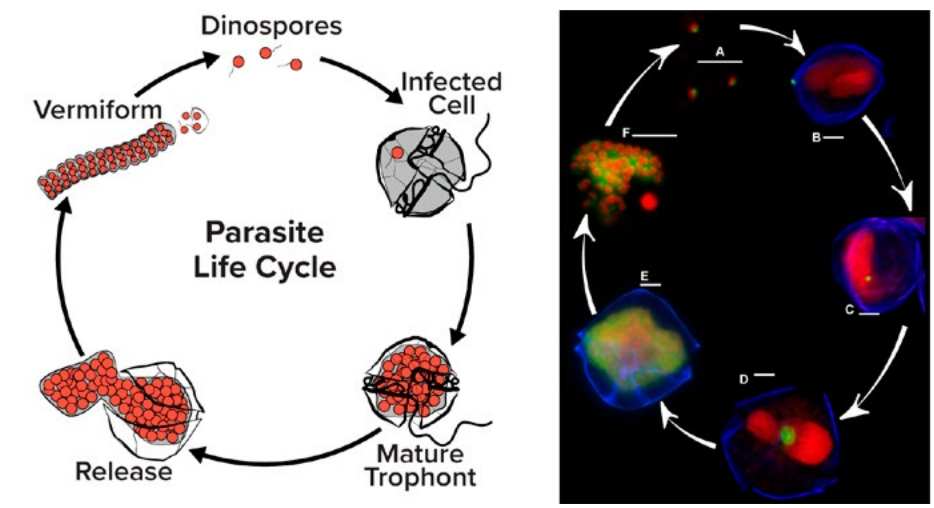
Fig. 2.15. Transmission electron microscopy (TEM) images of virus-like particle (VLP) infected brown tide cells, *Aureococcus anophagefferens*. 1. In natural populations during a 2002 brown tide bloom in Little Egg Harbor, New Jersey, showing a tightly packed array of > 50 VLPs in cross section. Each VLP is ~ 140 nm in diameter. The remaining chloroplast (Chl) is usually the last organelle visible in a highly infected cell. 2. Two *A. anophagefferens* cells cultured in the laboratory and infected with a virus isolated from Quantuck Bay, Long Island, NY, in 2002. The smaller cell on the left appears as yet uninfected and has an intact nucleus (N) with no visible viral capsids; Va = vacuole; the one on the right (infected) shows similar viral capsids to those found in natural populations in (1). Scale bars = 1 µm. *Figure adapted with permission from Gastrich et al. (2004).*



- Fungal parasites have been documented to infect HAB species (reviewed by Gleason et al., 2015). Advanced genomic tools are beginning to support these observations (e.g., Berdjeb et al., 2018; Garvetto et al., 2018), and show changes in host-parasite interactions across varied temporal scales (Gerphagnon et al., 2017; Berdjeb et al., 2018).
- *Amoebophyra* spp. are dinoflagellates that can successfully infect other dinoflagellates (Fig. 2.16) owing to their rapid growth within the host cell, followed by release of numerous new cells poised to infect their next host (Coats and Park, 2002; Chambouvet et al., 2008).
- Other examples of microbial co-existence do not involve infection. For example, blooms of the dinoflagellate *Karenia brevis* and filamentous cyanobacteria are common in the Gulf of Mexico (Steidinger, 2009; Tullis-Joyce and Roy, 2021). Their association is linked to nitrogen fixation by *Trichodesmium* which is needed to fuel and sustain *Karenia* blooms (Mulholland et al., 2014).
- Allelopathy of HAB species (the production of metabolites that can inhibit growth of other co-occurring microorganisms) has been demonstrated in the laboratory (e.g., Hattenrath-Lehmann and Gobler, 2011;

Poulson-Ellestad et al., 2014; Xu et al., 2015; Song et al., 2017). This competitive advantage can shape phytoplankton community structure and play a role in bloom formation and persistence (e.g., Granéli et al., 2008; Hattenrath-Lehmann and Gobler, 2011).

Fig. 2.16. Different life-cycle stages of the dinoflagellate parasite *Amoebophyra* sp. infecting the host *Alexandrium fundyense* in Salt Pond, Eastham, Massachusetts: s revealed in the right panel by by the FISH-TSA fluorescence method (in situ hybridization coupled with tyramide signal amplification) (from Velo-Suárez et al., 2013). Green fluorescence shows an *Amoebophyra* genus-specific probe targeted to the parasite. Red and blue fluorescence mark the host nucleus and theca or cell wall, respectively. (A) Free-living dinospores, (B) initiation of infection, with dinospore attached to the host theca, (C) early stage of infection, (D) intermediate stage when the parasite occupies a large portion of the host nucleus and (E) mature or "beehive" stage of infection; (F) free-living "vermiform" stage. Scale bars = 10 µm. The left panel shows a schematic of the various stages. Such studies are used to determine the role of parasites in *Alexandrium* bloom dynamics (e.g., bloom termination).



- Grazing by microbes or macrofauna is a critical determinant of bloom progression. Inhibition of grazing due to a HAB species' unpalatability, toxicity, or unsuitable size/cell morphology, or from mass mortality of grazers, can contribute to bloom initiation and development. This was the case for the Texas brown tide alga *Aureoumbra lagunensis*, in which grazing breakdown of coot clams and ciliates was a major contributor to bloom development (Gobler and Sunda, 2012).
    - Initial ingestion of neurotoxic algae, e.g., paralytic shellfish toxin (PST)-producing dinoflagellates, can lead to feeding incapacitation of bivalve grazers, but HABs can also produce metabolites that act as feeding deterrents. For example, production of extracellular polymeric substances (EPS) by HAB species such as *A. lagunensis* was shown to inhibit or disrupt grazing by microzooplankton and contributed to the persistence (~ a decade) of brown tides in Texas (reviewed by Gobler and Sunda, 2012).

- Large-volume (>100-300 L) mesocosms have proved useful for the study of HAB-grazer interactions and nutrient dynamics that simulate natural field conditions and community-level function, as they allow experiments to last hours to days before the enclosures cause artifacts (Paerl et al., 2015).
- Colonial cyanobacteria are resistant to many zooplankton grazers and cyanobacterial blooms can reshape the zooplankton community composition (Lürling, 2021; Ger et al., 2016).

- Other compounds produced by algal species can have detrimental effects on fish and other aquatic organisms, particularly those reared in aquaculture settings. These include surfactant-like proteins that can inhibit thermal regulation in seabirds (Jessup et al., 2009), reactive oxygen species (ROS) and polyunsaturated aldehydes (PUAs) associated with fish gill damage and mortality (Mardones et al., 2015, reviewed in Diaz and Plummer, 2018), and gelatinous/mucilaginous materials (e.g., Alderkamp et al., 2007) that allow cells to aggregate and form dense colonies that physically affect surrounding organisms (via light attenuation, clogging, effects on motility).
  - In general, all blooms have the capability of seriously affecting ecosystems through light attenuation due to high biomass and reducing dissolved oxygen in the surrounding water column as blooms decompose.

2.5.2. KNOWLEDGE GAPS AND UNDERDEVELOPED CAPABILITIES

- The complexity of studying natural systems, and the sometimes contradictory data from laboratory experiments (limited in their ability to fully mimic all synergistic environmental factors), make it challenging to ascertain definitive linkages between shifts in climate-driven parameters (i.e., long term vs. seasonal) and HABs (Fig. 2.9).
  - Recent meta-analysis, skewed towards dinoflagellates due to greater data availability, demonstrated that toxin content and toxicity responses to partial carbon dioxide pressure (pCO_2) and increasing temperatures were not always consistent; species at higher latitudes responded to warming via increased growth rates while those at lower latitudes did not respond in the same manner (Bradenburg et al., 2019).
- Studies of bloom dynamics even of well-known HAB species have raised many additional questions about the nature of drivers for bloom events, for example:
  - *Alexandrium* blooms (associated with paralytic shellfish poisoning) have been well documented in the Gulf of Maine (Kleindinst et al., 2014), yet the depth at which viable cysts reside in the sediment remains unknown.
  - Domoic acid-producing *Pseudo-nitzschia* blooms (associated with amnesic shellfish poisoning [ASP]) are well known along the west coast (Trainer et al., 2012) and have recently emerged along the Alabama and Florida coasts (MacIntyre et al., 2011; Liefer et al., 2013; Bates et al., 2018) and

Gulf of Maine (Clark et al., 2019). Even on the west coast where strong upwelling/relaxation events have been associated with bloom events (Trainer et al., 2012), these conditions do not always coincide with a toxic event (Bowers et al., 2018). Furthermore, the source of cells for bloom initiation is unclear and may vary during and across events (resting stages have not been described for this genus).

- *Dinophysis* spp. (associated with diarrhetic shellfish poisoning) are found along both coasts of the US; however, toxic outbreaks have not yet been documented in the southern east and west coasts (Anderson et al., 2021a). The drivers of blooms are not well understood, and as obligate mixotrophs the full complement of prey species supporting growth of *Dinophysis* spp. has not been fully recognized. *Dinophysis* spp. have been shown to prefer ammonium over nitrate as part of their nutritional strategy (Hattenrath-Lehmann et al., 2021). In some regions, cells are found year-round over a broad range of fluctuating environmental conditions (including nutrients) which challenges the ability to pinpoint bloom drivers (Schultz et al., 2019). Finally, cell concentrations needed to produce a toxic event can be low (10^2 cells L^{-1}; reviewed in Reguera et al., 2012), thus posing a challenge to detection for public health risk.

- *Karenia brevis* blooms (associated with neurotoxic shellfish poisoning) occur annually on Florida's southwest coast and can be advected along the east coast as well as to the northern Gulf of Mexico (reviewed in Anderson et al., 2021b). These bloom events vary drastically in duration and severity which, along with an incomplete understanding of their full life cycle, challenges the identification of bloom drivers.

- *Gambierdiscus* spp. (associated with ciguatera poisoning) are benthic and epiphytic algae occurring in tropical and subtropical regions. Due to their attachment to substrates (e.g., macroalgae, coral), cell dislodgement can occur after environmental disturbances (hurricanes, coastal development, coral bleaching) leading to toxic events (Hales et al., 1999; Lehane and Lewis, 2000; Ruff, 1989). Difficulties in studying bloom dynamics can be related to differing substrate preference as well as regional differences in macroalgal host relationships (reviewed in Parsons et al., 2012 and Rains and Parsons, 2015).

- Peak cell density and bloom frequency and/or duration of many HAB species are expected to shift under changing parameters like temperature (Paerl and Huisman 2008, 2009; Ho and Michalak, 2020), nutrient ratios (Glibert and Burkholder, 2018) and CO_2 levels (Raven et al., 2020). However, synergistic interactions (Fu et al., 2012; Wells et al., 2015; Glibert, 2020) and the full scope and nature of these effects (including those on HAB cell toxicity) are often unknown.

    - The influence of changing light intensities (due in part to changes in cloud cover, particle flux, stratification especially in shallow areas, and fluctuations in greenhouse gases) on phytoplankton in general, and HABs specifically, is poorly understood (reviewed in Wells et al., 2015).

    - The ecological role of many HAB toxins is unknown - studies support the notion that some HAB toxins may function as allelopathic compounds, grazer deterrents, or play a role in chemical communication (Zimmer and Ferrer, 2007) but this has not been confirmed for all toxins, and further confounds our understanding of how different environmental drivers can influence changes in toxin profiles of bloom-forming species.
    - Studies on long-term increased CO_2 and subsequent algal response are complicated by the fact that diurnal and seasonal levels (particularly in coastal and eutrophic systems) vary widely and can exceed projected global values (Berdalet et al., 2017).
- Given the number and diversity of potential nutrient sources, it becomes difficult to study them synergistically and prioritize those of greatest concern in relation to local and regional management and mitigation decision-making (Heil et al., 2014; Glibert et al., 2017). The complexity of available nutrients (organic/ inorganic and their ratios) complicates unraveling the holistic scenario in which blooms occur and are sustained.
    - We have limited understanding of the role that other constituents play in bloom dynamics, namely trace metals (Sunda, 2006) and vitamins (Tang et al., 2010).
- The study of nutritional requirements in the field can be challenging with algae like *Dinophysis* that occur at low concentrations even during a toxic event. Field studies have revealed the potential for varied feeding strategies (reviewed in Reguera et al., 2012); however, the only successful culturing approach thus far has been to provide cells with a ciliate prey (*Myrionecta rubra*) that is in turn fed a cryptophyte (*Telealux* sp.; Park et al., 2006).
- We lack an adequate understanding of how stringent or flexible overall feeding and nutrient acquisition strategies are among genera/species/strains in the field, and poorly understand their capability to adapt to changing nutrient input scenarios (e.g., Flynn et al., 2018, reviewed in Glibert et al., 2020). Some HAB genera, like *Margalefidinium*, can exhibit a wide range of nutrient acquisition strategies which further complicates interpretation of field studies (Kudela and Gobler, 2012).
- Additional studies are needed on HAB response to extreme environmental disturbances such as oil spills and use of dispersants (Bretherton et al., 2019, Park et al., 2020), and their relationship to large-scale meteorological (hurricanes) and oceanographic (El Niño) events (Glibert et al., 2020; Phlips et al., 2020; Fiorendino et al., 2021). The response of HABs to smaller-scale, more localized perturbations (e.g., unusual rainfall events that alter salinity, acute nutrient discharges, material run-off/deposition following large fires) are also poorly understood. These types of events have the potential to markedly alter food web structure, including that of the phytoplankton assemblage at its base.
- Resting stages for many HAB species have not been identified. Therefore, the source of cells that seed recurring blooms remains uncertain.

- Recent studies using in situ instrumentation have demonstrated that laboratory-based culture studies often underestimate the true rates of growth, toxin production, and encystment/excystment that promote or terminate bloom events in natural waters (Brosnahan et al., 2015, 2017).
- As more data are generated about the high variability in genetics and physiology among species/strains within the same genus (Lelong et al., 2012; Xu et al., 2016), more questions arise about how these differences influence bloom dynamics.
    - Granular insight/discovery has been constrained by resource limitations since data collection is often carried out in the context of a rapid response (i.e., after bloom initiation, McCabe et al., 2016), or over a time frame defined by scheduled funded activities (Bowers et al., 2018).
    - The molecular mechanisms underlying algal toxin production have yet to be fully elucidated for most HAB species (see sec. 2.3.), and this knowledge gap hinders the development of targeted assays that could be used to track toxin production throughout various bloom stages.
- The intricacies of colony and mat formation in freshwater microalgae (e.g., *Microcoleus, Microseira*), are not fully understood, including the underlying genomics (i.e., strain variation) and nutrient acquisition that lead to their development into nuisance events (McAllister et al., 2016; Tee et al., 2020; Bouma-Gregson et al., 2022).
- HAB sampling often overlooks attached algae (e.g., benthic, or epiphytic algae attached to substrates) and its role in contributing to bloom ecology and dynamics (Wood et al., 2020; Vadeboncoeur et al., 2021).
- Macroalgal responses (growth and distribution) to global changes (e.g., ocean acidification, air/sea temperature) are poorly understood (Harley et al., 2012; Lapointe et al., 2018; Raven et al., 2020 and references within). In turn, the impacts due to release of dissolved and volatile compounds (e.g., toxic hydrogen sulfide) from a bloom into the surrounding water column and water/air interface are also not well known (reviewed in Lapointe et al., 2018) or monitored adequately.
    - Studies undertaken to establish the macroalgal biomass needed to affect benthic organisms have reported varying numbers (Bona et al., 2006; Scanlan et al., 2007; Green et al., 2014; Sutula et al., 2014), suggesting that impacts will vary depending on the environmental conditions within a geographic location (Lapointe et al., 2018).
    - Free-floating macroalgae can challenge efforts to reliably survey, sample and model blooms given that they are subject to advection by currents, tides, etc. (Smetacek and Zingone, 2013).
    - Toxic dinoflagellates are known to raft on *Sargassum*, which could lead to further expansion of Florida red tide events related to influx of macroalgal biomass.

- Because microbial associations (bacteria, viruses, protists) exist in complex interactive webs (leading to competition, mutualism, cell-to-cell encounters, signaling mechanisms, varying modes of nutrient acquisition and cycling, varying temporal and spatial scales, multiple life stages, diverse and sometimes shared genetic material) the full nature of these interactions is inherently difficult to study in a holistic manner, although new genetic tools can assist in unraveling these associations (Garvetto et al., 2018; Hattenrath-Lehmann et al., 2019). These factors challenge our ability to address bloom-related questions, namely: what controls shifts in species diversity, especially those leading to bloom development, when one or only a few species become dominant? How important is the role of infective organisms in bloom termination and how does it vary under different environmental conditions?
    - While advances in genetic techniques have greatly increased the ability to identify multiple species from an environmental sample, studies are still limited by the difficulty in isolating bacteria (many are "unculturable") and viruses and performing more targeted physiological studies with key species. This "shotgun" approach cannot determine which pathogens are linked to a particular HAB species in a given sample. Further, such studies often produce a percentage of sequences that cannot be linked to species in existing global genetic databases.
    - Nevertheless, insights into parameters like host-dependency, susceptibility to pathogens, genetic variability, and infectivity can be gleaned from complex experiments exposing unialgal cultures to well-characterized pathogen communities (e.g., Carlson et al., 2016).
    - Beyond diversity and infectivity, there is a need to uncover the genetic basis for defense mechanisms (Papoulis et al., 2021), especially how these may be related to toxin production by HAB species (Gleason et al., 2015; Bates et al., 2018 and references therein). Behavioral responses such as cyst formation to elude infection are also underexplored (Chambouvet et al., 2011).
    - The discovery of *Amoebophrya* spp. as parasites to a variety of host dinoflagellates has been a critical step towards understanding mechanisms of bloom control; however, it is important to undertake regional studies and avoid extrapolating results to all environments. For example, Mazillo et al. (2011) found that strong upwelling conditions during 2007 likely allowed a common dinoflagellate host, *Akashiwo sanguinea*, to escape infection and develop into a massive bloom. These oceanic conditions are common to eastern boundary systems such as those on the US west coast, but do not occur on the east coast where *Amoebophrya* spp. are also common (Gunderson et al., 2002).
    - Changing parameters like ocean temperatures, nutrients and pH are leading to shifts in species distributions (as mentioned above) and it is not clear how these changes will affect organismal interactions: will they remain coupled or become decoupled? Will there be subsequent adaptive

changes in behavior and/or infectivity rates? Will novel predator-host relationships develop?

- The role of extracellular polymeric substances (EPS) in the resilience of both marine and freshwater microalgae to stressors such as grazers and environmental disturbance remains poorly understood. EPS are also directly implicated in the disruption of desalination plant operations by algal blooms.
- Many questions remain about the types of compounds produced by HAB species, e.g., what are the surfactant-like proteins that affect thermal regulation in seabirds, and why do some species produce variable amounts of reactive oxygen species (what are the mechanisms for production, are they part of a more complex pathway leading to fish kills? How does production contribute to food web dynamics and biogeochemical cycling) (reviewed in Diaz and Plummer, 2018)?

2.5.3. PATHS FORWARD AND RECOMMENDATIONS FOR THE FUTURE

- Sustained support is needed to vastly expand large observational datasets over time and space to provide continuous measurements versus the current practice of discrete datasets that are constrained and defined by funded project timelines. In situ measurements of HAB species and their toxins, coupled with molecular ("omics") analyses and physicochemical contextual data serve as a comprehensive approach to elucidate drivers of bloom growth and toxicity aimed towards improving predictive model accuracy.
  - These efforts can be leveraged with "cruises of opportunity" in which planned operations can be augmented with increased sampling efforts.
  - Deployment of vast and diverse resources during extreme weather/climatic events (see examples in Trainer et al., 2020a, 2020b) can provide unique opportunities to investigate multiple HAB drivers (e.g., temperature, salinity, nutrients, turbulence) within an unprecedented context.
  - As there is no "one size fits all" prescribed scenario for bloom formation that fits all locations (across the US or globally), it is important to support long term regional and localized studies.
- Genomic characterization of blooms should expand to holistically include species and strain detection (DNA), transcriptomics (gene activity, toxin genes in particular), proteomics (physiological condition or response to environmental change), and metabolomics (cellular responses to changing environments) (Fig. 2.10).
  - Simultaneous analysis of multiple toxins within an ecosystem will broaden insights into the synergistic mechanisms impacting these environments.
  - Complementary sampling of attached algae (e.g., benthic and epiphytic species) would serve to provide a more comprehensive understanding of the ecosystem, including inter-organismic relationships and nutrient cycling.

  - Metabolomic/proteomic profiles will aid our understanding into the complexity of allelopathy and how it shapes bloom events.
  - This multi-faceted sampling approach should be used to greatly expand cyanobacterial species characterization across inland lakes.
- Continue to improve the way multiple environmental stressors are measured at the population/community level to understand physiological effects (including toxin production) and trophic interactions among HAB species and their grazers and better predict bloom formation, maintenance, and termination, especially as these stressors (e.g., temperature, acidification) shift with global changes in climate (reviewed in Wells et al., 2020). There is a need to:
  - Uncover HAB species adaptations to shifts in stressors towards improved prediction of potential changes in bloom activity and distribution (e.g., geographic expansions, increased toxicity).
  - Characterize secondary metabolites produced by HABs (including EPS), and the threshold concentrations of these that induce grazing deterrence and allelopathic effects. Production of these compounds can occur in parallel to that of toxins. Biological interactions (allelopathy, grazing deterrence, chemical signaling) need to be studied at a species- or even strain-specific level.
  - Better understand the environmental factors that drive the production of the other major cyanotoxins other than microcystins, i.e., cylindrospermopsins, STXs and anatoxin-a, guanitoxin (formerly known as anatoxin-a(s), as well as novel toxins, e.g., anabaenopeptins.
- Computing infrastructure is needed to accommodate storage needs for larger datasets, and standardized curating is needed to ensure accessibility and utility.
- Artificial intelligence (AI) approaches, including machine learning (ML), are starting to be explored in the realm of HAB bloom ecology with respect to threats to aquaculture practices (Cruz et al., 2021), inland lakes (Lin et al., 2018b), and coastal regions (Yu et al., 2021) and should be fostered. Integration of AI with community science (see sec. 1.2.) can serve as a powerful means to fill critical knowledge gaps across time and space.
- Myriad factors need to be studied in a multidisciplinary context to better understand the full macroalgal bloom paradigm (initiation/ maintenance/ termination), acute and long-term effects (ecosystem, human and organismal health, economies), natural product uses, and responses to factors like sea level rise which may provide new shallow habitat (Harley et al., 2012).
  - There is a need to uncover the interplay between existing parameters that support blooms such as nutrient loading and circulation patterns, with changing climatic variables (Wang et al., 2019).
  - Tracer experiments should continue to further our understanding of nutrient sources informing mitigation and management strategies.

  - The beneficial uses of macroalgae as fertilizers, natural products, and biofuels including biochar (Lapointe et al., 2018; see discussion by Joniver et al., 2021) should be further explored.

- Morphological and genetic screening of algal cultures for putative parasites would provide a reference database for insights from field analyses of host-parasite interactions (reviewed in Coy et al., 2018; Charon et al., 2021), thereby moving the field beyond morphological observations alone. Integrative and multidisciplinary experiments can further our understanding on more granular scales.

- Full life cycle elucidation of algae is required, especially identification of resting stages that may contribute cells to seeding future bloom events.

- Long-term, regional datasets are needed to support findings regarding the spatio-temporal distribution of host-parasite interactions and their response to biotic and abiotic changes in aquatic environments.

- Continued reporting of HAB events to "The Harmful Algal Event Database" (HAEDAT) that includes measurements of environmental conditions will contribute to a better understanding of regional and global bloom drivers.

  - Efforts are underway to include reports of macroalgal blooms in HAEDAT (Anderson et al., 2021b), and the IOC-ICES-PICES Harmful Algal Event database.

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Water quality monitoring buoy deployed during algal bloom in Washington Park Lake, Albany, New York. Photo credit: M. Stouder.

3 HAB COLLABORATIVE MANAGEMENT AND EVENT RESPONSE: PREVENTION, CONTROL, AND MITIGATION STRATEGIES

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Summary

Prevention, control, and mitigation are useful common strategies to cope with harmful algal blooms (HABs) in affected areas, that are often integrated into successful event response and management programs. Therefore, it is important to define the differences between each of these technical areas and programs. Specifically, prevention refers to environmental management actions taken to reduce the incidence and extent of HABs prior to their initiation, which are typically longer-term and have slower response times compared to direct bloom control strategies. Therefore, prevention typically focuses on nutrient reduction to restore "natural" conditions, and/or methods to limit harmful species' dispersal and proliferation. As such, prevention approaches often have multiple purposes, i.e., nutrient reduction alongside ecosystem restoration. Many methods of control (typically with rapid response times) can also be applied preemptively to prevent HABs

from reoccurring. Ecosystem restoration has many purposes but is occasionally studied to prevent HABs. Activities such as restoring bivalves, fish, and benthic macrophytes; aerating bottom sediments, and stimulating beneficial algae, are all approaches that have been investigated[3]. Long-term nutrient reduction, however, is widely considered the most effective means of preventing HABs in some regions and, as such, has been the focus of much prevention research.

Control refers to strategies that directly kill HAB cells and/or destroy their toxins, physically remove cells and/or toxins from aquatic systems, and/or limit their growth and proliferation. These strategies are typically short-term and have faster response times compared to bloom prevention strategies. Control is arguably the most challenging and controversial aspect of HAB management and is among the least developed of all areas of HAB science in the US. Many among the public and in government expect HAB research to move aggressively towards increasing our understanding on this topic, but progress remains slow in part due to questions of cost-effectiveness and scalability, and regulatory and funding limitations. As climate change scenarios predict that conditions favoring some HABs may become more widespread in the coming years, long- and short-term control strategies will become increasingly important in protecting human and ecosystem health. While complete elimination of blooms is unlikely, control methods can lead to substantial mitigation of impacts under some circumstances.

Mitigation refers to responses to an existing or ongoing bloom by taking steps to limit, delay, or inhibit associated undesirable impacts on the ecosystem, human health, and/or surrounding economies and communities. Mitigation is the aspect of HAB management where the most immediate potential exists to reduce HAB impacts, particularly as many activities related to mitigation are currently underway. Some emerging control technologies currently in the research phase have the future potential to transition into operational management programs, i.e., using control methods when blooms cannot be eliminated but can be reduced, thus mitigating their impacts. Furthermore, discerning the underlying causes and inherent biology of HABs will allow for the development of more cost-effective, early warning prediction and intervention strategies.

Emerging evidence of the connectivity between cyanobacterial HABs in freshwater ecosystems and the marine environment is a new management challenge where coordination in both monitoring and management is critical. The transport of cyanotoxins into the marine environment is a nascent field of research and was not described in the prior "Harmful Algal Research and Response: A National Environmental Strategy" (HARRNESS 2005). In the last 15 years, there has been a growing understanding of the extent and magnitude of this problem including potential transport mechanisms for cyanotoxins and cyanobacteria through watersheds and demonstration of the negative ecosystem impacts, including human health impacts, of this phenomenon. Cyanotoxins and cyanobacteria can be transported hundreds of miles from inland waterbodies to downstream receiving waters, including estuarine and marine waters. Further, multiple cyanotoxins and mixtures of marine and cyanotoxins have been detected simultaneously. Integrated

3 For more information in freshwater see the 2020 ITRC Strategies for Preventing and Managing Harmful Cyanobacterial Toxins. 6. Management and Control Strategies for HCBs

studies and monitoring across the freshwater-to-marine continuum to examine the transport of HAB cells and toxins from inland freshwaters to marine waters are difficult to undertake due to the need for cross-jurisdictional coordination. Currently there are few monitoring efforts to better characterize this issue and develop management strategies. A major gap in assessing the severity of the issue is a lack of regulatory guidelines or health thresholds addressing cyanotoxin ingestion via shellfish. Additionally, the potential synergistic effects on human health or aquatic life from acute or chronic exposure to multiple cyanotoxins or mixtures of marine and freshwater toxins are poorly understood.

Rapid Event Response (ER) is required in the face of unprecedented HABs (new and recurring events) in terms of scale or timing. In 2003 NOAA National Centers for Coastal Ocean Science Competitive Research Program (NCCOS CRP) established the current, very small, national HAB ER program, partnering with the US HAB National Office at the Woods Hole Oceanographic Institution (WHOI). HARRNESS 2005 recommended "a well-coordinated, national HAB event response capability that could rapidly deploy HAB scientists around the country at a moment's notice to document blooms and HAB impacts from inception to demise." The Research, Development, Demonstration, and Technology Transfer (HAB RDDTT) 2008 report devotes an entire chapter to ER, which includes funding for rapid response and state, local, and tribal capacity building, but that plan has never been implemented. There is thus an urgent need for comprehensive and established ER programs for freshwater and marine HABs given projected climate changes in HAB frequency, magnitude, and duration.

Finally, in the context of this report, management refers to actions that federal, state, tribal and local governments take to better address HAB impacts. These actions directly benefit the environment and stakeholders including commercial fishermen and aquaculture farmers, operators of drinking water facilities, and members of the public such as recreational users of coastal waters. Furthermore, many of the advances in prevention, control and mitigation research are directly implemented through management, and therefore coordination between mitigation science and manager needs is essential to protect public and wildlife and domestic animal health and preserve aquatic resources.

3.1. HAB Prevention

3.1.1. CURRENT STATE OF KNOWLEDGE AND SIGNIFICANT ADVANCES

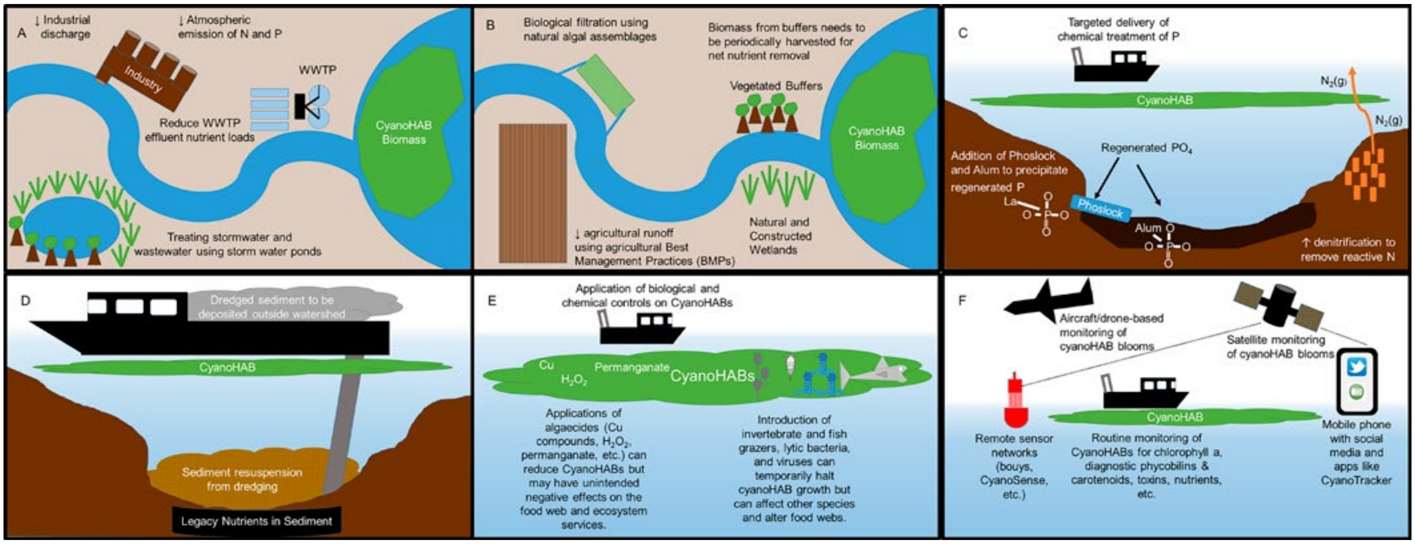
A. *Nutrient Reduction*

There is substantial knowledge of the use of nutrient reduction strategies coupled with several in-water technologies to limit harmful algal blooms (HABs) in many freshwater systems (Fig. 3.1.), although less so in coastal marine or estuarine/brackish systems. In many cases consideration must be given to nitrogen (N), phosphorus (P), and sometimes silicate, together and separately. Their relative abundance and form may be as important as their absolute concentrations (e.g., inorganic vs. organic, particulate vs. dissolved). Finally, multiple sources of nutrients must also be considered including benthic and water column regeneration, riverine inputs, upwelling, etc.

- Models can be used to compare the role of different nutrient sources and prioritize approaches for nutrient reduction to prevent HABs.
    - Several models have been developed to estimate nutrient source contributions and associated load reductions from changes in Best Management Practices (BMPs):
        - Watershed scale: Better Assessment Science Integrating Point and Non-point Source (BASINS), Soil and Water Assessment Tool (SWAT), SPAtially Referenced Regression On Watershed Attributes (SPARROW), and Model My Watershed. More information is available in the US Environmental Protection Agency (US EPA) report, "Nutrient and Sediment Estimation Tools for Watershed Protection" and many states and partnerships have their own models beyond these examples (e.g., Chesapeake Bay models).
        - Field scale: The Agricultural Conservation Planning Framework (ACPF) toolbox helps to identify locations for placement of structural BMPs. The Nutrient Tracking Tool (NTT) and On-Field Ohio estimate nutrient contributions from various agricultural practices and determine how changes in these can reduce loads. The US EPA's Spreadsheet Tool for Estimating Pollutant Loads (STEP-L) helps calculate nutrient and sediment loads from different land uses and how BMPs can reduce those loads.
    - Scenario forecasting using ecosystem models: These models are widely dispersed throughout the US (e.g., Great Lakes, Chesapeake Bay, Gulf of Maine), ranging from box models to complex 3-D models. They often link physical and hydrological dynamics to biogeochemical processes that cycle nutrients among terrestrial, atmospheric, and aquatic environments.
- Through the Clean Water Act, Total Maximum Daily Load (TMDL) requirements and Nine Element Plans have been established to reduce nutrients from point and nonpoint sources (at limited scales and funding support) to meet TMDLs and indirectly reduce HABs. Some policy measures directly related to reducing nutrients include:
    - Nutrient additive restrictions (P limits in detergents and fertilizers),
    - Local fertilizer ordinances (requiring slow-release fertilizers or pulsed nutrient applications),
    - Maintenance/upgrade/replacement of individual septic systems,
    - BMPs in agriculture (see Table 3.1),
    - US Environmental Protection Agency (US EPA) National Pollutant Discharge Elimination System (NPDES) for stormwater and wastewater.
- Federal funding programs through the US Department of Agriculture (USDA) and US EPA have been established to help improve/update infrastructure for wastewater and stormwater:

  - USDA Rural Development water and wastewater loans and grants. As of 2019, $18.6 billion were invested to build new or improved infrastructure (66% loan, 34% grant, 25% leveraged with other funding sources) and $272 million in technical assistance funds provided to rural communities,
  - US EPA Clean Water State Revolving Fund and Water Infrastructure Finance and Innovation Act water infrastructure loans and grants, $7 billion in annual funding,
  - US EPA CWA National Park Service control grants FY20 $172 million. Approximately 80% of funding addresses nonpoint source nutrient impairments, USDA-Natural Resources Conservation Services (NRCS) programs (Conservation Reserve Program, Environmental Quality Incentives Program, Regional Conservation Partnership Program, etc.).
- Environmental stewardship, guidance, and management programs:
  - National Study of Nutrient Removal and Secondary Technologies,
  - 4Rs nutrient stewardship concept (right source, rate, time, and place),
  - Interstate Technology and Regulatory Council (ITRC) Strategies for Preventing and Managing Harmful Cyanobacterial Blooms (2021),
  - The Chesapeake Bay Program lists more than 100 BMPs and the efficiencies for nutrient and sediment removal,
  - USDA-NRCS offers information on many conservation practices, many of which target nutrient runoff reduction.

Figure 3.1. Conceptual diagram illustrating multiple, interacting controls in cyanobacterial management. Climatic influences have led to the need to reduce nutrient loading below previous reduction standards, putting additional pressure on reducing nutrient inputs from (A) point source and (B) nonpoint source pollution, (C) regenerated nutrients, and (D) legacy nutrients (nutrient inputs from previous years that are temporarily stored in the watershed) through various mechanical, chemical, and biological means. (E) Short-term (several months) chemical and biological treatment approaches used. (F) Appropriate monitoring is essential for assessing the scale of cyanobacterial HABs and efficiency of management approaches. *Reproduced with permission from Paerl and Barnard, 2020.*



- Several technologies have been evaluated to draw down nutrients and are at various stages of development and implementation. These technologies are generally applicable to both marine and freshwater systems and are broadly applied in two ways (see Table 3.1.).

1. *Land-based*: nutrient reduction BMP (a land use change) that is a natural or engineered terrestrial treatment to reduce nutrient loading in aquatic ecosystems,
2. *In waterbody:* nutrient reduction BMP applied directly to a waterbody, inlet, or receiving waters diverted to land constructed flow ways to reduce nutrients in aquatic ecosystems.

B. *Limitation of HAB Dispersal*

- Several technologies have been proposed to limit the dispersal of HAB species or prevent initiation from resting stages and cellular proliferation, including:
    - Ballast water treatment and prevention/regulation of discharge in sensitive coastal locations,
    - Dredging or sediment mixing to remove HAB resting stages directly or bury them at depth where germination cannot occur,
    - Capping of sediments with sand or other material that can bury HAB resting stages such that resuspension or germination are reduced.

- Under the National Syndromic Surveillance Program (NSSP), all states are restricted from transferring or relaying commercial bivalves harvested from growing areas in a closed status (e.g., bivalves with toxin concentrations meeting or exceeding the guidance level during a HAB event). Transfers at other times are not restricted, although they are hypothesized to possibly disperse HABs if viable HAB cells or cysts are contained in the bivalve pallial cavity or gut and are released at the new location.

3.1.2. KNOWLEDGE GAPS AND UNDERDEVELOPED CAPABILITIES

A. *Nutrient Reduction*

- The effectiveness of nonpoint source nutrient reduction approaches is largely unknown and is complex to address in places such as urbanized estuaries with poorly functioning septic systems and aging wastewater infrastructure (Brewton et al., 2022). More detailed information on specific approaches for nutrient removal are included in Table 3.1., but some of the knowledge gaps are listed below.
  - Lack of monitoring to determine the effectiveness of nutrient reduction strategies at watershed scale,
  - Lack of scenario models to predict impacts of nutrient reduction strategies and climate change on nutrients in water bodies,
  - Many nutrient reduction strategies are site-specific, have limited scalability or only target specific nutrients,
  - Cost-effectiveness must be determined and guide implementation since some effective methods are expensive to implement and others that are less costly but also less effective, are often used.
- USDA uses a distributed instead of a targeted funding model that favors reducing nutrient loads from most poorly performing land areas. More targeted BMPs and conservation practice implementation within USDA would reduce larger nutrient and sediment loads rather than ensure an equitable distribution of funds in each region.
- Information on type and number of implemented nutrient BMPs is not publicly available and limits the ability to determine overall effectiveness of practices at a larger watershed scale. It would be helpful if data on BMPs and conservation practice implementation were made available from federal funding agencies (NRCS, US EPA, Great Lakes Restoration Initiative [GLRI], etc.) on at least the hydrologic unit code (HUC) 12 watershed scale. Supporting programs such as the Ohio Agricultural Conservation Initiative that collect and consolidate BMP implementation data at a national scale would substantially enhance the ability to evaluate the efficacy of BMP practices across a range of conditions.

- Funding is insufficient to address infrastructure needs such as increasing the level of wastewater treatment (e.g., biological nutrient removal), replacement of poorly functioning individual waste treatment systems, or implementing BMPs at scales needed to address downstream impacts (the US EPA Clean Water and Drinking Water Infrastructure Gap Analysis 2002).
- There is a lack of sustained support for stream gaging and nutrient monitoring networks, especially those used in long-term monitoring critical for trend analyses such as the US Geological Survey (USGS) Federal Priority Streamgages and National Water Quality Network.
- Distribution of, access to, and training for user-friendly, down-scaled modeling tools is limited and warrants greater support.
- The role of high nutrient wastewater discharges from ships in HAB initiation is unknown, especially in small coastal embayments.

B. *Limitation of HAB Dispersal*

- Methods to limit the dispersal of HAB species via ballast water treatment have been proposed (Sellner and Rensel, 2018), but few experiments have looked at their effectiveness against highly resistant HAB resting stages. Method effectiveness to prevent HAB cell dispersal is not always considered in regulating ballast water discharges. Likewise, some studies have examined the effectiveness of burying or capping HAB resting stages or overwintering vegetative 'seed' beds to limit bloom inoculation, but more research is needed, particularly on the logistics of conducting such operations in effective yet environmentally acceptable ways.
- The transfer of shellfish from a HAB-affected area to an unaffected one is typically not restricted but is hypothesized to potentially disperse HAB species.

Table 3.1. Land-based and in-water body strategies for nutrient and algal bloom reduction[4]

PREVENTION STRATEGIES	EFFECTIVENESS, CHALLENGES AND TECHNOLOGICAL GAPS
Land-based: Natural or engineered terrestrial treatment	
Riparian Vegetation Zones	Widespread effectiveness at reducing sediment-associated particulate phosphorus as well as some removal of dissolved nitrogen species. Additional information is needed on reducing dissolved nutrient loads
Land Conservation and Acquisition	Site-specific efficacy. Many economic, legal, and bureaucratic challenges
Wetlands	Results are mixed on the efficacy of wetlands as long-term nutrient sinks. Requires close monitoring and management to ensure nutrient sinks do not become nutrient sources (may require dredging or vegetation removal to maintain removal capacity). Constructed wetlands designed for wildlife habitat may be less effective than those designed for nutrient control. As sea level rises, the area of wetlands may be reduced, compromising their capacity as a nutrient sink
Stormwater Management Strategies	For practices that slow stormwater flow and serve as sediment traps, applied data on efficacy for nutrient removal are limited
Agricultural BMPs for Nutrient Control	Some practices, such as wood chip bioreactors and phosphorus filters, are highly effective at dissolved nutrient removal but are often expensive and may be difficult to scale. Data on effectiveness of discrete 4R[4] practices, saturated buffers, and cover crops on dissolved phosphorus removal is limited (although nitrate removal is high). In addition, data on the cumulative impact of these practices at the watershed scale are limited (most data are from edge of field monitoring)
Agricultural BMPs for Sediment Control (for soil bound nutrients)	Generally effective at reducing sediment-associated particulate phosphorus. Data on effectiveness of these practices on dissolved nutrient removal is limited. In addition, data on the cumulative impact of these practices at the watershed scale is extremely limited (most data are from edge of field monitoring)
In Waterbody: Applied directly to a waterbody, inlet, or receiving waters	
Algal Flow Ways	Effective at removal of dissolved nutrients and particulate-associated phosphorus. Potential risk of toxic cyanobacteria colonization and associated release of extracellular cyanotoxins into receiving water. If in-water, potential concerns for navigable waterways. Challenges to waterbody/lake scale application
Phosphorus Binding Agents (freshwater)	Long-term toxicity studies are needed. Nitrogen release from bottom sediments can accompany application of some commercial phosphorus-binding agents. Resuspension and regrowth are possible in shallow sediments, requiring frequent re-application
Floating Wetlands	Effective at removing dissolved nutrients and particulate-associated phosphorus in small areas and flow ways. Require extensive annual harvesting and maintenance. Challenges to large waterbody/lake scale application
Submerged Aquatic Vegetation	Effective at reducing nutrient inputs from point and nonpoint sources. Ecologically friendly approach providing habitat and nursery grounds for marine organisms

3.1.3. PATHS FORWARD AND RECOMMENDATIONS FOR THE FUTURE

A. *Nutrient Reduction*

- Modeling efforts that can be used to verify the link between nutrient loading and HABs and test the most effective nutrient reduction approaches by running scenarios with different nutrient reduction treatments are needed.
- Targeting critical, high-nutrient, and high-sediment load areas ('hotspots') for BMP implementation and monitoring to evaluate effects on water-quality conditions.
- Increase the number of long-term monitoring locations throughout the US that include continuous measurement of streamflow and collection of samples for

4 4R Strategy: Right fertilizer source at the Right rate, at the Right time and in the Right place

nutrient analysis; better address nutrient impaired waterways that contribute to HABs through programs such as the Clean Water Act Section 319.

- Conduct projects that assess the overall in-stream and receiving water impacts of agricultural nutrient reduction BMPs (move beyond edge of field to watershed scale monitoring).
- Wastewater infrastructure improvements that reduce P and N loading to nutrient-impaired streams are needed.
- Investigate whether high nutrient discharges from vessels stimulate HABs in small, pristine coastal embayments and, when necessary, develop strategies to mitigate the impact of these discharges.

Limitation of HAB Dispersal

- Conduct studies on environmentally acceptable and logistically feasible approaches to limit the inoculation of HABs from bottom sediments in both marine and freshwater systems.
- Develop and enforce regulations that restrict release of HAB organisms and resting stages by ballast water or shellfish transfer into sensitive waters.

3.2. HAB Control

3.2.1. CURRENT STATE OF KNOWLEDGE AND SIGNIFICANT ADVANCES

- In response to Congress, the National Oceanic and Atmospheric Administration (NOAA) established the Prevention, Control and Mitigation of Harmful Algal Blooms (PCMHAB) Program in 2010 to fund extramural research on HAB control and mitigation in the oceans and Great Lakes and additionally conducts intramural research on control. NOAA research does not generally include inland lakes, ponds, reservoirs, and rivers as these are outside NOAA's purview. However, NOAA develops and evaluates products at a national scale that may be transferred to other aquatic systems. Additionally, NOAA partners with other agencies that directly support research in rivers and inland freshwater systems.
- The US Army Engineer Research Development Center (USACE-ERDC's) Freshwater HAB Research & Development (R&D) Initiative has accelerated progress toward filling the HARRNESS 2005-identified freshwater HAB R&D gap (Michalsen et al. 2024). The Water Resources Development Act of 2018 (WRDA 2018) authorized USACE-ERDC to implement a 5-year technology demonstration program intended to deliver scalable technologies for HAB detection, prevention and management to reduce HAB frequency and effects in our Nation's freshwater resources across scales (e.g. small lakes to river reaches), ecoregions (e.g., subtropical to temperate), and system types (e.g., riverine, lakes). The USACE also partners with other agencies to leverage the

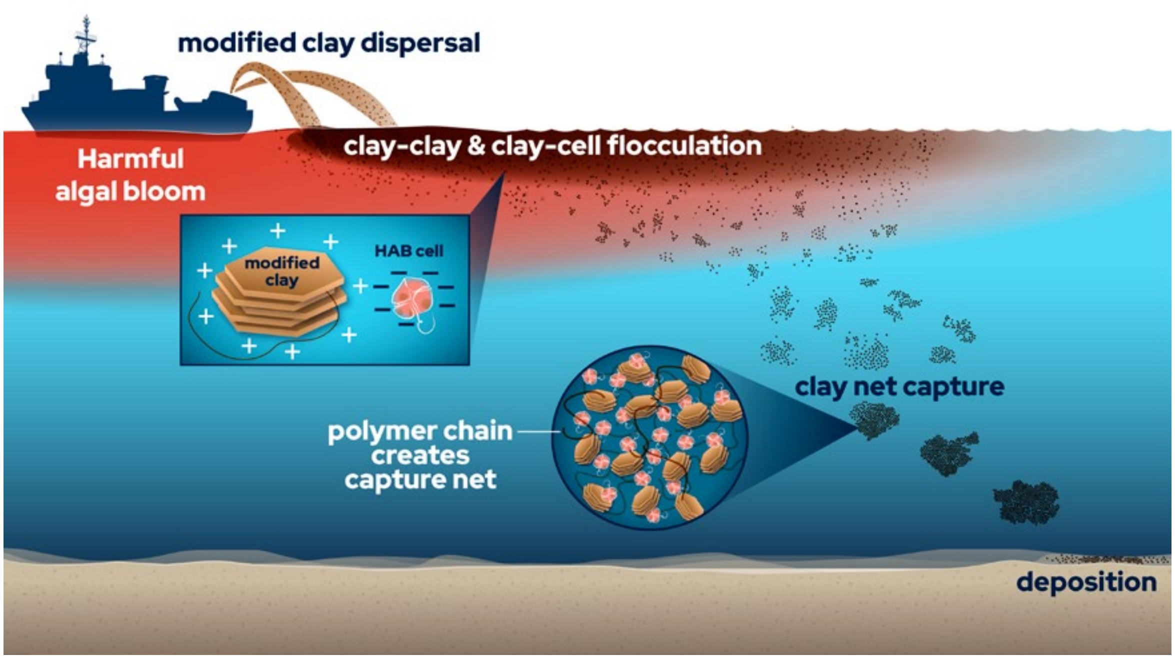
development of resources and tools to predict, monitor, control, and prevent HABs in freshwater systems.

Only limited additional R&D funding for control strategies, including their transition to field application, has been provided by states (for example: OH, FL, NY, CA) and other federal agencies (US Army Corps of Engineers [USACE], US Environmental Protection Agency [US EPA], US Fish and Wildlife [US FWS], Bureau of Reclamation [BoR]). While these Federal agencies are working hard to improve communication and coordination of HABs control research and demonstrations, the scale of the problem would benefit greatly from additional and continued coordination efforts.

- Agencies focused on applied science (e.g., Bureau of Reclamation [BoR]) have only recently become involved and are establishing HAB programs and research strategies.
- HAB control in coastal marine and estuarine environments lags behind the significant advances in terrestrial pest control (agriculture, silviculture), aquaculture, and freshwater HAB control.
    - The vast majority of marine HAB control technologies (reviewed in Anderson et al., 2017; Sellner and Rensel, 2018) remain in the development phase in which studies are conducted in test tubes, flasks, and mesocosms. Some of the more promising strategies include the use of ozone for destruction of cells and toxins, clay flocculation for aggregation and settling of HAB cells, and the use of bacteria or bacterial exudates, or viruses to selectively control and/or suppress HAB growth within the plankton community.
    - In US coastal marine waters, only two marine bloom control technologies (ozone and clay flocculation) have been tested in limited controlled field trials. Clay flocculation has been used for more than two decades to control numerous blooms in Asia over scales of tens to hundreds of km^2 (Park et al., 2013). This approach has been the subject of research studies in the US (Fig. 3.2.) as well as in other countries but has not yet been accepted for use in the US, partly due to more stringent environmental regulations and the lack of impact studies using US HAB species. Its effectiveness varies greatly depending on the HAB species (e.g., thecate vs. non-thecate dinoflagellate, motile vs. non motile cell, clay type, concentration and additives used, and environmental conditions [especially flow]). The processes involved in HAB control using clay are illustrated in Fig. 3.3.

Fig. 3.2. **Clay flocculation for HAB control.** A field study was conducted over 1400 m^2 at a canal site in Sarasota, FL, targeting a bloom of *Karenia brevis* in December 2018. A kaolinite clay modified with an inorganic polymer that enhances cell removal was sprayed onto the water surface. Flocculation of the clay particles with each other and with *Karenia* cells leads to flocs that settle to the bottom, killing or incapacitating *Karenia* cells. This and similar studies are examining the impacts on HAB cells, as well as on co-occurring phytoplankton, zooplankton, and benthic animals. Changes in water chemistry were also investigated. This field study was supported by the Florida Fish and Wildlife Research Institute. *Photo credit: D. Kulis, Woods Hole Oceanographic Institution.*

Fig. 3.3. 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.*



- Suspension-feeding bivalves are capable of high filtration (clearance) rates and thus removal of HAB species from the water column. They were shown to be capable of HAB initiation control in experimental mesocosms (e.g., for brown tides of *Aureococcus anophagefferens*) (Cerrato et al., 2004). Their role in controlling bloom initiation in shallow, enclosed embayments remains to be confirmed and could justify bivalve stock enhancement practices.
- A range of control strategies for freshwater pelagic cyanobacteria have been evaluated in laboratory, mesocosm, and field-scale experiments and a subset are being used routinely by lake managers. Existing strategies vary in effectiveness and many promising new strategies are still in the research and development phase (see Tables 3.2 and 3.3). Additional information and details are available in the following resources:
    - US EPA *Control Measures for Cyanobacterial HABs in Surface Water* website https://www.epa.gov/cyanohabs/control-measures-cyanobacterial-habs-surface-water,
    - Global HAB *Solutions for Managing Cyanobacterial Blooms: A Scientific Summary for Policy Makers* 2019 http://www.globalhab.info/files/Cyano_mitigation_GlobalHAB2019.pdf,
    - Interstate Technology and Regulatory Council (ITRC) *Strategies for Preventing and Managing Harmful Cyanobacterial Blooms* interactive web site https://hcb-1.itrcweb.org/,
    - Mitigation Subcommittee of the California Cyanobacteria and Harmful Algal Bloom Network Algae *Mitigation Technique Selection Process for Lakes* 2019 https://mywaterquality.ca.gov/habs/resources/docs/flow_chart_draft_20190515.pdf,
    - New England Interstate Water Pollution Control Council (NEIWPCC) *Harmful Algal Bloom Control Methods* 2015 https://www.neiwpcc.org/neiwpcc_docs/NEIWPCC_HABControlMethodsSynopses_June2015.pdf,
    - Water Quality Research Australia *Management Strategies for Cyanobacteria (blue-green algae): a Guide for Water Utilities Research Report 74* 2010 https://www.researchgate.net/publication/242740698_Management_Strategies_for_Cyanobacteria_Blue-Green_Algae_A_Guide_for_Water_Utilities,
    - American Water Works Association *Algae: Source to Treatment* Manual *M57* 2010. https://engage.awwa.org/PersonifyEbusiness/Bookstore/Product-Details/productId/39312113,
    - US Army Corps of Engineers *Cyanobacteria Harmful Algal Blooms (HABs) and US Army Engineer Research and Development Center (ERDC): Research and Services* 2021 https://apps.dtic.mil/sti/pdfs/AD1143892.pdf.
- Benthic marine and freshwater blooms pose largely unknown environmental and human health concerns and information on benthic bloom control strategies is limited.

3.2.2. KNOWLEDGE GAPS AND UNDERDEVELOPED CAPABILITIES

A. *Programmatic Gaps*

- There is no national program specifically for inland freshwater bloom control.
- There are no regional/national programs for monitoring of coastal marine benthic HAB species which hinders efforts for control of prolific benthic mats in these habitats.
- Funding for bloom control is still vastly below what is needed, particularly since projects that try to transition laboratory-based control approaches to large-scale field application are often expensive and require multi-year, multi-investigator interdisciplinary efforts.
- The current rotation among NOAA HAB funding programs, namely Prevention, Control, and Mitigation of Harmful Algal Blooms (PCMHAB), Ecology and Oceanography of Harmful Algae (ECOHAB) and Monitoring and Event Response for Harmful Algal Blooms (MERHAB) can lead to multiple years without the start of new PCMHAB projects for marine and Great Lakes HABs. Furthermore, the PCMHAB program also funds research on socioeconomics, monitoring, and prevention, which can take away from control project funding (i.e., there is no dedicated funding for HAB control).
- There are no current coordinated programs for independent third-party evaluation of emerging HAB control technologies.
- There are few interactions among the HAB community and researchers and managers who work on control of terrestrial pests or even between freshwater and marine HAB communities focused on HAB control.

B. *Technical Gaps*

Tables 3.2. and 3.3. list current and emerging control strategies and associated data gaps. The efficacy and feasibility of all control strategies are dependent on dosage, timing, bloom species, physicochemical environmental conditions, scalability, cost-benefit, location, and whether targeting pelagic or benthic blooms.

Table 3.2. Current HAB control strategies and data gaps. Technologies applicable to freshwater and marine systems are indicated as FW or M, respectively. Multiple technologies can potentially be explored together for added benefit or increased efficacy.

CONTROL STRATEGY	TECHNOLOGICAL GAPS
Well-Developed and Demonstrated Strategies	
Registered Algaecides (FW): US EPA Approved Copper (Cu) and Hydrogen Peroxide-based Formulations	Unknown efficacy at lower temperatures and on different cyanobacterial genera, including benthic cyanobacteria and mixed-species blooms. Toxicity of long-term Cu exposure to lake flora and fauna unknown
Phosphorus Binding Agents (FW)	Long-term toxicity studies are needed; applicability and efficacy not yet demonstrated at larger scales
Shading Compounds (FW)	Applicability and efficacy not yet demonstrated at larger scales
Promising Preliminary Data but not Widely Adopted in the US	
Clay and Surfactants (M & FW)	Widely used in Asia over large areas (up to 100's km^2), but not yet accepted for use in the US. Permitting is the major constraint. Impact studies are needed to better define efficacy with toxic HABs and impact to non-target organisms. In shallow FW systems, can be combined with capping materials to limit resuspension and foster benthic plant growth; the addition of nanoparticles may increase reoxygenation of bottom sediments
Barley Straw (FW)	Need to identify/define dose-response relations, efficacy on different HAB genera, potential impact to non-target organisms and on total organic carbon, drinking water treatment efficacies, and in some systems, dissolved oxygen
Hydraulic Controls (FW)	Impacts on downstream systems are unknown
Available but Unproven Efficacy	
Sonication and Ultrasound (FW)	The mode of action has not been confirmed and most data are proprietary (frequencies employed, exposure durations, and results)
Aeration, Diffusion, and Mechanical Mixing (FW)	Data on effectiveness is inconclusive and more work is needed to determine if these approaches can be effective at larger scales

Table 3.3. Emerging HAB control technologies and information gaps. New technologies that are still in the research and development phase need to be tested at suitable scales. These strategies often present permitting challenges. M and FW as in Table 3.2.

TECHNOLOGY & BRIEF DESCRIPTION	INFORMATION GAPS
Biological	
Algaecidal and Cyanocidal Bacteria (FW & M) Use of antagonistic bacteria capable of selectively killing various algal groups, either by direct attachment or naturally occurring bacterial metabolites	Similar information gaps exist for all the emerging biological control technologies: Mesocosm and large-scale field studies to demonstrate implementation, feasibility, and success Mass production and optimization Cost and feasibility assessments Fate and transport Dose-response relationships Specificity and non-target impacts Human health considerations
Algal Viruses and Cyanophages (FW & M) Viruses that specifically infect and subsequently kill algae and cyanobacteria. Can exploit class, genera, species, or even strain-level specificity	
Parasites (M) Parasites (e.g., *Amoebophrya*) that specifically infect and subsequently kill dinoflagellates, diatoms, and other HABs	
RNA-based Gene Silencing Agents (FW) Highly specific genetic (DNA or RNA-based) constructs designed to reduce expression of genes relevant to critical biosynthetic pathways like photosynthesis or nitrogen assimilation. Strain-level specificity in cyanobacteria	
Bacterial Remediation of microcystins (FW)* Use of heterotrophic bacteria to naturally metabolize and degrade algal toxins into benign breakdown products	
Bio-physical Techniques (FW) Deployment of near-bottom aerators or diffusers, followed by oxygenation of bottom sediments via bacteria or their enzymes, and subsequent micronutrient additions favoring non-cyanobacterial productivity	
Physical	
Harvesters and Skimmers (FW) Physical aggregation and subsequent removal of biomass via flocculation (biopolymers) or flotation and skimming	In addition to the gaps listed under biological control, beneficial reuse and proper disposal of harvested biomass needs further study
Physicochemical	
Hydrodynamic Cavitation and Ozone Nanobubbles (FW & M)* Destruction of HAB Cells and Toxins via Chemical Oxidation and Oxygenation (Ozone Systems).	In addition to the gaps listed under biological control, efficiency of nanobubble formation (mechanism comparison), longevity of nanobubbles, and relative effects of hydroxyl radicals vs. ozone need further study
Ultraviolet (UV) light (FW)* Use of UV radiation to destroy algal and cyanobacterial cells and degrade associated toxins. Currently only operational in drinking water and wastewater facilities	Primary gap is the potential for transfer of existing technology to water bodies (streams, reservoirs, lakes), including scalability
Novel Oxidant Materials (FW & M)* -Titanium dioxide -Graphene oxide Chemical-mediated HAB Control through Adsorption to Cells and Release of Oxidants from Novel Materials	In addition to the gaps listed under biological control, the ability to retrieve and dispose of potentially toxic waste byproducts needs further study
Allelopathic Chemicals (FW & M) Inhibition of Phytoplankton Growth and Physiological Rates. Includes flavonoids and other naturally occurring chemicals.	In addition to the gaps listed under biological control, toxicity of breakdown products needs further study
*Strategies also potentially capable of toxin destruction	

C. *Additional Technical Gaps*

- Scalable, selective control strategies that have been validated for both freshwater and marine systems,
- Tiered evaluation that allows for assessments of treatment efficacy and environmental and human health risks with increasing complexity and scale (laboratory to mesocosm to field),
- Mesocosm facilities that would allow large-scale studies of HAB control independent of natural bloom occurrence,

- Treatment methods for freshwater and marine benthic HAB events,
- Information on accumulation and degradation of HAB toxin byproducts from control technologies and proper disposal and beneficial reuse of that material,
- Lack of direct funding for diversity/taxonomic studies focused on elucidating target organisms that cause blooms. This lack of proper algal identification directly affects approaches for control and mitigation strategies since species can vary greatly (e.g., in terms of growth rate, genomes, physiology, toxin potential) in their bloom dynamics.

D. Regulatory Barriers

Regulatory barriers impede field testing of new HAB control technologies and approaches on natural blooms at small to large scales. Approval of the broader implementation of new technologies and treatments will not be possible if the only supporting data are from laboratory studies. Barriers to field scale trials include:

- Restrictions under the National Environmental Protection Act (NEPA). For example, Programmatic Environmental Assessments (PEAs) need to be frequently updated to support testing and implementation of innovative control strategies,
- Other federal permit requirements (Federal Insecticide Fungicide and Rodenticide Act [FIFRA] algicide registration, National Pollutant Discharge Elimination System [NPDES] pesticide general permits and inconsistent or undefined individual state requirements),
- In assessing the environmental impacts of control methods, the "do-nothing alternative" in impaired waters is rarely used. Far too often, impacts of control technologies are compared to non-bloom environmental conditions, rather than HAB impacts.

3.2.3. PATHS FORWARD AND RECOMMENDATIONS FOR THE FUTURE

A. Programmatic Recommendations

- Congressional support should be provided to federal agencies such as the US EPA, USACE, BoR, and US Geological Survey (USGS) to establish and provide adequate multi-year funding for control research and demonstration programs for inland freshwater bodies including lakes, reservoirs, and rivers, like the National Oceanic and Atmospheric Administration (NOAA) Prevention, Control, and Mitigation of Harmful Algal Blooms (PCMHAB) program.
- Increase the amount of multi-year funding specifically for research on coastal HAB control (marine, estuarine and Great Lakes) and hold competitions annually, either as part of NOAA's PCMHAB program or a separate program.
- Ensure federal interagency coordination on HAB control research (see sec. 3.7).
- Develop and institute mechanisms for better coordination and collaboration between state and federal HAB control research to avoid duplication.

- Require NOAA (or interagency) PCMHAB projects state managers either as investigators or as Technical Advisory Committee (TAC) members during early planning stages.
- Include Federal PCMHAB expertise in state HAB control programs and vice versa.
- Support organizations (e.g., Interstate Technology and Regulatory Council [ITRC], national and state Sea Grant programs, North American Lake Management Society) to facilitate annual federal-state communication on new, ongoing, and completed control projects and updates to HAB control guidance.

- Periodically, as additional methods for marine and freshwater HAB control are developed, conduct independent evaluation of efficacy, scalability, and cost similar to that for current inland HABs by the Interstate Technology and Regulatory Council (ITRC).
  - Differentiate HAB species in marine environments as either planktonic or benthic to inform separate funding needs.
- Develop publicly available, centralized, interactive websites that identify and evaluate HAB control and mitigation methods (e.g., ITRC Harmful Cyanobacterial Bloom portal).
- Conduct outreach on newly available HAB control methods and associated regulatory issues that must be addressed.
- At the biannual US HAB meeting:
  - Increase funding for attendance of managers by soliciting participation of more federal agencies.
  - Hold sessions focused on HAB control.
- Convene a subgroup of the Interagency Working Group on Harmful Algal Bloom and Hypoxia Research and Control Amendments Act (IWG HABHRCA) focused on federal regulations that prevent field testing of HAB Control (see *Regulatory Recommendations* below).
- Encourage sessions on HAB control methods at regional HAB meetings that include federal, state, and tribal agencies and nations, as well as HAB control businesses and participants with terrestrial pest control experience.

B. *Technical Recommendations*

- Encourage, via coordinated and targeted requests for proposals (RFPs), novel applied research to address data gaps identified in Tables 3.2 and 3.3. Additional considerations include:
  - Scalability, feasibility, and cost must be assessed during early stages of development and testing of control technologies.

    - Modeling of treatment strategies/scenarios to predict outcomes, likelihood of success, and duration of control should be included.
    - Control strategies for freshwater and marine pelagic and benthic blooms need to be evaluated separately, as control strategies will work differently in each case due to many factors such as unique species, salinity, and hydrodynamics.
    - Potential risks of control measures to human, other animal and environmental health, either by direct exposure to the control method itself or subsequent exposure to algal toxins, need to be evaluated.
    - Additional investment is needed in the development of 'scalable green control technologies', i.e., those that are environmentally benign.
    - Better documentation of HAB impacts on pelagic and benthic communities is required to allow comparison between the "do-nothing alternative" and proposed control strategies.
- Special issues of *Harmful Algae* (Elsevier) and other journals (e.g., *Lake and Reservoir Management*) dedicated to HAB control research findings (both marine and freshwater) would enhance timely communication about the state of the science.

C. *Regulatory Recommendations*

Regulatory recommendations are intended to streamline the assessment of environmental impacts of control methods so that additional methods become rapidly available. They include:

- Expand PEAs to include additional approaches and streamline the approval process.
- Request that the IWG HABHRCA convene a working group of federal agencies with regulatory purview over use of control methods and representatives of state agencies with major HAB problems to develop clear federal and state guidelines on:
    - Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) regulations to determine whether new HAB control technologies should be classified as algaecides and fall under these regulations,
    - Pesticide general permit restrictions,
    - Data needed to address potential impacts on non-target organisms (bench scale) prior to full scale treatment approval,
    - Provide options for research-scale exemptions or limited-use permits to allow for the progression of research and demonstration of new control technologies,
    - Designate HAB hotspot test areas where permitting is streamlined, and control methods can be more easily evaluated/compared,

- Designate acceptable disposal methods or beneficial reuse of HAB treatment byproducts or contaminated materials,
- Require comparison of impacts of control methods with the no-treatment of blooms alternatives.

3.3. Mitigation Strategies

3.3.1. CURRENT STATE OF KNOWLEDGE AND SIGNIFICANT ADVANCES

The National Oceanic and Atmospheric Administration (NOAA)'s Prevention, Control, and Mitigation of HABs Program, established in 2010, funds extramural research focused on mitigation. This research has focused on developing tools for early warning, including forecasting and sensors. Other federal agencies have programs that directly or indirectly fund research leading to mitigation, e.g., National Science Foundation/National Institute of Environmental Health Sciences (NSF/NiEHS) Oceans and Human Health, National Aeronautics and Space Administration (NASA) Research Opportunities in Space and Earth Science (ROSES). Other aspects of mitigation (e.g., monitoring and forecasting) are covered in more detail in sec. 1.

A. *Efforts to mitigate impacts to human health*

- The US EPA established both drinking water health advisory levels and freshwater recreational health guidelines for two cyanotoxins: microcystins (MCs) and cylindrospermopsin (CYN).
- Some states (e.g., FL, NY, VT, OH, KS, CA) have established their own protocols for freshwater advisories for drinking and recreational water exposure during bloom events related to both cells and toxins. For the latter, several states have developed guidelines for freshwater toxins, saxitoxins (STXs) and anatoxin-a.
- In the absence of federal recreational health guidelines in marine waters, some state or local governments have issued or are developing advisories for recreational exposure during bloom events (e.g., FL).
- For management of seafood in interstate commerce, all states adhere to the guidance limits for marine toxins, as outlined in the most recent National Shellfish Sanitation Program Guide for the Control of Molluscan Shellfish and the US FDA Fish and Fishery Products Hazards and Controls Guidance.
- Many states manage recreational and subsistence seafood harvesting through testing for marine toxins according to federal guidance levels for commercial seafood or by applying seasonal or blanket closures.

B. Methodological advances to improve mitigation strategies in freshwater and marine systems

Collectively, the advances made in the areas listed below provide more time for mitigation and response efforts. They include:

- Monitoring and forecasting/modeling for both HAB cells and their toxins (see sec. 1.3).
- Establishing protocols to issue advisories or closures, maintaining safe seafood, and protecting drinking water to limit exposure to HABs and prevent human illness.
- Advances in our understanding of the effectiveness of treatment technologies for destruction/removal of cyanotoxins in drinking water has reduced the risk of associated human health impacts. For example, guidance has been developed by the US EPA, World Health Organization (WHO), American Water Works Association (AWWA) and some states for the removal or destruction of MCs and CYN.
- Advanced diagnostics and therapeutics for the treatment of domestic animal and wildlife HAB-associated illnesses are in development.
- Increasing public awareness of HABs has been possible through new outreach and education methods and communication strategies.
- Availability of streamlined methods for reporting of HAB events to management agencies has improved public health protection.

- Integration of new forecasting products into more comprehensive monitoring programs has allowed for timely and proactively executed mitigation actions such as closure of fisheries, management of aquaculture, or optimization of drinking water treatment, in many cases before a bloom becomes a health hazard.
- Some mitigation tools are available to states and industry to reduce the economic impacts of HABs on commercial fisheries and aquaculture, including:
  - Moving fish or shellfish prior to impact.
  - Some states (e.g., OR) are independently developing processing protocols for crustaceans (e.g., eviscerating crabs) to reduce their toxicity.
  - Intensive monitoring to identify subregions safe for harvesting, rather than closing entire coastlines or commercially important areas.
  - Mitigation using physical containment methods has also been used in some cases (e.g., to maintain *Sargassum* blooms away from valuable waterfront in the Caribbean [Fig. 3.4]).

Figure 3.4. Example of mechanical methods used to mitigate coastal macroalgal blooms: floating booms deflect *Sargassum* from coastal properties in the Caribbean. *(Photo credit: Lapointe et al., 2018)*. This nuisance brown seaweed occurs throughout the Caribbean, including the US Virgin Islands and Puerto Rico, and also affects South Florida (from Miami to the Florida Keys) (Lapointe 2020). The *Sargassum* influx from the tropical Atlantic is impacting not only the Caribbean region, but also the Gulf of Mexico and east coast of Florida. During summer 2022, the heavy *Sargassum* influx affected much of Florida's east coast (Florida Keys north to Cocoa Beach).

3.3.2. KNOWLEDGE GAPS AND UNDERDEVELOPED CAPABILITIES

A. *Human, domestic animal and wildlife health*

- There are no federal requirements (timing or methodology) for routine monitoring of HABs in recreational or drinking waters, and monitoring is inconsistent at the state level.
- Federal health advisory levels are lacking for several existing and emerging freshwater and marine algal toxins in drinking water, recreational water, and tissues of commercially harvested resources, including fish and shellfish.
- There is a lack of understanding of the effects of HAB toxins, especially emerging toxins, on human and wildlife health, particularly in systems experiencing multiple HABs and other stressors, i.e., anthropogenic contaminants (e.g., pesticides, excess nutrients) and climate change.
- Adequate protocols, resources, and infrastructure are lacking for the timely detection of HAB toxins and other bioactive compounds in exposed humans, domestic animals, and wildlife.

B. *Commercial fisheries and aquaculture*

- Strategies to mitigate toxicity via food processing methods are lacking for commercial and recreational fish and shellfish (e.g., Dungeness crab toxicity can be mitigated by eviscerating the crabs before sale, but this substantially reduces their value. Alternate methods are being investigated and are needed for other species).
- State and federal guidance is inconsistent or lacking on toxin testing and seafood processing methods to reduce toxicity other than in a few select bivalves and crustaceans.
- There is a lack of HAB socioeconomic models that include direct impacts and indirect costs at local and regional scales.
- State monitoring agencies lack adequate resources to maximize seafood harvesting while protecting public health from HAB toxins. For example, resources are often lacking to test individual species within a growing area, despite established differences in toxicity among species thus preventing the implemention of biotoxin management by species.
- Expansion of aquaculture both offshore and nearshore has increased demand on state resources for monitoring seafood toxicity.

C. *Mitigation methods*

- Funding is needed for implementing mitigation strategies. Most HAB funding is designed to develop new approaches to mitigate bloom impacts; however, the scope and diversity of resources impacted by HABs require additional funding for state and federal agencies to operationally implement research mitigation strategies.
- While much progress has been made in forecasting science (see sec. 1.3), forecasting tools are not easily transferred among HAB species or locations, so many of these lack forecasts for specific HABs. Thus, the forecasting model developed for *Alexandrium* in the Gulf of Maine is not applicable to other species in that region or for *Alexandrium* bloom forecasting in other regions.
- Forecasts for small inland water bodies are lacking.
- HAB early-warning products, based on satellite remote sensing, are not available for small, inland lakes and reservoirs that are primary drinking water sources for local communities. The major limitation is the spatial and temporal resolution of satellite sensors. This is particularly important for natural resource managers and public health officials to implement more effective HAB-specific management actions.
- Additional research is needed on the feasibility of proactively protecting endangered species that inhabit high-risk HAB-affected areas.
- There is limited information on the effectiveness of drinking water treatment technologies on emerging cyanotoxins, mixtures of cyanotoxins, and their

treatment byproducts. Full scale studies are lacking that also evaluate the impact of representative source water characteristics, including high natural organic matter concentrations typical during HABs.

D. *Integration of technologies into mitigation programs*

- There is a lack of integration of emerging control technologies into mitigation and response efforts that could be used to decrease response times and limit environmental and human health impacts. For example, many emerging control strategies have been evaluated in pilot studies; however, their feasibility and scalability to mitigation programs on natural blooms is underexplored.
- Significant barriers exist for deploying control strategies in mitigation programs, specifically permitting, environmental clearance, and funding issues further discussed in the Control section.
- Although several HAB control strategies are being explored in the laboratory and demonstration phases, the environmental impact of these activities is generally not being explored in either marine or freshwater systems.

3.3.3. PATHS FORWARD AND RECOMMENDATIONS FOR THE FUTURE

- Expand tools available for HAB detection to support more effective routine monitoring programs and rapid response efforts.
  - Incorporate new forecasting products into monitoring programs to assist with mitigation during large-scale HAB events.
  - Develop new remote sensing technologies/platforms (e.g., aircraft and unoccupied aircraft systems) for use in monitoring and forecasting efforts to enhance resolution in rivers, streams, and small lakes/reservoirs.
    - Gain a better understanding of new higher resolution satellite imagers like Sentinel 2 for use in small water bodies.
  - Develop novel in situ tools for rapid, accurate identification of HAB species and toxins to supplement recently available technologies such as the Imaging FlowCytobot (IFCB), FlowCam, Environmental Sample Processor (ESP), and HABscope (see sec. 1).
  - Develop new mobile and fixed platforms for in situ deployment of HAB sensors.
- Develop local/regional socioeconomic models to assess impacts and costs of HABs and associated mitigation efforts.
- Develop specific tools and strategies for protecting wildlife, aquaculture, domestic animals, and humans:
  - Standardize clinical sample collection protocols, improve diagnostic/confirmatory methods, and infrastructure for HAB toxins allowing timely detection of exposure in humans, domestic animals, and wildlife (e.g., to

support health studies or investigate suspected exposures and large-scale toxicity events).

- Model long- and short-term risks to ecosystems from HABs/toxins and the outcomes of various mitigation technologies.
- Produce clinical therapeutic guidance, case definitions, and novel therapeutics for toxin-associated illnesses.
- Specific to wildlife and aquaculture:
  - Develop, evaluate, and apply rehabilitation approaches to reduce mortalities of contaminated animals.
  - Develop and implement strategies for the relocation of aquaculture resources during severe HAB events.
  - Develop and disseminate guidelines on how to appropriately delineate the optimal size of closure areas and duration of closures due to toxin bioaccumulation.
  - Evaluate additional processing methods that reduce toxin concentrations to below regulatory guidance levels.
  - Develop predictive models/approaches to assess potential introductions of HAB species via relocation of cultured and wild bivalves.
  - Develop and implement methods for monitoring HAB toxins that can be readily and economically used by the seafood industry.
- Specific to humans and domestic animals:
  - Expand communication and outreach programs to make information on HAB poisoning syndromes available to the medical and veterinary community in a timely manner.
  - Enhance disease surveillance for human and domestic animal illnesses and deaths associated with biotoxin exposure by supporting existing surveillance systems such as the Centers for Disease Control and Prevention's One Health Harmful Algal Bloom System (OHHABS). This system also collects data on wildlife illnesses.
  - Develop and validate biomonitoring and biomarker methods to diagnose toxin exposure effects and disease status.
  - Fund applied research on optimization of drinking water treatment for removal and destruction of cyanotoxins and their byproducts, especially in the presence of natural organic matter; full-scale studies that move beyond bench scale information are needed.
  - Update existing guidelines for cyanotoxin exposures, develop more methods for cyanotoxin removal from drinking water and create more treatment optimization protocols for removal of cyanotoxins,

e.g., the Powdered Activated Charcoal (PAC) calculator for Cyanotoxin Removal (p. 20) developed by the AWWA.

- Proven management strategies are needed that will mitigate HAB events or minimize their impacts on human health, living resources, and coastal economies when they do occur. Recommendations include:
  - Conducting large-scale interdisciplinary investigations on the application of various options for short- and long-term mitigation,
  - Characterizing the short- and long-term environmental impacts of these mitigation strategies on natural communities and the environment, including the fate and transport of algal and cyanobacterial toxins,
  - Using modeling approaches to understand the impact of mitigation strategies on food webs and assess their potential environmental impacts, both adverse and beneficial,
  - Minimizing regulatory hurdles such as permits and preliminary impact assessments.
- Assess overall public awareness and understanding of HABs and design risk communication strategies to educate and protect the public more effectively. This will help to build community resilience while minimizing socioeconomic impacts during HAB events.
- Increase communication of HAB forecasts and/or predictions to stakeholders, state officials, industry representatives and the public to enable them to take appropriate actions to avoid or minimize exposure to HABs. Impacts of HABs can be greatly reduced if accurate and timely information is widely distributed through appropriate communication channels.
- As the harvest of wild-caught fisheries and aquaculture product increases, resources for monitoring need to increase and the seafood industry needs to share more of the costs.

3.4. Event Response

3.4.1. CURRENT STATE OF KNOWLEDGE AND SIGNIFICANT ADVANCES

- HAB events have occurred around the US, including the rapid onset of known HABs at unexpected times or places or at much greater magnitude than usual. Further, new potentially toxic and nuisance HAB species have begun to emerge.
- The National Oceanic and Atmospheric Administration (NOAA) HAB Event Response (ER) program (applicable only to marine systems and the Great Lakes):
  - Provides rapid assistance to plan and mount responses to unusual or emerging HABs that threaten public health and/or coastal economies, cause sudden, unexplained animal mortalities, and/or provides an unusual opportunity to collect data during a major HAB event,

  - Provides limited funding ($13.4K per year per event) and technical expertise for 4-6 events per year in marine and Great Lakes coastal areas. Funding available in 2020 was $100K.

- The NOAA Analytical Response Team (ART, NOAA NCCOS) and Wildlife Algal-toxin Research and Response Network for the US West Coast ([WARRN-West; NOAA Northwest Fisheries Science Center [NWFSC]) programs were established to provide rapid and accurate identification/quantification of marine algal toxins in suspected HABs, marine animal mortality events, and human poisoning outbreaks; however, these programs are largely unfunded. A similar program for freshwater cyanotoxin impacts does not exist.

- The NOAA Marine Mammal Health and Stranding Response Program, and within it, the Marine Mammal Unusual Mortality Event Program (UME), has established that since 1991, at least 19% of UMEs are due to HABs (Fig. 3.5). In many of the UMEs for which no cause was determined, it was suspected that HAB toxins were at least a partial factor.

- The USGS National Wildlife Health Center has a Disease Investigations Services program. While not HAB-specific, the Center can provide assistance during freshwater and marine animal mortality events.

- Multiple federal agencies, including many parts of NOAA, the US EPA, USACE, Centers for Disease Control and Prevention (CDC), and USGS, and some states and universities provide expert advice and in-kind assistance during some events.

- Awareness and response to HAB events is more likely in areas where sustained and pilot programs exist to routinely monitor HAB species or toxins; these include programs established by states (e.g., CalHABMAP, FL, Fish and Wildlife Conservation Commission [FWC], Red Tide Current Status, OH EPA public water system monitoring rules, WA ORHAB and SoundToxins), academics, citizen monitoring groups (e.g., NOAA Phytoplankton Monitoring, University of Delaware Citizen Monitoring Program, HABscope), federal agencies Cyanobacteria Assessment network (CyAN), and other entities (e.g., Texas Sea Grant Red Tide Rangers, NOAA HAB forecasts and bulletins).

- Historically, cell counts have been widely relied upon but new methods of cell and toxin detection such as the Imaging Flow Cytbot (IFCBs), HABscope, satellite remote sensing of specific algal groups, molecular screening, and enzyme-linked immunosorbent assays (ELISA) for toxins, (see sec. 1), have improved early warning and rapid response in some situations.

- There have been a limited number of comprehensive socioeconomic studies that demonstrate the significant economic impacts of freshwater and/or marine HAB events (Hoagland et al., 2002; Moore et al., 2019).

- The HAB and Hypoxia Research and Control Act (HABHRCA 2019) calls for NOAA and US EPA to declare HAB and Hypoxia Events of National Significance (HHENS) at the request of a state governor so that funding for assessment and mitigation can be made available.

Fig. 3.5. Marine mammal strandings due to HABs. 1. On the US Pacific Northwest coast related to the domoic acid outbreak "The Blob". *Photo credit: R. Mittleman/Gon2Foto/Alamy Stock Photo.* 2. Loggerhead sea turtle affected by a *Karenia brevis* red tide on the Florida SW coast. *Photo credit: A. West/The News-Press.*

3.4.2. KNOWLEDGE GAPS AND UNDERDEVELOPED CAPABILITIES

- The amount of funding for the NOAA HAB ER Program is inadequate for HAB response in marine and Great Lakes coastal areas.
- Not all state and regional HAB managers are aware that funding for event response activities is available through the existing NOAA HAB ER program.
- There is no inland freshwater HAB ER Program, which is critical given the projected increase in freshwater HAB events due largely to eutrophication and climate change.
- Few certified/approved federal laboratories are available or adequately funded to perform toxin analyses on water, human or animal tissues for marine or freshwater HAB events when a state, tribe, or local agency needs this information but lacks the capability to undertake them. There is no formal mechanism for facilitating communication and coordination among laboratories and institutions to expand analytical capacities available to local entities, which can be overwhelmed during major or novel events.
- The US lacks a response plan to quickly address the identification and characterization of novel HAB species and potential emerging toxins.
- There are limitations on methods available to detect novel species and toxins that hinder event response to HABs of emerging concern.
- Additional rapid, field portable or automated in situ or remote sensing methods for HAB cells, toxins, and environmental conditions are needed to support both routine monitoring and event response.
- Directed congressional appropriations were only provided once in 2005 for the UME Contingency Fund (no-year fund), which supports responses to Marine Mammal UMEs, including those caused by HABs. Therefore, the UME Contingency Fund will soon become insolvent.

- The socioeconomic impacts of HABs are difficult to characterize and quantify, as no plans, programs, or funding are in place for collecting data prior to, during or following HAB events.
- NOAA and US EPA have not yet published guidance or policy concerning the declaration of a Health Care Electronic Notification System (HENS) or outlining HAB/Hypoxia Events of National Significance (HHENS), and there are no funds available to aid with assessment and mitigation.

3.4.3. PATHS FORWARD AND RECOMMENDATIONS FOR THE FUTURE

- Provide adequate funding for NOAA ER programs (>$100K annually).
- Establish and fund an inland freshwater HAB ER Program.
- Establish and fund marine and freshwater HAB ER programs focused on socioeconomics that include new and existing tools (e.g., approved surveys) and common metrics to measure impacts, and explore the use of a benefits transfer approach to allow more rapid determination of lost benefits (costs) of HAB impacted resources.
- As detailed in the HAB RDDTT Plan, conduct a needs-based assessment to identify deficiencies in local, state, and tribal resources for responding to HAB events, including expertise and analytical approaches, tools and methods, funding shortfalls, communication and evaluation needs, and any other resources that are lacking or insufficient in quantity, duration, and geographic distribution. Based on this assessment:
  - Establish a Technical Assistance Fund to augment existing resources and capabilities needed to improve HAB event response,
  - Establish one or more regional committees focused on providing analytical expertise and support to managers and public officials responding to HAB events, e.g., toxin analysis, HAB species identification, histology, and pathology, appropriate to the specific event (also see sec. 3.6).
- Improve toxin analysis capabilities and capacities by providing adequate funding to the NOAA Analytical Response Team (ART; NOAA NCCOS) and Wildlife Algal-toxin Research and Response Network for the US West Coast (WARRN-West, NOAA NWFSC) programs.
- Request that Congress require an action plan to address how federal agencies will work together to respond to a HAB event with novel species/toxins that have severe human health or ecosystem impacts.
- Provide new or sustained funding for the UME Contingency Fund, so that Marine Mammal UMEs can be adequately assessed, given that collecting samples and analyzing them for biotoxins is costly.
- Request that Congress pass legislation that more fully describes HHENS declarations and the funding sources for assistance.

- Widely disseminate information to managers about the availability of ER funding.

3.5. Management

3.5.1. CURRENT STATE OF KNOWLEDGE AND SIGNIFICANT ADVANCES

A. *Programmatic*

- The National Oceanic and Atmospheric Administration (NOAA) Monitoring and Event Response for Harmful Algal Blooms (MERHAB) Program has supported assistance in the development of enhanced HAB monitoring and early warning capacity in the US Coastal and Great Lakes waters to help state and tribal monitoring agencies and regional coastal ocean observing systems keep pace with the expanding HAB problem.
- The NOAA Event response (ER) Program has provided modest but immediate assistance to help federal, state, and local officials manage events and advance the understanding of HABs as they occur in coastal and Great Lakes waters (see sec. 3.4.).
- Other agencies such as US EPA, USACE, USGS, NASA, NIEHS, and NSF, have independently supported some freshwater research and response out of existing programs focused on broader aquatic issues.
- Most coastal states have monitoring programs that test for HAB toxins in marine seafood to protect public health and use HAB cell monitoring (e.g., via state or community monitoring programs) for early HAB warning (Fig. 3.6). Since their establishment there have been no reported human illnesses or deaths due to regulated HAB toxins in commercial seafood in the US.
- Some states have established freshwater HAB programs to address both drinking water and recreational water impacts for resource managers.

Fig. 3.6. **Sign in Washington State warns beachgoers about the public health risks of harvesting shellfish contaminated with paralytic shellfish toxins.** The warning text is also translated into five languages – Vietnamese, Cambodian, Laotian, Chinese, and Spanish – to communicate risk to non-English speakers who may be harvesting shellfish. *Photo credit: V. Trainer, Seattle, Washington.*

B. Collaboration between research and management communities

Our understanding of the causes and impacts of HABs has increased substantially in the last 15 years. State, local, and tribal managers have participated, either as researchers or members of Technical Advisory Committees (TAC), leading to applications with immediate benefits to HAB management. Managers and researchers are increasingly working together to apply new information and develop new approaches to better monitor and predict HABs, detect HAB cells and toxins, mitigate HAB impacts, and/or control blooms. Federal funding support (e.g., by NOAA, US Food and Drug Administration [US FDA], US Environmental Protection Agency [US EPA]) enables some state and local managers to participate in national and international HAB meetings.

C. Monitoring and early warning systems

- NOAA's Harmful Algal Bloom Monitoring System generates visualization products for the Gulf of Maine, Lake Erie, and in Florida, Louisiana, and North Carolina that identifies the location and extent of HABs. NOAA scientists provide customized satellite images and interpretation to state managers upon request during novel events.

- NOAA provides operational Harmful Algal Bloom Forecasts for the Gulf of Mexico, Lake Erie and the Gulf of Maine. These HAB forecasts and bulletins alert coastal managers, drinking water suppliers, and recreational users to blooms before they result in serious human health threats and environmental and economic impacts.
- US EPA, NASA, NOAA, and USGS-funded Cyanobacteria Assessment Network (CyAN) projects, using satellite remote sensing to detect HABs in lakes greater than 1 km in width, have revolutionized surveillance of cyano-HABs for early detection in inland waters that are drinking water sources and recreational waters.
- Current National Centers for Coastal Ocean Science (NCOOS) and Integrated Ocean Observing System (IOOS) funded projects are piloting regional HAB observing networks that incorporate advanced HAB sensors, such as the ESP and IFCB (see sec. 1), to provide high resolution, near real-time information for incorporation into HAB early warning monitoring networks and forecasts. The Framework for the National HAB Observing Network: A Workshop Report (2020) and the Implementation Strategy for a National HAB Observing Network (2021) link these regional efforts to a National HAB Observing Network (NHABON). These monitoring networks demonstrate the power of integrating data on HAB cells and their toxins with modeling efforts to better inform resource managers and improve HAB forecasting efforts.
- Federal funding has helped coastal and Great Lake states initiate monitoring programs and encouraged and enabled new regional partnerships to improve monitoring programs.
- In many areas citizen monitoring now plays an important role in providing early warning and provides an opportunity to educate the public.
- Shellfish harvesting has resumed in federal waters off Georges Bank, formerly closed due to paralytic shellfish poisoning (PSP) toxins, using newly developed protocols for monitoring of HAB toxins in these remote offshore waters (Fig. 3.7.). Interest in harvesting and growing shellfish and fish in federal waters has increased; NOAA National Marine Fisheries Service (NMFS), US FDA, and the Interstate Shellfish Sanitation Conference (ISSC) are examining ways to ensure that commercial seafood from remote areas is free of biotoxins.
- The abundance of HAB species is increasingly being used as part of state shellfish monitoring programs to provide early warning of HAB events and trigger direct sampling of toxins in seafood during events.

Fig. 3.7. Offshore Atlantic shellfisheries on Georges Bank are affected by blooms of *Alexandrium catenella,* a producer of paralytic shellfish toxins (PSTs), and routine monitoring of toxins, as implemented for coastal shellfish, is made difficult by their distant location. As part of the GOMTOX-ECOHAB project, Degrasse et al. (2014) implemented use of a rapid shipboard toxin assay to prescreen bivalves harvested in federal waters, followed by onshore toxin quantitative analysis, as a strategy to reduce the risk of bringing contaminated product to shore. This biotoxin management strategy is now referred to as "pre-harvest screening with lot testing". 1. Harvesting of ocean quahogs, *Arctica islandica*, onboard the *Misty Dawn* vessel; 2. Harvesting of sea scallops, *Placopecten magellanicus*; 3. Onboard processing of offshore-harvested bivalves, including surf clams, *Spisula solidissima*, known for their prolonged retention of PSTs. *Photo credit: S. Wiggins, FDA.*

D. *HAB toxin guidance, testing capacity and expertise*

- Some alternatives to animal testing have been approved for regulatory measurement of HAB toxins in bivalves, e.g., non-animal-based methods for diarrhetic shellfish poisoning, paralytic shellfish poisoning, and neurotoxin shellfish poisoning (limited use) toxin testing are now available.
- US FDA, US EPA, and states have set regulatory action limits, guidance levels, or guidelines for thresholds in commercial seafood, drinking water, and recreational waters, for some toxins.
- Several marine and freshwater toxins are known, and well-described, but new toxins and their congeners continue to be documented.

- Federally approved methods have been recently developed for three freshwater toxins (microcystins [MCs], cylindrospermin [CYN], anatoxin-a).
- The US and European Union (EU) have reached an agreement about equivalence on the sanitary protection of shellfish, which includes protections from HAB toxins, allowing the resumption of trade between select US states and EU members.
- US EPA developed technical guidance for public water systems on cyanotoxin drinking water treatment, source monitoring, management, and risk communication.

E. *Training*

- Some marine and freshwater training courses have been available such as those in HAB species identification, use of new instrumentation, and toxin analysis methods. Most courses are available on an irregular schedule. Highlighted successes include:
  - Annual NOAA funded courses in marine HAB identification, provided at no cost for HAB managers, at the Bigelow Laboratory, Maine, were successfully piloted with a MERHAB award from 2016-2019. Beyond capacity building, they helped develop a network of young managers that are now a community resource. The course will be available for a nominal fee on an annual or biannual basis depending on demand.
  - Regional freshwater HAB workshops provided by US EPA to state managers, bringing in experts on HAB monitoring, drinking water treatment, control, and other topics of interest.
  - Short courses on taxonomy, new methods of detection, and new instrumentation have been offered prior to recent US HAB meetings, e.g., workshops at 10th US HAB, and on an occasional basis by states, academic institutions, and laboratories around the country, e.g., low-cost freshwater HAB workshops at the Ohio State University Stone Laboratory 2011-2019 and reinstituted as a virtual workshop in 2021.

F. *Disaster assistance*

- HAB events, especially long-lasting ones, can disrupt local economies and be socially devastating. Disaster assistance has been provided as loans by the Small Business Administration after the declaration of an emergency. After Fisheries Failures Declarations and an appropriation by Congress, awards have been made to states for economic mitigation and/or improved HAB management.

3.5.2. KNOWLEDGE GAPS AND UNDERDEVELOPED CAPABILITIES

A. *Programmatic*

- There is no overarching federal program for inland freshwater HABs. Ad hoc funding exists for freshwater HABs within multiple agencies but is not coordinated nor sustained, e.g., there are no freshwater programs analogous to the NOAA MERHAB and HAB ER Programs.
- Not all states monitor for HAB cells and toxins, and existing programs and capabilities vary widely in scope.
- The current rotation among HAB NOAA funding programs (Prevention, Control, and Mitigation of HABs [PCMHAB], Ecology and Oceanography of HABs [ECOHAB] and MERHAB) can lead to multiple years without initiation of new MERHAB projects. Additionally, adequate multi-year funding for the MERHAB program is needed to address widely varying capabilities among existing HAB monitoring programs.

Collaboration between research and management communities

- The leadership of state and tribal management agencies is often unsupportive of staff involvement in research (e.g., projects, research prioritization workshops, conferences) because that is not their primary responsibility. As a result, state and tribal managers often cannot actively participate in research projects or travel to regional, national, and international meetings, which makes it more difficult to incorporate new technologies or strategies into their management programs.
- Researchers often lack awareness of management needs and program functions. Managers are often not asked about their needs before research proposal planning commences and are often asked to be co-PIs, participate in TACs, or provide letters of support after proposals are written, immediately prior to submission in response to funding agency requirements.

B. *Monitoring and early warning systems*

- While some HAB forecasts are operational for some species and in some regions (*Karenia* in the Gulf of Mexico and cyanobacterial HABs in Lake Erie) and some are ongoing projects (e.g., *Pseudo-nitzschia* on the Pacific Northwest [PNW] and CA coast, and *Alexandrium* in the Gulf of Maine), all are supported with non-sustainable, short-lived research funding. For example, the PNW HAB Bulletin is currently supported by MERHAB research funding but requires permanent support as it is heavily relied upon by WA and OR state fishery and health managers in decision-making.
- Predictive models are lacking for many HABs, e.g., *Alexandrium* sp. in Puget Sound and the entire west coast, and ciguatera poisoning in Caribbean and Florida coastal waters.

- New automated observing tools and approaches (e.g., CyAN, NHABON) are being tested or proposed to improve the spatio-temporal coverage and ease of use in HAB monitoring but are currently supported with short-term research funding and are thus not sustainable.

C. *HAB toxin guidance, testing capacity and expertise*

- While some states have excellent laboratories for testing seafood for marine HAB toxins to protect human health, many states have limited or non-existent capabilities. In addition, all states may need assistance during a large or complex HAB event response. There are few federal or commercial laboratories that can assist. This issue is of particular concern as NOAA's Office of Aquaculture is promoting development of offshore aquaculture, yet many coastal states cannot take on that responsibility.
- The number of adequately validated methods of toxin analysis for regulatory seafood testing is insufficient, many are antiquated, and there are emerging toxins for which there are no acceptable methods.
- The existing process within the ISSC for approval of new regulatory methods of toxin analysis for bivalve molluscan shellfish is unclear and unacceptably slow and hence is an impediment to progress in this area.
- There is no federal guidance regarding appropriate sample sizes and approved methods for regulatory testing of seafood other than bivalve mollusks.
- Toxicological information on toxin congeners, metabolites, or emerging toxins is often unavailable for determining risk or making management decisions.
- Adequately validated methods for many of the freshwater toxins are lacking, particularly for STXs in drinking and recreational waters and the detection of microcystin congeners in recreational waters.
- There is no federal guidance on cyanotoxin testing methods or on federal regulatory limits for cyanotoxins in freshwater fish or shellfish.
- Health guidance for anatoxin-a, STXs, CYNs, and total MCs is lacking.
- There is insufficient laboratory capacity for testing of freshwater toxins at the state and federal level.
- Development and deployment of field portable, rapid tests for toxins has been slow and requires further research and development.
- Toxicological information and guidance values are lacking on newly documented marine and freshwater toxins and congeners of known toxins.
- Government agencies lack information on human and animal health consequences that result from low level, chronic exposure, or exposure to multiple toxins. There is a need to establish effective health risk criteria (see sec. 4).

D. *Training*

- Currently there are only limited opportunities for training to build state, local, and tribal agency, and industry capacity for HAB monitoring and toxin analysis, and funding for developing and sustaining such courses and providing travel expenses for participants is lacking.

Disaster assistance

- No programs exist for providing financial mitigation after a significant HAB event for losses that are not included in economic loss calculations of fisheries failures (e.g., losses to tourism, changes in real estate values, 'halo' effects on other fisheries, public health costs, etc.).
- The social costs of HAB events have rarely been identified and there are no programs to mitigate these problems, even though they may impose substantial socioeconomic consequences on communities.

3.5.3. PATHS FORWARD AND RECOMMENDATIONS FOR THE FUTURE

A. *Programmatic*

- Establish a MERHAB program to improve management capabilities for inland freshwater HABs.
- Establish a HAB Event Response Program for inland freshwater HABs (see sec. 3.4).
- Establish programs to fund the purchase of new equipment needed by states for HAB management and foster partnerships that would provide rapid access to existing equipment.
- Provide base federal funding for sustained national and regional HAB forecasting and monitoring infrastructure, so they are no longer dependent on short-term research funding. National and regional partnerships are critical to success. Forecasting and monitoring designs must be flexible to accommodate regional needs. Recommendations include:
    - Establish a National NHABON, as described in the NHABON Framework and Implementation Strategy and demonstrated by NCCOS MERHAB and IOOS HAB observing pilot projects.
    - Support the NOAA HAB Ecological Forecasting program so that coastal forecasts developed with research funding (for example, PNW HAB Bulletin) are transitioned to sustained and improved use.
    - Provide sustained funding for evaluating and improving products from the freshwater HAB remote sensing (CyAN) project. Adapting these products to smaller-scale systems will require drones or aerial overflights for assessment instead of satellite remote sensing tools, unless satellite sensor spatial resolution is improved.

  - Support development, implementation, and maintenance of HAB databases/web portals for use by managers and researchers to input/access data and provide decision support tools.

B. *Collaboration and cooperation*

- Increase engagement and bidirectional communication among senior leadership at federal, state, tribal and nations agencies to improve public health protection and local resource management.
- Increase exchange between researchers and managers and incorporate new technologies into management programs by supporting manager participation in research projects, conferences/workshops, committees, and career development opportunities.
  - Researchers should strive to include managers in research projects from inception, as collaborators, members of TACs, or when requesting letters of support.
  - More funding should be made available for state managers to attend the US National and International HAB Meetings.
  - The National HAB Committee (NHC) should establish mechanisms to increase participation by marine and freshwater state managers.
  - More focus should be placed on non-research career development (in federal and state agencies, industry) by the National HAB Committee (NHC) and at the US National HAB meeting.
- Facilitate routine, recurring, regional HAB collaborative discussions, task forces, and communication platforms, e.g., Gulf of Maine HAB Stakeholder group, ORHAB, Benthic HABs Work Group, EPA Freshwater HABs Newsletter, FL HAB and Blue-Green Algae task forces.
- Encourage the NHC to survey the HAB community for ways to improve engagement among researchers, managers, and industry.

C. *Monitoring and early warning systems*

- Identify toxin-producing algal and cyanobacterial species and toxin profiles, as well as the factors influencing toxin production/composition.
- Determine appropriate triggers (cell abundance, toxin thresholds, molecular detection methods, etc.) for initiating more rigorous toxin analysis in shellfish, drinking water, or recreational waters.
- Develop new or improve existing methods to rapidly identify toxin-producing HAB species and toxins in water samples or net tows for use in the field by managers and community scientists such as inexpensive microscopes with cell phones and HAB recognition software (e.g., HABscope), Solid Phase

Adsorption Toxin Tracking (SPATT), a tool for monitoring HAB toxins in water, or dip-stick toxin tests.

- Develop new or improve existing methods of automated, in situ continuous monitoring of HAB cells and toxins (e.g., IFCB, ESP, optical phytoplankton detectors [OPD]/Programmable Hyperspectral Seawater Scanner [PHYSS], FlowCam).
  - Expand species/toxins/regions for which the remote, automated devices can be used.
  - Reduce purchase cost or provide leasing alternatives, improve ease of deployment, minimize operational and maintenance costs, and develop standard data products.
- Encourage improvements in spatio-temporal HAB monitoring by airborne and spaceborne imaging (remote sensing) to provide enhanced quality information for management of HABs for which remote sensing is an appropriate tool:
  - Support evaluation and improvement of satellite-based HAB detection and monitoring techniques for use in routine regional and global applications, including real-time monitoring, and climatological studies. Emphasis should be placed on developing capability for monitoring small, remote water bodies that are currently difficult to monitor using common practices.
  - Encourage methods development to integrate remote sensing with multiple geospatial observation technologies and biological, ecological, and environmental models to improve HAB detection and management. For example, develop methods to integrate data from various polar-orbital satellites to increase the frequency of HAB monitoring. This allows for better detection and includes temporal information that can aid in HAB modeling and prediction.
  - Support technological advances in platforms including satellites (e.g., nanosatellites such as Cube-Sat and geostationary satellites), unoccupied aircraft systems (drones), and airplanes.
  - Support sensor development including hyperspectral and unique multispectral imagers with specialized configurations for target populations (i.e., cyanobacteria, *Karenia brevis* red tide, etc.). Encourage development of these HAB detection capabilities in sensor design for future satellites.
  - Improve real-time access to satellite data and data products with end-user feedback.
- Develop and/or improve predictive models of HAB cells and toxins and the accumulation of toxins in biota (e.g., shellfish, fish, seagrasses) to enable:
  - Short-term forecasts of geographic distribution, intensity, toxicity in cells and biota, and transport.
  - Longer-term seasonal predictions to aid planning.

    - Hindcasting of past events to understand underlying mechanisms.

D. *HAB toxin testing capacity and expertise*

- Set national guidance levels for freshwater toxins in drinking and recreational waters and products consumed by humans (e.g., dietary supplements, plants grown with irrigation and animals fed with those plants, and animals harvested from fresh and marine waters).
- Develop monitoring guidelines/regulations for seafood grown/harvested in offshore (federal) waters and laboratory capacity for testing seafood harvested in federal waters.
- Develop, approve, and adopt for regulatory use additional methods for toxin detection in biological samples (tissues, blood, urine), drinking waters, and recreational waters, including:
    - Screening methods for qualitative or semi-quantitative detection of toxins that are:
        - Field deployable by managers, community scientists, and industry,
        - Reliable (no false negatives and minimal false positives),
        - Inexpensive, rapid, and easy to implement.
    - Quantitative and confirmatory analytical methods such as liquid chromatography (LC) and liquid chromatography with mass spectrometry (LC-MS) are available for some toxins and species, but they require costly instrumentation and considerable technical expertise. Multiple additional methods are needed with the following characteristics:
        - High throughput,
        - Minimal cost and need for technical expertise,
        - Require less costly instrumentation.
- Develop a plan and provide funding to ensure that there is adequate laboratory testing capacity for HAB cells and toxins in water and seafood during exceptional blooms. This might involve state and federal laboratories being funded to maintain regional capacity for particular toxins.

E. *Training*

- Funding needs to be provided for developing and sustaining courses held nationally or internationally, i.e., payment of instructors and materials, and travel expenses for participants. Funding could be obtained from federal and state sources or industry partners for:
    - Training for managers and industry in HAB cell identification and quantification and specific methods for toxin analysis and drinking water management. Further, managers would benefit from formal training on

the approach for integrating databases into federal and other existing databases.

  - Attendance by managers at the US Symposium on Harmful Algae and the International Conference on Harmful Algae (ICHA) in alternate years.

- Creating awareness and training on new and existing tools (see ER Program on provision of equipment and tools).
- Training and low-cost equipment for networks of volunteers/managers to conduct real-time phytoplankton observations.

F. *Disaster assistance*

- Develop guidelines and policies for NOAA (marine) and EPA (freshwater) to declare HAB and Hypoxia Events of National Significance, as directed in the HAB Hypoxia Research and Control Amendments Act (HABHRCA), so that Congress can aid states in assessing and mitigating the impacts of HABs,
- Develop evaluation criteria and mechanisms for mitigating social impacts as well as economic impacts.

G. *Policy Implications*

1. Develop guidance for HAB cell and seafood toxicity monitoring of fisheries and aquaculture product in offshore federal waters to ensure safe seafood harvesting.
2. Develop drinking water health advisory levels and recreational guidance for STXs and anatoxin-a.
3. Develop regulations mandating drinking and recreational water cyanotoxin monitoring and issuance of advisories.
4. Develop testing methods, monitoring guidance, and consumption advisories for cyanotoxins in fish and shellfish from marine and freshwater systems.
5. Establish freshwater HAB research and response programs.
6. Develop and implement a plan to maintain necessary HAB toxin testing capacity to ensure safe seafood, drinking water, and other consumable products.
7. Develop policy and procedures for declaring HAB and Hypoxia Events of National Significance so that disaster assistance can be provided if Congress appropriates funds.
8. Sustain national and regional HAB observing and forecasting capabilities to provide early warning and forecasts to protect public health, as outlined in the NHABON Framework and Implementation Strategy and demonstrated by NOAA HAB Forecasts.

3.6. New Management Challenges at the Freshwater-to-Marine Continuum

3.6.1. CURRENT STATE OF KNOWLEDGE AND SIGNIFICANT ADVANCES

- Cyanotoxins and cyanobacteria can be transported hundreds of miles downstream from the original bloom source from inland waterbodies to downstream receiving waters, including estuarine and marine waters. This transport can be geographically extensive, from a few to hundreds of kilometers downstream. There are several well documented examples in the Klamath River in southern OR and northern CA, and the Lower Great Lakes (Davis et al., 2014; Otten et al., 2015, Howard et al., 2022). Blooms of cyanobacteria are widespread in inland waters, including lakes, reservoirs, wetlands, rivers, and streams, representing a growing potential for the transport of cyanotoxins and cyanobacteria into estuarine and marine systems (Paerl et al., 2018).
- Cyanotoxins have been persistently detected in marine outflows in CA, WA, FL, and LA in the US as well as globally, including Argentina, Brazil, Estonia, Finland, Japan, Turkey, Uruguay, Portugal (see review by Preece et al., 2017; Peacock et al., 2018; Howard et al., 2022).
    - Regulatory discharges from Lake Okeechobee, FL, into the Caloosahatchee River and the St. Lucie Canal and Estuary caused an extensive cyanobacterial bloom and the Governor of Florida issued a state of emergency for three affected counties (Rosen et al., 2018),
    - Closure of Mississippi beaches from June to August 2019 was partially due to the opening of the Bonnet Carre spillway in LA to manage Mississippi River flooding by releasing freshwater to the coast. Coastal shellfish growing areas were also placed in the closed status due to this event.
- Multiple toxins and mixtures of marine and freshwater toxins have been detected simultaneously. The co-occurrence of multiple cyanotoxins from a single location has been documented globally.
- Salinity can influence bloom formation and toxin production and is relevant to the transport of cells and toxins from freshwater to brackish and marine environments. A wide range of salinity tolerance has been documented for different species and strains of cyanobacteria (see review by Preece et al., 2017). For example, transport of freshwater cyanobacteria to brackish and marine waters can cause loss of membrane integrity and release of intracellular toxins into the surrounding water.
    - *Microcystis aeruginosa* is tolerant of salinities up to 32 ppt (Miller et al., 2010) while *Dolichospermum circinale* does not tolerate salinities >7.5 ppt (Rosen et al., 2018).
- Benthic cyanobacteria have been historically overlooked as an inland source of cyanotoxins, but cyanobacterial mats in rivers and streams are known to be capable of cyanotoxin production (Quiblier et al., 2013; Fetscher et al., 2015;

McAllister et al., 2016; Bouma-Gregson et al., 2018; Graham et al., 2020; Wood et al., 2020).

- For example, CA statewide assessments revealed that benthic algae in wadeable streams were a source of cyanotoxin production and supported high occurrence of potentially toxic genera and species (Fetscher et al., 2015).
- A regional study collected water samples from wadeable streams in the southeastern US and detected nicrocystins (MCs) in 39% of these streams (Loftin et al., 2016).
- A survey of large rivers throughout the US found cyanobacteria, cyanotoxins, and cyanotoxin synthetase genes throughout the sampling locations (Graham et al., 2020).

- There are multiple mechanisms for the physical transport of cyanobacteria and cyanotoxins, including upstream scouring, release from upstream sources such as reservoirs, runoff and natural flows, and buoyancy mechanisms for benthic cyanobacterial mats.
  - Cyanobacterial cells can survive release from reservoirs via hydroelectric dams and can be viable for growth and toxin production following downstream transport (Ingleton et al., 2008; Graham et al., 2012; Otten et al., 2015; Bouma-Gregson et al., 2017; Genzoli and Kann, 2016; Williamson et al., 2018). This provides a mechanism for both downstream blooms and transport of cyanotoxins.
  - Cyanobacterial mats form vertical spire-like shapes due to the production of oxygen bubbles in the mats' intracellular mucus (Bouma-Gregson et al., 2017). These spires are delicate, can easily be detached, and the clumps are able to float to the surface where they can be transported and accumulate hundreds of meters downstream.
- Transfer of freshwater toxins into the marine environment has led to a variety of impacts to the latter including marine wildlife mortalities and recreational beach closures.
  - Microcystin poisoning that endangered southern sea otters in the Monterey Bay National Marine Sanctuary resulting in mortality of over 30 individuals (Miller et al., 2010; Gibble and Kudela, 2014).
  - Cyanotoxins can bioaccumulate in marine shellfish resulting in contamination of marine food webs and higher trophic level wildlife.
  - Cyanotoxin exposures have been documented in marine birds (Gibble et al., 2017), sea otters (Miller et al., 2010), cetaceans in Southern CA and FL (Brown et al., 2018; Danil et al., 2021), and bull sharks in the Indian River Lagoon, FL (Edwards et al., 2023). Negative effects from exposure include mortality in sea otters and toxic and immune health impacts on coastal bottlenose dolphins in Florida (Brown et al., 2018; Miller et al., 2010).

- MCs have been detected in shellfish throughout the US coast and accumulated in marine shellfish in CA (Miller et al., 2010; Gibble and Kudela, 2014; Gibble et al., 2016; Peacock et al., 2018; Tatters et al., 2019), WA (Preece et al., 2015), VA (Buckaveckas et al., 2018), LA (Garcia et al., 2010) and NY (C. Gobler, Stony Brook University, NY, pers. comm.).
- A study examining rates of MC depuration showed that they are relatively low, on the order of several weeks for mussels, indicating that MC retention provides ample time for transfer through the food web (Gibble et al., 2016).
- Oysters (*Crassostrea* sp.) depurated MCs much faster than California mussels (*Mytilus californianus*), but a low concentration of MCs remained in the oysters for weeks (Gibble et al., 2016).
- A recent comparison study indicated that Asian clams (*Corbicula fluminea*) were able to depurate microcystin faster than Eastern oysters (*Crassostrea virginica*). The latter can accumulate and retain MCs and are more likely to be a vector for hepatotoxic shellfish poisoning (Straquadine et al., 2022).
- Mixtures of marine and freshwater toxins were common in caged and wild shellfish in San Francisco Bay, CA (Peacock et al., 2018).

3.6.2. KNOWLEDGE GAPS AND UNDERDEVELOPED CAPABILITIES

- Currently there are no regulatory guidelines or health thresholds for cyanotoxins in shellfish.
  - California's Office of Environmental Health and Hazard Assessment (OEHHA) set a guidance level for MCs in fish tissue for human consumption of 10 µg per kg wet weight of tissue (https://www.waterboards.ca.gov/drinking_water/programs/habs/).
  - Many states have documented that this guidance value was exceeded in marine shellfish (Garcia et al., 2010; Miller et al., 2010; Preece et al., 2015; Gibble et al., 2016; Bukaveckas et al., 2018; Peacock et al., 2018).
- Routine monitoring data is inadequate in most states to know how frequently and at what concentrations cyanotoxins are present in marine waters (e.g., most of the year, seasonally, or only after flushing events).
  - For intermittent estuaries, cyanotoxins can potentially accumulate at the bottom of the watershed and enter marine waters episodically during storms, times of pronounced or exceptional tidal exchange, etc. However, there are very few studies that have focused on this mechanism of transport of cyanotoxins into marine waters.
  - Some areas have shown persistent, ubiquitous MCs in CA, e.g., San Francisco Bay, Monterey Bay, and parts of Southern CA (Gibble et al., 2014; Howard et al., 2017; Peacock et al., 2018; Tatters et al., 2019; Howard et al., 2022).

- Cyanotoxins are not measured in most marine monitoring programs despite studies in various states along the US coast documenting cyanotoxin accumulation in marine shellfish.
    - This includes the east coast (VA and NY), the Gulf Coast (LA), and the west coast (CA and WA) (Garcia et al., 2010; Preece et al., 2015; Bukaveckas et al., 2018; Peacock et al., 2018; Straquadine et al., 2022, C. Gobler, Stony Brook University, NY, pers. comm.).
- Mechanisms for cyanotoxin accumulation into the food web need to be better understood.
    - Suspension-feeding bivalves can concentrate MCs from the water column by >100-fold and they concentrate both particulate and dissolved toxins (Miller et al., 2010; Gibble et al., 2016), thereby making both fractions important to monitor.
    - Uptake and depuration rates of toxins in relevant estuarine and marine organisms need to be evaluated.
    - Other potential vectors for bioaccumulation and thereby transfer to higher trophic levels need to be identified.
- Research on buoyancy and transport mechanisms of cyanobacterial cells and mats is needed as there is a lack of understanding of these pathways for both planktonic and benthic cyanobacterial blooms.
- There have been some evaluations of the salinity tolerance of cyanobacteria, but more information is needed to understand the dynamics of their survival in brackish and saline waters.
- Potential synergistic effects (on human health and/or aquatic life) from acute and chronic exposure to multiple cyanotoxins and/or mixtures of marine and freshwater toxins are poorly understood.
    - Acute effects from oral ingestion of three very common cyanotoxins in the US (anatoxin-a, MCs and cylindrospermopsin (CYN) in drinking and recreational waters were characterized and documented by the US EPA in three Health Effects Support Documents (see advances in Public Health in sec. 4).

3.6.3. PATHS FORWARD AND RECOMMENDATIONS FOR THE FUTURE

- Regulatory requirements and guidance need to be developed for cyanotoxins focused on human consumption of fish, shellfish, and aquatic plants.
    - Guidance on levels for harvesting of shellfish or aquatic plants affected by cyanotoxins, as developed for marine toxins (e.g., domoic acid [DA] and paralytic shellfish toxins [PSTs]).
- US EPA water quality criteria and waterbody impairment assessment should be implemented (or state thresholds should be adopted).

    - Methods for impairment assessment due to HAB toxins and biomass need further development. CA and OH have started to list waterbodies as impaired due to HAB toxins (see methods developed by Davis et al., 2019).

- Water quality criteria need to be developed for other cyanotoxins such as anatoxin and saxitoxin (STX).

- Most HAB monitoring programs are not designed to capture the movement of toxins from headwaters to downstream receiving waters and need to be redesigned to address this important emerging issue and to ensure effective management and mitigation strategies can be implemented (Howard et al., 2022). HAB management and mitigation strategies need to focus holistically on the watershed inclusive of all hydrologically interconnected waterways from the headwater sources to the downstream receiving waterbodies that make up the freshwater-to-marine continuum (Paerl et al., 2018; Howard et al., 2022). A new integrative HAB monitoring strategy provides recommendations for a comprehensive approach necessary to develop effective mitigation and management strategies across interconnected bodies of water (Howard et al., 2022).

    - Monitoring programs need to be designed across the freshwater-to-marine continuum to cross state, international, regional, and local boundaries, and jurisdictions. This requires multiple entities, organizations, government agencies, tribes, and waterbody managers to work together to implement a cohesive monitoring program (Paerl et al., 2018; Howard et al., 2022).

    - Mixtures of both cyanotoxins and marine algal toxins can occur across many coastal systems with diverse hydrologic influences. Therefore, marine and estuarine HAB monitoring should be expanded to include cyanotoxins and assess the presence of toxin mixtures (Howard et al., 2022).

    - HAB monitoring programs should include multiple sampling approaches and modalities to improve our understanding of how HAB toxins and cells are transported through connected freshwater and marine waters and transferred through the food web. This combination of sample types and matrices should be fit-for-purpose and determined based on the objectives of the monitoring program (Howard et al., 2022).

- New monitoring tools need to be developed to monitor across the freshwater-to-marine continuum.

    - Hydrological events such as storms, droughts, estuary breaches, and flushing events are becoming more frequent and present many physical challenges to monitoring.

    - These events often result in changes to the hydrology of water transport, including changes in the locations of estuarine outflows to marine waters.

    - These changes make it difficult for field crews to sample during or right after these events; passive sampling devices and other types of continuous monitoring instruments are valuable to capture ephemeral pulses of toxins during these events.

- Studies characterizing the consequences of both acute and chronic exposure to multiple cyanotoxins and mixtures of marine and freshwater toxins for human, wildlife and ecological health are needed.
  - There is a poor or rudimentary understanding of the consequences stemming from toxin mixtures or the effects from chronic exposure of toxin mixtures for humans, wildlife, livestock, etc.
- Studies to improve our understanding of transport mechanisms of cyanotoxins and cyanobacteria for both planktonic and benthic blooms are required, including those investigating buoyancy mechanisms for benthic cyanobacterial mats and how they contribute to downstream transport.
- Research is needed to provide a more comprehensive understanding of benthic cyanobacterial blooms and mats, including the environmental conditions that promote blooms, the spatial and temporal dynamics of blooms and toxin production and benthic cyanobacterial life cycles. Wood et al. (2020) provides a more in-depth review of related challenges, solutions, and research needs.

3.7. Collaborations and Partnerships

3.7.1. CURRENT STATE OF KNOWLEDGE AND SIGNIFICANT ADVANCES

A. *Collaborative Organizations and Communication*

- Multiple organizations at the **international**, **bi-national**, and **national** level are entirely or primarily concerned with fostering collaboration and partnerships. Some are focused solely on HABs, and others address related issues that include HABs. These include official HAB-related organizations and partnerships, as well as voluntary efforts to improve HAB coordination and collaboration. A listing of these organizations is provided in Table 3.4, and summarized below:
  - Scientific societies and professional organizations that sponsor and promote conferences, workshops, and training programs for HAB researchers,
  - Intergovernmental organizations that coordinate research and management activities on HABs at the international level,
  - Working groups or commissions convened under broader international organizations referenced in Table3.4 to address specific topics or efforts, and
  - International, national, or regional organizations and commercial entities focused on particular research, technology development, or regions.
- Many states have HAB monitoring programs that involve interactions among multiple state agencies, commercial shellfish harvesters and other fishers, and local stakeholders. Additionally, efforts to mitigate HAB events often involve

multiple state agencies, academia, and industry. Active science\management collaborations that promote greater situational awareness during HAB events or sharing of latest research and management strategies have formed in many states. Task forces and other advisory bodies established at the state level are actively considering options to help states better organize their HAB response efforts. A comprehensive listing of these organizations is provided in Table 3.4, and summarized below:

- Organizations involving academic researchers, federal and state managers, and stakeholder groups focused on improving research, surveillance, and management of one or more HAB issues through information exchange and coordination, as well as collaborative research,
- Regional groups established under a national organization to improve observing capabilities nationwide,
- State advisory groups established to provide advice on a particular research or policy issue. These groups are too numerous to describe succinctly in Table 3.4; however, a few recurring groups are highlighted below, e.g.:
    - Florida HAB Task Force and Blue-Green Algal Task Force: provide advice on policy and research gaps,
    - California CyanoHAB Network: leads efforts to develop a long-term vision and strategic plan for identifying and managing HABs,
    - California Ocean Protection Council and Ocean Science Trust: policy guidance and advancement of science and partnerships via provision of funding.
- State-level organizations established to improve HAB surveillance and management. These organizations are too numerous to describe succinctly in Table 3.4; however, a few recurring groups are highlighted below, e.g.:
    - California HAB Monitoring and Alert Program (HABMAP),
    - Washington - Olympic Region HAB partnership (ORHAB) and SoundToxins, Texas HAB Work Group,
    - Maryland annual HAB meeting (includes Virginia, District of Columbia),
    - The North Central US Algal Bloom Action Team Region.

- In addition to the above organizations, HAB-focused communication including workshops, conferences, and HAB-focused journals and newsletters play an important role in fostering collaborations within the HAB community, in the US as well as internationally. There are at least three national meetings and one international conference devoted to HABs, as well as three HAB-focused newsletters and publications (see Table 3.4).

B. *Collaborative Research*

INTERNATIONAL AND BI-NATIONAL

- Organizations that fund formal collaborative research are listed in Table 3.4.
- Informal exchanges exist between US and foreign scientists in many countries, including neighboring Mexico, Canada, Cuba, and the Caribbean.
- Collaborative research on HABs has recently been established between investigators in the US and Cuba through the NSF Partners in Research and Education (PIRE) initiative as well as through research and capacity building programs sponsored by the International Atomic Energy Agency (IAEA). These partnerships have focused on establishing baseline data on HABs in Cuba, particularly regarding ciguatera, and developing analytical and nuclear capabilities for biotoxin testing and molecular techniques for species identification and monitoring.

NATIONAL

- There are several federal programs and agencies that fund extramural collaborative HAB research between academic institutions, federal, state, local, and tribal and nations agencies, non-governmental organizations (NGOs), and industry.
    - Agencies/Programs that primarily or mostly fund HAB research:
        - NOAA extramural HAB research programs such as Ecology and Oceanography of HABs (ECOHAB), Monitoring and Event Response for HABs (MERHAB), Prevention, Control, and Mitigation of HABs (PCMHAB), HAB Event Response;
        - National Science Foundation-National Institute of Environmental Health Sciences Oceans and Human Health Program (NSF/NIEHS OHH).
    - Agencies/Programs that fund HAB research to a lesser extent: NOAA Sea Grant, NOAA IOOS Ocean Technology Transition Program, US EPA, NASA, NSF, NIEHS, the NIEHS/ NSF Oceans and Human Health Program, US Army Corps of Engineers (USACE), Bureau of Reclamation (BoR), and US Geological Survey (USGS).
    - Federal funding for industry partnerships through the Small Business Innovation Research (SBIR) Program. Each agency has an SBIR Program, e.g., both NOAA and US EPA have SBIR programs that have funded HAB-related projects.
- Federal agencies also conduct intramural collaborative HAB research and response, namely NOAA, US EPA, Centers for Disease Control and Prevention (CDC), US Food and Drug Administration (FDA), USGS, USACE, US Fish and Wildlife Service (US FWS), National Park Service, BoR.

- A few formal cross-agency federal partnerships exist as programs or projects, although informal collaborations are more frequent:
  - USACE and BoR, where research projects are cost and resource-shared between agencies on mission relevant topics, including HABs,
  - NSF/NIEHS OHH Program (see above),
  - CyAN Project, between US EPA, NOAA, National Aeronautics & Space Administration (NASA), and USGS to develop an early warning indicator system to detect algal blooms in US freshwater systems.

3.7.2. KNOWLEDGE GAPS AND UNDERDEVELOPED CAPABILITIES

C. *Collaborative Organizations, Communication, and Research*

INTERNATIONAL

- There is limited coordination addressing causes and occurrence of *Sargassum* or other Caribbean HABs.
- HAB prevalence is increasing in the Arctic, especially *Alexandrium* sp. and *Pseudo-nitzschia* sp., yet there is limited coordination between countries conducting research on these problems in the Arctic, including the US, Canada, Russia, Korea, Japan, and China.

BI-NATIONAL

- The US and Mexico have no formal collaboration mechanism for Gulf of Mexico and Pacific HABs.
- There is limited formal coordination between US and Canadian organizations or states/provinces and federal agencies for research, event response, and regulation of HAB toxins in marine waters.
- Great Lakes region entities (US states and Canada) have different regulations, monitoring methodologies, and spatiotemporal coverage. Difficulties in communications and responses persist and there is limited event response coordination.
- Recent progress in US-Cuba partnerships regarding ciguatera poisoning and other HABs has been greatly hindered by travel restrictions enacted between 2017 and 2020.

NATIONAL

- While the National HAB Committee (NHC) includes strong federal agency representation from NOAA, US EPA, USFDA, USACE, CDC, National Institute of Health (NIH), and NSF, it lacks adequate representation from states engaged in HAB research and management.

- There is limited federal interagency coordination to fund HAB technology development, research, and response.
    - Cross-agency research funding programs:
        - There is often lack of communication and coordination among agencies funding similar topics.
        - Interagency funding programs for HAB research are lacking.
        - Mismatch in funding cycles/availability of funds and agency mandates can make it difficult to initiate and sustain coordinated federal agency research partnerships.
    - Cross-agency research project administration:
        - Some federal agencies do not allow extramural funding to go to other agencies and/or there are limitations on who is eligible to compete for funding.
        - Establishing formal interagency agreements to facilitate research collaboration is challenged by lengthy (6-8 mo. depending on the agency) and varied processes required to establish formal partnerships through Cooperative Research and Development Agreements and Memoranda of Agreement or Understanding. Further challenges arise from delayed appropriations and requirements to spend appropriations before the end of the fiscal year, leading to expired funding, and appropriation delays due to continuing resolution authorities (CRA).
- Collaborative data sharing platforms and leveraging of monitoring and surveillance programs are lacking.

REGIONAL AND INTER-STATE

- There is a lack of sharing of data across regional collaborative HAB and water quality monitoring and surveillance programs.
- Regional fora such as the Gulf of Maine HAB Science Symposium and the Great Lakes HAB Collaborative (Table 3.4), that promote periodic sharing of information and knowledge among scientific and non-scientific communities, are lacking in some regions of the US (Gulf of Mexico and West coasts).
- There is a lack of consistency at state and/or local level in responding to trans-boundary HAB events (including regional and international events, e.g., domoic acid in Dungeness crab along the Pacific coast).
- There is a lack of federal guidance for coordinated multi-state response to HAB events in trans-border settings, e.g., cyanobacteria HAB events in large rivers.
- Interstate Fisheries Commissions currently lack regional HAB response plans.

INDUSTRY PARTNERSHIPS

- While there are examples of industry partnerships with academia and government, few occur for a variety of reasons such as:
  - Lack of public seed funding programs without considerable bureaucratic hurdles for public-private partnerships that target new technology development and application.
  - Lack of mechanisms for research and industry partners to develop collaborative partnerships.
  - State/federal agency restrictions for working with industry partners.

3.7.3. PATHS FORWARD AND RECOMMENDATIONS FOR THE FUTURE

A. *Collaborative Organizations, Communication, and Research*

The following are recommended:

INTERNATIONAL

- Establish an international *Sargassum* Task Force to coordinate responses to combat this problem in the Caribbean.
- Establish a path forward for HABs in the Arctic including better coordination among the US, Canada, Russia, Korea, Japan, and China in their ongoing Arctic research programs.

BI-NATIONAL

- Establish formal coordination between US and Mexican federal and state agencies on HABs in marine coastal waters.
- Establish formal coordination for research, event response, and regulation between US and Canadian Federal agencies and states/provinces on HABs occurring in marine coastal waters and bi-national freshwater bodies.
- Improve and expand coordination between the US and Canada to communicate and collaborate on Great Lakes HAB research, event response, and regulations, although different regulations, methods, and coverage areas exist. Develop a formal strategy for coordinating trans-border event response in these regions.
- Establish a procedure to obtain information on HABs from Cuba and identify possible collaborative opportunities.

NATIONAL

- Encourage regional representation from state HAB researchers and managers on the National HAB Committee (NHC).
- Increase resources and coordination of cross-agency research funding programs:

  - Where possible, encourage federal agencies to coordinate funding efforts even if they operate on different cycles.
  - Support independent cross-agency projects to align research activities. For example, develop coordinated proposals that are funded internally by each agency to preclude the need for exchange of funds so they can operate on different annual funding cycles.
  - Encourage participation in portfolio reviews between federal agencies to avoid duplication and increase coordination on overlapping research efforts.
  - Suggest loaning of researchers/personnel among agencies with overlapping missions to encourage and promote collaboration and communication and reduce duplication of efforts.
- Ease the project administration burden of transferring funds to collaborating agencies/partners:
  - Streamline mechanisms for establishing formal funding agreements among agencies to reduce paperwork and speed-up formal approvals.
  - Initiate paperwork for formal agreements among agencies early in the fiscal year before funds are available to ensure timely completion of agreements even during appropriation delays due to continuing resolution authorities.
  - Urge federal agencies that do not allow other federal agencies to participate in projects receiving extramural funding, to reverse this policy, especially in cases where a federal agency has unique capabilities.
- Increase leveraging of ongoing monitoring, surveillance, and data sharing.
  - Implement a National HAB Observing Network (NHABON), as described in two recent reports outlining a Framework and providing an implementation strategy, to provide a mechanism for collaboration on data sharing platforms and leverage monitoring and surveillance networks.

REGIONAL AND INTER-STATE

- Support establishment of regional groups that support regional sharing of HABs and water quality monitoring data at federal, regional, and state levels. Two existing partnerships that can serve as models are the Global Lake Ecological Observation Network (GLEON) and the Cyanobacteria Monitoring Collaborative. These types of initiatives support coordination among HAB community/managers and organizations/stakeholders engaged in research and monitoring.
- Support existing regional groups (Gulf of Maine HAB Science Symposium, Great Lakes HABs Collaborative) and establish/expand other regional fora (Gulf, West coast) to encourage periodic sharing of information and knowledge

among researchers, non-research academic institutions, federal, state, local, and tribal and nations agencies; and other interested HAB and industry partners.

- Improve coordination of HAB event response across state (and international boundaries):
    - Establish plans or guidance for state agencies to work together in areas where cross-boundary HABs are common, for example large rivers or estuaries bordered by multiple states.
    - Establish federal guidance to enable states to better coordinate response to multi-state frequent HAB events.
    - Establish the HAB Event Response Program outlined in the HAB RDDTT Report (see sec. 3.4) to prepare and assist state, local, and tribal governments response to new and sometimes overwhelming HABs.
- Engage Fisheries Commissions on the impacts of HABs and encourage them to establish management plans or guidelines.

INDUSTRY PARTNERSHIPS

- Support programs such as SBIR and Florida Department of Environmental Protection (DEP) Innovative Technology Grants Program, and develop new ones that provide seed funding to industry and researchers to develop and test new sensors and rapid tests for HAB cells and toxins, new HAB control methods, and methods to mitigate the impacts of toxins.
- Encourage HAB researchers to participate in industry organizations for industries impacted by HABs, e.g., ISSC, national, regional, and state aquaculture associations.
- Expand opportunities for industry to participate in HAB-focused meetings such as the US HAB Symposium.

Table 3.4. List of organizations that promote collaboration and partnerships in the HAB community.

Name	*Partners*[a]	*Purpose and Contribution to HAB Community*
International		
International Society for the Study of Harmful Algae (ISSHA)	*All*	Promotes and fosters research and training programs on harmful algae. Sponsors the bi-annual International Conference on Harmful Algae (ICHA) and publishes the Harmful Algae News newsletter
UNESCO Intergovernmental Oceanographic Commission (IOC) Intergovernmental Panel on HABs (IPHAB)	*US Federal Govt., other National Govts., researchers*	Coordinates HAB international research and management activities. Develops the Harmful Algae Event Database (HAEDAT), international collaboration on ciguatera, creates the Global HAB Status Report, creates and maintains the IOC-UNESCO Taxonomic Reference List of Toxic Plankton Algae, and provides guidance on HABs and desalination.
International Council for the Exploration of the Sea (ICES) - IOC Working Group on Harmful Algal Bloom Dynamics (WGHABD)	*US Federal Govt., other N. Atlantic National Govt., researchers*	Reviews and analyzes HAB events within the ICES region, and provides annual reports, advice, and updates on the state of HAB research and management. Facilitates science interactions and provides a forum for HAB technology transfer, including holding of intercalibration workshops
GlobalHAB	*All*	Continues objectives of the Global Ecology and Oceanography of Harmful Algal Blooms (GEOHAB) program. Fosters international coordination and collaboration on ecological and oceanographic controls for HABs including HAB effects on human society in a changing world
North Pacific Marine Science Organization (PICES)	*All*	Works with Intergovernmental Oceanographic Commission (IOC) programs to build capacity as well as coordinate, promote, fund, and initiate research projects on HABs in the North Pacific and its adjacent seas
International Atomic Energy Agency (IAEA)	*All*	Funds workshops and research focused on using nuclear techniques to detect and measure algal biotoxins in seafood
Cyanobacteria Monitoring Collaborative	*All*	A 3-tiered program (Bloomwatch, Cyanoscope and interstate CyanoMonitoring) focused on the US Northeast and Midwest with international participation. Provides hands-on training, consistent method descriptions, collaborative shared data collection efforts, development of publicly shared data, data visualization and exploration tools, etc.
Freshwater Benthic HAB Discussion Group	*US federal agencies, other countries, academics*	Accelerates mutual understanding of benthic HABs in rivers and lake systems, by sharing data and monitoring protocols, experiences and lessons learned. Holds 2-3 virtual annual meetings (posted on the US EPA website)
Bi-National		
Great Lakes Water Quality Agreement (amended in 2012)	*US and Canada*	Restores and protects waters of the Great Lakes on a variety of issues, including those related to algae and cyanobacteria that interfere with aquatic ecosystem health or human use
Great Lakes HABs Collaborative	*Academics, state, and provincial, federal government agencies*	A "collective laboratory" that seeks to improve communication among scientists, and between scientists and decision-makers on issues related to HABs in the Great Lakes. A major goal is to establish a common knowledge base of current HAB science, future science needs, and how the region can work together to better prevent and manage HABs
National		
The US National Office for Harmful Algal Blooms	*Federal govt, academia, regional/ local govt.*	Coordinates the interests of, and fosters collaboration among, the many stakeholders in HAB research and mitigation. Maintains the Harmful Algae webpage and Harmful Algae Facebook page and the US HAB mailing list server. Provides support to the US National HAB Committee, coordinates international and national HAB research and management and compiles information on marine HAB events
US National HAB Committee (NHC)	*All*	Facilitates coordination and communication of activities for the US HAB community at the national level. Facilitates HARRNESS implementation, provides support and advice to HAB Symposium organizers, fosters communication and coordination with related national and international programs, responds to requests from Congress or federal and state entities for information or guidance on HAB issues, and forms ad hoc technical advisory committees as needed to address issues or requests
Interagency Working Group on the Harmful Algal Bloom and Hypoxia Research and Control Act (IWG-HABHRCA)	*Fed. govt.*	Coordinates and convenes federal agencies to discuss HAB and hypoxia events in the US and develop action plans and assessments of these events
Interstate Technology and Regulatory Council (ITRC)	*State-led, All*	Publishes strategies for preventing and managing pelagic harmful cyanobacterial blooms; training sessions will follow. Currently developing strategies and training for benthic harmful cyanobacteria blooms
Interstate Shellfish Sanitation Conference (ISSC)	*Federal, states, tribal agencies, and shellfish industry; some other countries*	Fosters and improves shellfish sanitation through cooperation and uniformity of state shellfish programs. Provides state-level guidance for implementing regulations concerning biotoxins in shellfish intended for sale into interstate commerce. International members also participate

[a] Partners typically include international, federal, state, tribal and local governmental agencies, NGO's, academia, and industry, but can also include the public

Name	*Partners*[a]	*Purpose and Contribution to HAB Community*
Alliance for Coastal Technologies (ACT)	*Academia, industry, state agencies*	Fosters the development and adoption of effective and reliable sensors and platforms for use in freshwater, coastal and ocean environments. Completed several HAB instrument evaluations and a 2017 HAB Sensors workshop
Regional		
Gulf of Maine HAB Science Symposium	*New England States*	Annual meetings that provide a forum for the discussion of observations and activities, as well as ongoing research and knowledge gaps
Great Lakes Restoration Initiative	*Federal, tribal, state, local agencies, industry*	Accelerates efforts to protect and restore the Great Lakes via US EPA funds. Provides funding to 16 federal organizations to strategically target the biggest threats to the Great Lakes including harmful/ nuisance algal blooms
Gulf of Mexico Alliance (GOMA) Water Resources Team (WRT)	*State, federal, academia, industry, non-profits*	A governors-led state regional ocean partnership, funded primarily by NOAA, working to sustain resources of the Gulf of Mexico. Focuses on hypoxia/nutrients, HABs, freshwater in-flow, impaired/non-impaired streams, and human health (pathogens/mercury)
Integrated Oceanographic Observing System (IOOS) Regional Associations (RAs)	*All*	Comprises eleven RAs, funded primarily by NOAA, that guide development of, and stakeholder input to, regional observing activities including HABs. The RAs serve the nation's coastal communities, including the Great Lakes, the Caribbean and the Pacific Islands and territories
North Central Region Water Network - Algal Bloom Action Team	*Land Grant Universities and interested partners*	As a 12-state collaboration, enhances connectivity across regional and state water projects, develops and carries out integrated outreach and education efforts, and coordinates projects with measurable short and long-term environmental and social impacts
HAB Specific Conferences and Communications		
International Conference on Harmful Algae (ICHA)	*Conference*	This biannual meeting sponsored by ISSHA, convenes worldwide scientists and students engaged in research on HABs. Presentations encompass a wide variety of research topics, including taxonomy, genomics, toxins, ecology, life cycles, impacts, HAB technologies, surveillance, management, and socioeconomic impacts
Symposium on Harmful Algae in the US	*Conference*	The US HAB symposium is the only national conference focused exclusively on HABs. Topics encompass HAB basic research and monitoring, or policy and management.in both freshwater and marine systems, on microalgae or macroalgae. This meeting was first convened in 2000 and is held biannually at various locations around the US
Gordon Research Conference on Phycotoxins and Mycotoxins	*Conference*	This biannual conference provides a forum for academic, government, and private sector scientists to exchange ideas on a variety of research topics pertaining to the occurrence and impacts of algal and fungal toxins
International Conference on Toxic Cyanobacteria	*Conference*	This biannual conference convenes the international research community focusing on the study of cyanotoxins and toxic cyanobacteria
Harmful Algae	*Peer Reviewed Journal*	Established in 2002 and published by Elsevier, this journal provides a forum for the publication of original research and review papers on harmful microalgae and macroalgae, research on the biology, autecology, taxonomy, and chemical ecology of freshwater and marine species, as well as monitoring, management, and control of these organisms
Harmful Algal News	*Newsletter*	An International Oceanographic Commission of UNESCO Newsletter on Toxic Algae and Algal Blooms
EPA CyanoHABs	*Newsletter*	Delivers the latest information on freshwater HABs including news, upcoming events, conferences, and webinars, useful resources, beach closures and health advisories, and recently published journal articles

[a] Partners typically include international, federal, state, tribal and local governmental agencies, NGO's, academia, and industry, but can also include the public

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The arrival of toxin-producing *Alexandrium catenella* blooms in Alaska's Arctic is a dangerous sign for communities that rely heavily on local food supplies. Photo credit: Design Pics Inc/Alamy Stock Photo.

4 HUMAN DIMENSIONS OF HABS (MARINE AND CYANOBACTERIA): PUBLIC HEALTH AND TRIBAL IMPACTS, SOCIOECONOMICS AND POLICY, OUTREACH AND EDUCATION

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Summary

This section covers the public health, socioeconomic, and tribal impacts of harmful blooms caused by algae or cyanobacteria (hereafter called harmful algal blooms or HABs) and their toxins, outreach, education, and socioeconomic issues. Since the previous "Harmful Algal Research and Response: A National Environmental Strategy" (HARRNESS 2005), considerable advances have been made in the analysis and detection of HAB toxins in environmental samples and clinical specimens. For example, the US Environmental Protection Agency (US EPA) developed guidance on human exposures to two important freshwater cyanobacterial toxins in drinking and recreational waters, providing state, tribal, and local governments with information to create and implement their own guidance to protect public health. However, many of the other needs identified in HARRNESS (2005) need to be addressed more fully, including clinical knowledge about the acute and chronic effects of exposure to HAB toxins, public health response planning for HAB events, and incorporation of toxin-related guidance into water quality standards for drinking and recreational waters.

Outreach and communications strategies have changed considerably since HARRNESS (2005). Public awareness of HAB events has increased and social media platforms have provided new opportunities for outreach and information sharing. Social media, however, pose their own challenges. HAB scientists and managers can benefit from training and practice, as well as working with communications specialists, to optimize their use of these platforms.

HARRNESS (2005) considered public health and socioeconomic impacts jointly and put forth 15 recommendations although only two of these were specific to socioeconomic effects: 1) *compile data and calculate the socioeconomic impacts of HAB events at local and regional scales*; and 2) *conduct socioeconomic studies of how user groups will benefit from HAB forecasts at different temporal and spatial scales*. Another recommendation that had a strong need for input from social scientists was to *identify susceptible populations based upon physiological traits, behavioral factors, socioeconomic status, and cultural practices.*

The Harmful Algal Research and Response: A Human Dimensions Strategy (HARR-HD) 2006 expanded on these recommendations in a targeted effort to bring social science research into the HAB community and offered example projects to advance the research agenda. However, the socioeconomic impacts of HABs remain poorly characterized and all of the areas identified in HARRNESS (2005) and HARR-HD 2006 remain underdeveloped. Knowledge generated over the past 15 years has deepened our understanding of the problem but has arisen from largely uncoordinated independent efforts and has not led to the development and adoption of transferable research approaches.

In this section, we summarize the current state of knowledge of the following issues associated with HABS: public health and tribal impacts of algae and cyanobacteria and their toxins, outreach and education, and socioeconomic issues. We highlight significant advances since 2005, identify knowledge gaps, and offer future paths forward.

4.1. Public Health Impacts

4.1.1. CURRENT STATE OF KNOWLEDGE AND SIGNIFICANT ADVANCES

- US EPA provided guidance on human exposures to microcystins (MCs) and cylindrospermopsin (CYN) in drinking and recreational waters.
- Studies found that cyanobacterial toxins can be aerosolized and inhaled (reviewed in Plaas and Paerl 2021).

A. *Characterization of acute and short-term effects of harmful algal bloom (HAB) toxins*

- The acute and short-term effects from ingestion of three common cyanotoxins in freshwater systems in the US (anatoxin-a, MCs, and CYN) were characterized and documented by US EPA in 2015 in three health effects support documents (US EPA, 2015a; 2015b; 2015c). US EPA also developed drinking water health advisories and recreational criteria and swimming advisories for MCs and CYN based on results of short-term oral exposures in laboratory animal studies. Recent toxicity studies by Ohio State University that characterized acute effects from exposure to MCs found localized liver effects and higher susceptibility to these toxins in female laboratory animals compared to males (Mrdjen et al., 2018; Mills et al., 2021).
- In 2019, US EPA conducted analyses to compare inhalation exposure in mice and skin exposure in human volunteers to incidental ingestion of two cyanotoxins (MCs and CYN) during recreation. These analyses are included in the Recommended Human Health Recreational Ambient Water Quality Criteria or Swimming Advisories for Microcystins and Cylindrospermopsin (US EPA, 2019).
- US EPA conducted toxicological evaluations of several toxins in laboratory animals to determine the potential risk of triggering adverse health effects. The studies included evaluations of the oral toxicity from multiple MC congeners, which cause acute toxicity and liver and other cancers with prolonged exposure (Chernoff et al., 2020, 2021), and characterization of the toxicity of subchronic exposures to CYN in drinking water (Chernoff et al., 2018). Many other studies have been published to characterize the health effects from acute and short-term exposure to cyanotoxins (see sec. 4.7. for a comprehensive list of toxicological and epidemiological studies on cyanotoxins conducted since 2005).

B. *Definition of mechanisms of vulnerability:*

- US EPA worked with the University of Cincinnati and Miami University to evaluate the effects of cyanobacteria in susceptible individuals, especially those with chronic rhinitis (Geh et al., 2015).

C. *Development of tools for clinical diagnostic support.*

- The Centers for Disease Control and Prevention (CDC) is developing analytical methods to detect and quantify human and other mammal (e.g., domestic dogs) exposures to algal toxins. These methods will detect exposure to domoic acid (DA), saxitoxins (STXs), neosaxitoxins, and MCs/nodularins in clinical specimens.

D. *Improvement in the surveillance of human exposure and disease and development of a system for archiving case and clinical samples.*

- In 2009, CDC transitioned national surveillance for foodborne and waterborne disease outbreaks to the National Outbreak Reporting System (NORS; National Outbreak Reporting System (NORS) | CDC), an electronic platform that all US states and territories can use to report these illness outbreaks associated with exposures to HABs. Subsequently, CDC released the NORS Dashboard (National Outbreak Reporting System (NORS) Dashboard CDC), a website that provides summary data searchable by etiology (e.g., paralytic shellfish poisoning [PSP]) and is updated annually.
- In 2016, CDC launched One Health Harmful Algal Bloom System (OHHABS), a national surveillance system available to public health officials and their designated partners to report information on HAB events and associated illnesses in humans, domestic pets, livestock, and wildlife (Fig. 4.1). OHHABS collects information about HAB exposures and resulting illnesses to improve disease characterization and refine case definitions. State, local, territorial, and national surveillance involves the collaboration and expertise of multidisciplinary partners to develop systems that support detection, investigation, response, and reporting activities. From 2016-2021, 23 states voluntarily reported:
    - 1,258 HAB events, predominantly freshwater cyanobacterial blooms but also algal blooms in brackish and marine water.
    - 664 human illnesses, including one mortality from paralytic shellfish poisoning
    - 4,665 animal illnesses involving domestic pets, livestock, and wildlife, including large numbers of bird, fish, and bat deaths. OHHABS data summary reports are available on the OHHABS Data webpage.
- CDC also maintains a HAB-associated illnesses website, which also includes general information about blooms, causes and ecosystem impacts.
- Continued work with partners and increased engagement of stakeholders such as other scientists and health care providers, can further improve surveillance through OHHABS and NORS by integrating new public health science, streamlining data collection, and improving systems used to collect and manage data.

E. *Expansion and improvement in documentation of the occurrence of algal toxins in drinking and recreational waters.*

- US EPA, in coordination with states and tribes, is assessing the quality of the nation's waters using a statistical survey design. Implemented on a rotating basis, the four individual surveys (coastal, lakes, rivers and streams, and wetlands) provide a snapshot of the overall condition of the nation's water. Two cyanotoxins (MCs and CYN), and related parameters are included in the coastal and lakes assessments (https://www.epa.gov/national-aquatic-resource-surveys).
- In drinking water systems, the US EPA is working with public water systems to implement a first-time national drinking water monitoring effort for cyanobacterial toxins through the US EPA's fourth Unregulated Contaminant Monitoring Rule (UCMR 4). Results of this effort are available to states and public water systems through the US EPA's web-based reporting system and are made publicly available on a quarterly basis on US EPA's website (https://www.epa.gov/dwucmr/fourth-unregulated-contaminant-monitoring-rule).
- The US Geological Survey (USGS) published several studies of the occurrence of cyanotoxins in lakes, reservoirs, and rivers that can be used to assess the potential risks associated with drinking water supplies and recreational water use (Graham et al., 2016; Loftin et al., 2016; Graham et al., 2020; Zuellig et al., 2021; Laughrey, 2022).

F. *Develop short-term response plans for water contaminated by algal toxins to protect public health*

- In 2015 and 2016, US EPA released several resources to assist public water systems and water managers in responding to cyanobacteria and their toxins in drinking and recreational waters. These resources include Recommendations for Public Water Systems to Manage Cyanotoxins in Drinking Water (US EPA, 2015d), and the Cyanotoxin Management Plan Template and Example Plans (US EPA, 2016) to assist state, tribes, and public water systems as they develop their own management strategies.
- In July 2017, US EPA released several materials to assist recreational waterbody managers interested in monitoring and responding to cyanobacteria and cyanotoxins in recreational waters, including the steps to develop Cyanotoxins Management Plans. These materials include a recreational water communication toolbox for cyanobacterial blooms (Communicating about Cyanobacterial Blooms and Toxins in Recreational Waters), and recommendations for monitoring cyanobacteria and cyanotoxins in recreational waters (Monitoring and Responding to Cyanobacteria and Cyanotoxins in Recreational Waters).
- The Interstate Technology and Regulatory Council (ITRC) developed recommendations for managing and mitigating the effects of cyanobacterial HABs (https://www.itrcweb.org/documents/planning/2018/1-strategies-for-preventing-and-managing-harmful-cyanobacteria-blooms.pdf).

- The Water Resources Foundation (WRF) created a tool kit for drinking water utilities to address cyanobacterial HABs (https://www.waterrf.org/research/topics/cyanobacteria-cyanotoxins.)
- Multiple states have developed cyanotoxin and cyanobacteria management plans to help them assess and manage the risks of HABs in fresh and marine waters (https://www.epa.gov/home/health-and-environmental-agencies-us-states-and-territories.)
- CDC has released the Waterborne Disease Outbreak Investigation Toolkit (Waterborne Disease Outbreak Investigation Toolkit | Water, Sanitation, & Hygiene-related Emergencies & and Outbreaks | Healthy Water | CDC) – a guide to help state and local health departments conduct waterborne disease outbreak investigations. It includes a HAB appendix.

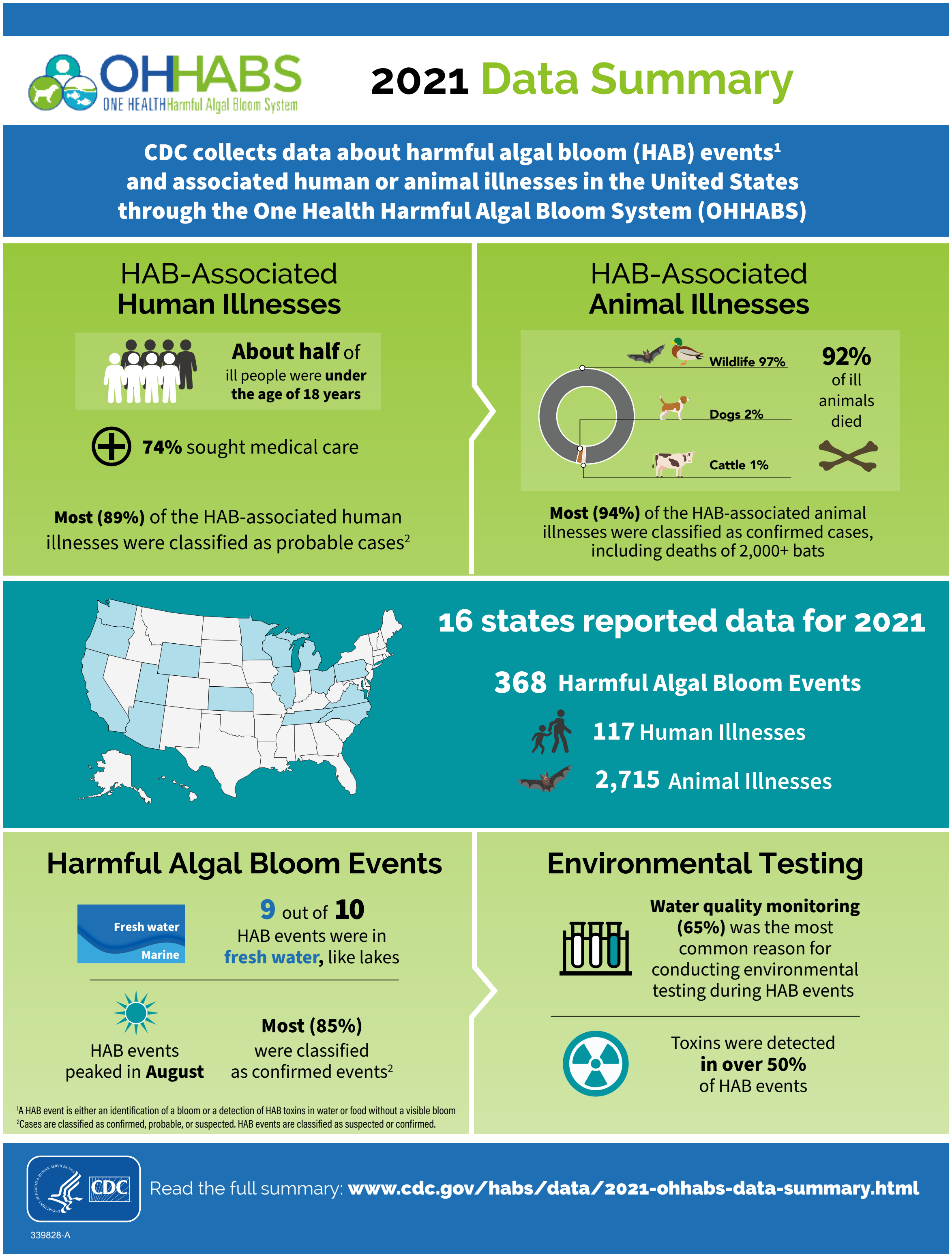
G. *Incorporation of algal toxins into water quality standards for drinking and recreational waters*

- In 2015, US EPA published Drinking Water Health Advisories for MCs (US EPA, 2015e) and CYN (US EPA 2015f) to assist federal, state, and local officials, and managers of public or community water systems to protect public health from cyanotoxins in drinking water.
- In 2019, US EPA issued final Recommended Recreational Water Quality Criteria/Swimming Advisories for MCs and CYN for water managers to protect people while they are swimming or participating in other recreational activities in and on the water; and for states, territories, and authorized tribes to consider their adoption into their water quality standards and use for Clean Water Act purposes (US EPA, 2019).
- Several US states have developed or implemented standards or guidelines that apply to cyanotoxins in drinking and recreational waters: https://www.epa.gov/home/health-and-environmental-agencies-us-states-and-territories.

H. *Provision of toxicological and pharmacokinetic information on HAB toxins and metabolites*

Several published studies have evaluated the toxicity and mechanism of toxicity for several freshwater cyanotoxins including MCs, CYN, saxitoxin (STX) and anatoxin (Chernoff, 2018, 2020; Mrdjen et al., 2018; Puddick et al., 2021; Zhang et al., 2021).

Fig. 4.1. Summary dissemination information produced by the Centers for Disease Control and Prevention (CDC) as part of the One Health Harmful Algal Bloom System **(OHHABS) initiative.**



4.1.2. KNOWLEDGE GAPS AND UNDERDEVELOPED CAPABILITIES

The following are needed to fill knowledge gaps and address underdeveloped capabilities:

- Incorporation of toxin-related guidance into drinking and recreational water quality standards,
- Epidemiologic studies to inform clinical presentation, treatment, and disease progression following exposure to HAB toxins,
- Development of new and improved analytical methods to detect toxins in biological specimens,
- Development of rapid analytical tests to guide water body management decisions,
- Development of public health preparedness and response plans for public health.
    - Studies to comprehensively understand the absorption, distribution, metabolism, and excretion mechanisms from exposure to freshwater and marine toxins.
- Develop health promotion and communication knowledge: health, tools, and products for diverse audiences, including the public, health departments, and healthcare providers.
    - Behavioral science methods and studies need to be incorporated into efforts to understand the communication needs and preferences of audiences receiving public health messaging.

Specific questions to address include the following:

A. *What are the short- (acute) and long-term (chronic) effects of exposure to HABs?*

Eating food, drinking water, or breathing aerosols contaminated with HAB toxins can cause acute illness in humans and other animals (see Figs. 2.5 and 4.2). Acute HAB toxin-associated poisonings are typically a diagnosis of exclusion and victims receive supportive care for signs and symptoms. Unfortunately, adequate toxicological data are unavailable to characterize the risks from chronic exposure to these toxins in drinking and recreational waters. Although several studies using laboratory animals and human populations have been published by Ohio State University on the relationship between exposure to cyanotoxins in drinking water and tumor promotion and cancer incidence (Lee et al., 2020; Gorham et al., 2020; Mrdjen et al., 2022), the risks for cancer occurrence and other long-term health effects such as cardiovascular disease, developmental defects, or neurobehavioral illnesses associated with these exposures are unknown. Thus, the treatments and follow-up that might be successful in addressing long-term illnesses are also unknown.

Fig. 4.2. A cyanobacterial *Anabaena/Dolichospermum* bloom in Southeast Oregon. Junipers Reservoir floating algal scum (left panel) resulted in the deaths of livestock (thirty two 14-month old steers) over 4 days in 2017 (right panel) (Dreher et al., 2019). Neurological symptoms included excitation, head tremors, staggering gait, tetany and death. Field necropsies of several animals showed pale livers, and histopathology revealed massive liver necrosis. Microcystin, the toxin presumably responsible for the observed acute liver damage, occurred at a concentration of 3,000 µg L^{-1} in a reservoir water sample (the World Health Organization's recommended guideline for safe drinking water is 1 µg L^{-1}) and at 7,100 µg L^{-1} in rumen contents of one of the dead steers. *Photo credit: T. Dreher, Oregon State University. Reproduced with permission from Dreher et al. (2019).*

B. ***What are the differences in health effects from exposure to algal toxins via different exposure routes?***

Further research is needed to better understand how the route of exposure affects cyanotoxin toxicity.

C. ***Are there differences in vulnerability to algal and cyanobacterial toxins?***

Multiple factors contribute to disease expression: physiological traits, age, sex, baseline health, brain reserve capacity, psychological status, risk perception, behavioral factors, cultural and traditional practices, socioeconomic status, genetic predisposition, collateral exposures and duration and severity of illness. It remains unknown which, if any, of these factors contribute to HAB toxin-linked illnesses. Further research is needed to determine health risks among populations of varying susceptibility, such as the elderly, children, pregnant women and their fetuses, and persons with underlying health conditions. Mechanisms underlying any identified differential vulnerability are also an area of needed research.

D. How can laboratory animal model data and wildlife exposure information be integrated with data from human exposures and disease?

Development of cross-disciplinary investigations among toxicologists will provide important information about toxic effects. Improved coordination among scientists, veterinarians, physicians, public health professionals, and wildlife managers is essential to characterize, predict, and prevent human illness.

E. Are there biomarkers for exposure and health outcomes related to HAB toxins?

Identifying and understanding which toxins, their metabolites, or both contribute to human or other animal illness will be helpful in determining which biological markers of exposure and health effects are necessary in evaluating short- and long-term exposures and health effects. For example, some marine species are known to metabolize algal toxins to conjugated, reduced, or oxidized forms that might retain toxicity in exposed humans and other animals. These chemicals might be useful as biomarkers of exposure even if they are non-toxic or are low in toxicity.

F. How can communication about the public health threat posed by exposure to HABs be improved?

Despite the presence of extensive information on websites from many government jurisdictions, the medical community (including veterinarians and Poison Control staff) and the public remain minimally aware of potential exposures and the possible health risks from exposure. Efforts to improve communication might incorporate current best practices related to health literacy (Develop & Test Materials | Health Literacy ; CDC); use new information to target messages to vulnerable, high-risk populations; or apply knowledge about communication preferences to more effectively reach audiences.

G. How can information about HABs, toxins, health effects, and risk factors that is widely scattered across federal, state, and local websites be integrated?

Consolidation of information, perhaps in a single clearinghouse-style website, would be helpful. Hardy et al. (2021) reviewed the status of cyanobacteria HAB outreach and monitoring efforts in the US. This study found that although the preferred outreach methods of state health departments are websites and press releases, public awareness is limited by the lack of funding for outreach and monitoring programs and by somewhat limited access to electronic resources.

H. What are potential sources of information describing HAB exposures and health outcomes?

Effective sources of exposure and illness information include state-based HAB monitoring, Geographic Information System (GIS)-based mapping, disease and outbreak surveillance, and electronic health records. CDC provides information and resources, including surveillance data summaries, on a HAB-associated illnesses website.

4.1.3. PATHS FORWARD AND RECOMMENDATIONS FOR THE FUTURE

Future work might focus on the following:

- Epidemiology studies to identify the health effects of exposure to HAB toxins in water, food, and aerosols, including those from surface recreational waters experiencing blooms. Studies that include potentially more susceptible populations (e.g., children, the elderly, and those with underlying health conditions) are needed.
- Toxicity studies to determine the adverse effects of short- or long-term exposures to cyanotoxins in food, drinking water, recreational water, and aerosols.
- Continue developing public health guidance for cyanotoxins that could be present in drinking and surface waters.
- Identify biomarkers of short- and long-term exposure and health effects to improve clinical understanding of HAB-related health effects.
- Increase the use of electronic medical records and Environmental Public Health Tracking (National Environmental Public Health Tracking, CDC) capabilities, and coordination with America's Poison Centers, states, and local environmental and health agencies.
- Improve public health surveillance, including support for local, state, and territorial One Health coordination on detection, investigation, response, and reporting to OHHABS and NORS, to further inform illness prevention efforts and characterize emerging concerns such as illnesses associated with benthic HAB blooms.
- Support and implement a sustainable repository for human and other animal clinical specimens, including those collected for epidemiological research, and analytical methods development.
- Develop cross-disciplinary networks involving toxicologists, veterinarians, physicians, public health professionals, and wildlife managers to improve coordination and prevent illnesses.
- Improve outreach activities to increase awareness, diagnosis, treatment, and prevention of HAB-associated illnesses:
  - Identify the tools and information needed by the medical community to diagnose, treat, and follow up on potential HAB-associated exposures and illnesses.
  - Provide training opportunities that include Continuing Medical Education (CME) credit for medical staff, including Poison Center staff, to make them aware of the potential for poisonings.
  - Conduct and evaluate outreach to the public and those with responsibilities for managing water resources to enhance the reach and effectiveness of messaging.

4.2. Socioeconomics

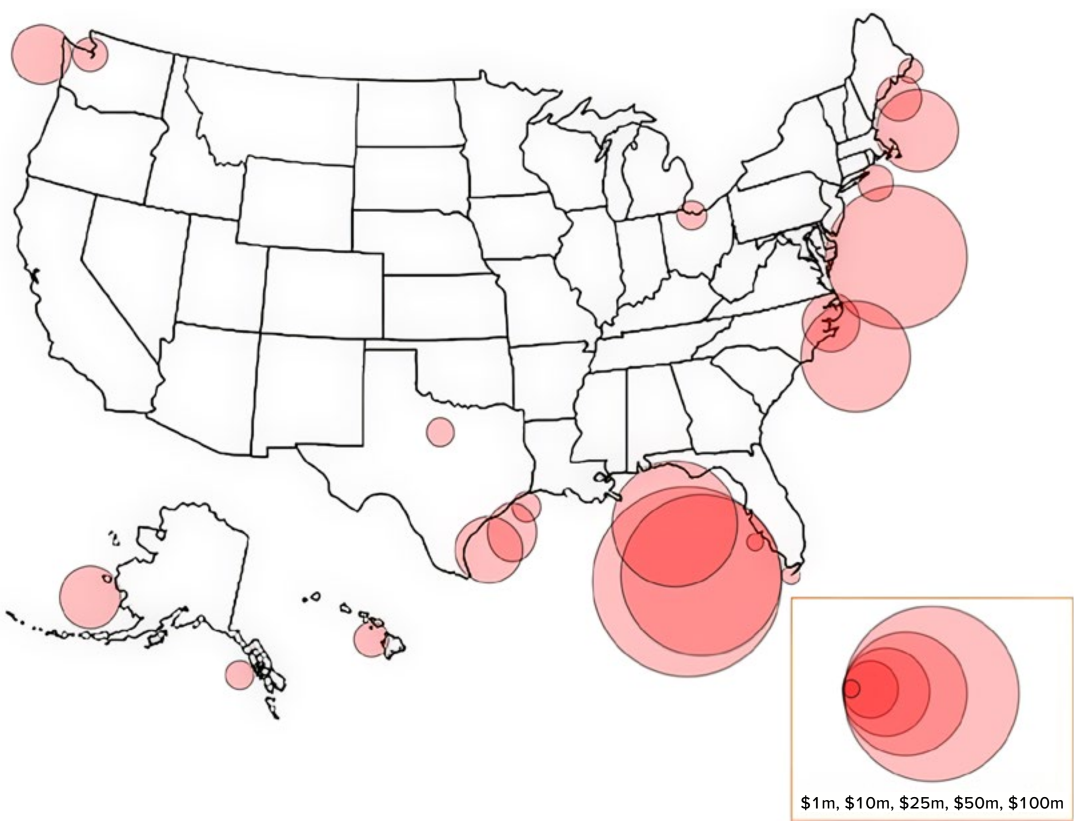
4.2.1. CURRENT STATE OF KNOWLEDGE AND SIGNIFICANT ADVANCES

A. *Economic impacts*

- The average annual economic impact of HABs in the US is estimated at $10 million to $100 million (USD) (Anderson et al., 2000; Hoagland et al., 2002; Hoagland and Scatasta, 2006; Adams et al., 2018). Most of these costs are incurred in the public health and commercial fisheries categories, with recreation and tourism and monitoring and management costs making up the remainder. This crude national estimate is a summation of reported impacts and underestimates the magnitude of losses experienced nationwide. It is challenged by data limitations and the use of analytical approaches that preclude aggregation (e.g., estimates of losses to the public vs. costs to specific industries or local and regional economies). Large individual HAB events tend to drive the national estimate in a particular year or even when averaged over several years. Smaller events might not be evaluated at all, even though they might be more numerous and cumulatively important. In addition, new categories of economic impacts have been identified that were not included in the national estimate, such as changes in real estate values after widely publicized blooms (Bechard, 2020).
- A wide range of analytical approaches have been used to estimate the economic effects of individual HABs or HAB events since the national estimate was derived, yielding new insights into the changes and impacts wrought by HABs (Fig. 4.3). Collectively, this work highlights the diversity of effects that arise through multiple mechanisms from different HABs occurring in different ecosystems and human contexts. This work emphasizes the complexity of the problem. Advances include:
  - Estimates of changes in consumer and producer surpluses (net economic benefits) in monetized markets such as seafood markets, real estate, or coastal tourism industries (e.g., lodging and restaurant sales), or where markets do not exist such as for recreation or the passive appreciation of nature (Whitehead et al., 2003; Parsons et al., 2006; Bingham et al., 2015; Alvarez et al., 2019; Mao and Jardine, 2020; Ferreira et al., 2023).
  - Consideration of the linkages among multiple industry sectors, directly or indirectly affected by HABs, to capture broader impacts in terms of changes in revenues, expenditures, and employment in local and regional economies (e.g., using input-output models) (e.g., Dodds et al., 2009; Dyson and Huppert, 2010; Holland and Leonard, 2020).
  - Cost-of-illness estimates that depend upon lost incomes or the costs of emergency care or hospitalization (e.g., Hoagland et al., 2009, 2014). These differ from measures of surplus changes or output impacts, and they typically omit estimates of the difficult-to-measure losses due to pain and suffering (of individuals, families) when HAB-related illnesses occur.

- Estimates of the value of scientific information (see below), costs of inadequate risk communication, changes in summary indicators (such as market prices), and willingness to pay to avoid HAB impacts (which can inform policy development for HAB response) (Jin et al., 2008; Jin and Hoagland, 2008; Bauer et al., 2010; Jardine et al., 2020; Dyson and Huppert, 2010; Lucas et al., 2010).

Fig. 4.3. **Selected historical examples of HABs in the US for which economic impacts (2015 $M) have been estimated.** The large range in scales of potential economic impacts is shown. Circles represent estimates of economic (not spatial) scales at different points in time, beginning in the 1970s, with circle size proportional to estimated economic impact. The maps of Alaska and Hawaii are not drawn to scale (but the circles are comparable). Large scale blooms continue to occur with severe impacts to local economies, (e.g. Fig. 4.4A and Fig. 4.4B). *Reproduced with permission from Adams et al. (2018).*



B. Social and cultural impacts

- HABs can significantly disrupt the social and cultural practices that enable groups and their members to survive and develop a social construct or meaning. These interactions may be social, political, organizational, interpersonal, or economic (Harmful Algal Research and Response: A Humans Dimensions Strategy [HARR-HD, 2006]). Losses to individual and community well-being can result when HABs disrupt these interactions. Sociologists and anthropologists have used qualitative and quantitative methods, from rapid ethnographic assessments (REAs) engaging local or traditional ecological knowledge (local ecological knowledge [LEK] or traditional ecological knowledge [TEK]), to conduct surveys and demographic analyses to characterize the effects of HABs on individuals or groups. Advances include the following:

- Documentation of the social and cultural impacts of HABs in some communities, enabling a deeper understanding of the pathways of effects and their sociocultural context (Ritzman et al., 2018; Crosman et al., 2019; Moore et al., 2020; Karnauskas et al., 2019; Kourantidou et al., 2022),
- Characterization of seafood consumption patterns to build a deeper understanding of dependence on and potential risk of exposure to HAB toxins (Mazzillo et al., 2010; Grattan et al., 2016; Tracy et al., 2016; Ferriss et al., 2017).

C. *Value of information*

- HAB prediction and monitoring is considered most helpful for reducing the impacts, especially for HABs that are not responsive to current prevention or control strategies. The value arises when some or all the damage caused by HABs can be averted by using mitigation strategies when advanced knowledge of the likelihood of occurrence of a HAB event is available, or taking protective measures when timely HAB monitoring information is available. The net value of the information to industry or individuals is given by the expected difference between the economic surplus that results when the prediction is used in decision-making (i.e., the dollar value of the benefits of the prediction minus the costs of producing and delivering it) and the surplus that results when the prediction is not considered (i.e., the dollar value of socioeconomic costs) (Harmful Algal Research and Response: A Human Dimensions Strategy [HARR-HD], 2006). The value of information can also be calculated excluding the cost of HAB prediction, and it can then be used to justify an appropriate level of investment in the prediction. Advances include:
  - Identification of the most important time frame (i.e., 1-2 weeks) for some HAB forecasts for shellfish growers, and development of a framework for measuring the value of HAB predictions that captures the effects of private and public responses (Jin and Hoagland, 2008).

D. *Community vulnerability*

- Some communities are at increased risk for socioeconomic impacts of HABs, as for other natural hazards; however, research to explicitly address or measure vulnerability to HABs is just beginning to emerge. The vulnerability (and resilience) of communities to HABs depends in part on how and to what extent communities depend on the affected resource(s) and in part on the social structure of communities including human relationships within and across communities. This type of information is critical for understanding the potential differential distribution of impacts (e.g., Jardine et al., 2020), the cumulative effects of HABs and other stressors, and the identification of thresholds that might render the sustained participation of a community in a resource related activity nonviable. Advances include the following:

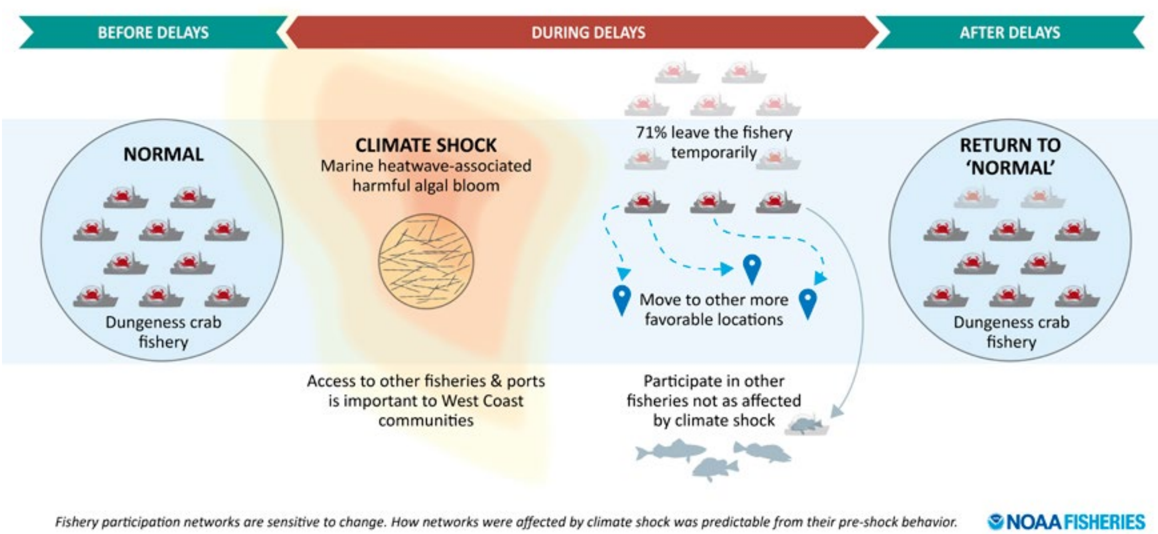
- Identification of characteristics that increase the likelihood of some individuals and populations experiencing economic loss or stress due to HABs (Moore et al., 2020; Jardine et al., 2020),
- A framework for identifying the communities most vulnerable to HABs that may help to focus response strategies (Moore et al., 2019),
- A framework for assessing the potential direct and indirect impacts of HABs and climate change trends and events on fisheries socio-ecological systems (Dudley et al., 2021),
- Identification of adaptation strategies employed by some communities when HABs occur (Moore et al., 2020; Karnauskas et al., 2019; Fisher et al., 2021; see Figs. 4.4A and B).

E. *Programmatic*

- Research on the socioeconomic effects of HABs is supported as one of several topics under the National Oceanic and Atmospheric Administration (NOAA) Prevention, Control, and Mitigation of HABs (PCMHAB) program.

Fig. 4.4 A. The 2014–2016 North Pacific marine heatwave, known as "the Blob", led to a *Pseudo-nitzschia* bloom of unprecedented scale. It substantially delayed the opening of the 2015–16 Dungeness crab fishery, which is vital to West Coast communities. This fishery typically produces ~26 % of all annual fishing revenue and supports >30 % of all commercial fishing vessels. Delays from this event were longest in CA, and over $25 million in disaster assistance was appropriated by Congress to support affected CA fishers. *Photo credit: B. Drummond, Ocean Conservancy.*

Fig. 4.4 B. Fisher et al. (2021) explored the impacts of the 2014–2016 North Pacific marine heatwave climate shock and associated HAB on communities' use of ocean resources. They found that 71 % of CA Dungeness crab fishing vessels temporarily left the industry and stopped fishing altogether during the delay of the crab fishing season. The two other strategies used by fishermen to cope with the disruption (see schematic) were: a) participating in other fisheries unaffected by the HAB; b) moving out of delayed areas to fish in other more favorable locations. Patterns of resource use were mostly normalized after the fishery re-opened, but it is unclear if these strategies that worked in the past will be sufficient to sustain fishers during future HAB events. *Image credit: NOAA NWFSC.* https://www.fisheries.noaa.gov/feature-story/dungeness-crab-fishing-industry-response-climate-shock



4.2.2 KNOWLEDGE GAPS AND UNDERDEVELOPED CAPABILITIES

In general, the socioeconomic impacts of HABs remain poorly characterized and all the areas identified in HARRNESS (2005) and HARR-HD 2006 remain underdeveloped. Knowledge generated over the past 15 years, largely uncoordinated independent efforts, has deepened our understanding of the problem but has not led to the development and adoption of transferable research approaches. Below we summarize the most pertinent knowledge gaps.

A. *Economic impacts*

- Reporting and data limitations are ubiquitous for addressing the socioeconomic impacts of HABs. With respect to the economic consequences of HABs, the paucity of available data has limited or prevented the following:
    - Establishment of baselines and measurements of change in economic value (e.g., consumer and producer surpluses) caused by HABs,
    - Assessments of HAB effects at the appropriate spatiotemporal scales, especially for smaller scale events,
    - Identification of long-term trends in HAB impacts at regional and national levels for public and private investment planning,
    - Identification of the cumulative impacts of HABs and of these combined with other disturbances.
- Incomplete understanding of the pathways for how HABs directly and indirectly affect individuals and communities, and for how economic losses to one sector permeate communities to affect other sectors. Because changes in the distribution of economic activities due to HABs are not well understood (i.e., switching from preferred activities, products, or sources to alternatives), studies are lacking for several economic sectors that are potentially affected by HABs.
- There is limited understanding of 'halo' effects, leading to widespread effects on other sectors not directly affected by HABs, that are driven by perceptions or miscommunication of risk.
- Costs of illnesses and fatalities due to HABs are largely unknown, especially for chronic, low-level cumulative exposure and long-term effects from acute or chronic exposure.
- The aggregate economic consequences to the public (full and part-time residents and tourists) of avoiding HABs, including the potential loss of outdoor activities – from walking and viewing sporting events to participating in coastal and nearshore recreation – have not been estimated.
- There is limited understanding of the effectiveness of policy responses in reducing the economic costs of HABs.
- There is limited understanding of the distribution of HAB economic impacts across communities/demographic groups/regions, and the potential for HABs to cause or amplify existing environmental justice issues.

- The value to the public of addressing HABs relative to other types of disturbances is unknown or only known anecdotally.
- Effects on labor markets from unstable working conditions are unknown, making it more difficult to provide the support needed to maintain economic activity.
- Understanding of potential HAB effects on emerging and growing ocean industries (e.g., aquaculture) is limited.

B. *Social and cultural impacts of HABs*

- Few baselines have been established for human well-being.
- There is a lack of understanding and reporting of the full range of human behavioral responses to HABs (and their associated economic welfare changes), and how beliefs and perceptions influence these responses (e.g., how people perceive, understand, and act or not on advisories and trust or not in government policy, and of other factors affecting decisions, behaviors, and outcomes [health, social, economic]).
- There is a lack of published work on the social, cultural, economic, and nutritional dependence of communities on potentially HAB-impacted resources.
- Social networks used for sharing natural resources and information on HABs are poorly understood.
- Few social impact assessments of HABs and HAB policies are available.
- There is limited understanding of HAB effects on social, psychological, and economic well-being, and changes in social cohesion and uncertainty.
- There is limited understanding of HAB effects on individuals, families, and communities of interest.
- There is also limited understanding of the cumulative effects of HABs and of HABs combined with other disruptive events.

C. *Value of information*

- There is little knowledge of the value of information from improved HAB forecasting, and how much to invest in HAB monitoring.
- Assessments of the net benefits of implementing new programs for formal monitoring, testing, and closure of fishing locations are rarely conducted.
- The effectiveness of traditional and local ecological knowledge or other cognitive constructs for reducing risk for impacted local communities is unknown.

D. Community vulnerability

- There is limited understanding of the characteristics that influence individuals'/communities' vulnerability to HABs, and how those vary across communities and for different HABs.
- There is little understanding of communities' abilities to withstand the socio-economic impacts of HABs.

E Programmatic

- There are no federal research programs specifically focused on the socioeconomic effects of HABs. Under the NOAA PCMHAB program, support for monitoring and prevention competes with socioeconomic research. Further, PCMHAB socioeconomic federal funding opportunities are not issued on an annual or regular basis, which can lead to multiple years between new projects.

4.2.3. PATHS FORWARD AND RECOMMENDATIONS FOR THE FUTURE

The following suggested paths forward draw heavily from the proceedings of the workshop on the socioeconomic effects of HABs in the United States held by the US National Office for HABs at the Woods Hole Oceanographic Institution and the NOAA National Centers for Coastal Ocean Science in 2020. The overall goal of the workshop was to enhance socioeconomic research to yield a more comprehensive evaluation of the social and economic effects of HABs in fresh and marine waters of the US, including the costs of responding to and mitigating those effects. Forty experts with equal representation of the social and natural sciences attended the workshop. Two sets of recommendations emerged from the workshop: a Socioeconomic Assessment Framework and a Socioeconomic Research Agenda that are adapted here.

Recommendations from the Socioeconomic Research Agenda are grouped into broader themes to be more consistent with those identified previously in HARRNESS (2005) and HARR-HD (2006). Following the latter, economic impacts are described separately from social and cultural impacts, although these are interconnected, and many of the recommendations are cross-cutting. A new, previously unidentified recommendation is offered, i.e., to assess and build resilience to future HABs.

A. Follow the recommendations for a Socioeconomic Assessment Framework and a Socioeconomic Research Agenda from the 2020 Workshop on the Socioeconomic Effects of HABs in the United States.

- Recommendations from the Socioeconomic Assessment Framework describe the institutional arrangements deemed necessary for successful implementation of a research agenda. They call for enhanced interagency coordination, improved research communication and coordination among research networks, integration of socioeconomic assessments into HAB forecasts and observing networks; open-access databases for establishing baselines and identifying departures from them, facilitation of rapid response studies; improvement of reporting of public health outcomes; fostering the use of LEK and TEK concerning HAB responses, engagement of communities affected by HABs in citizen science, and graduate students in HAB socioeconomic research.

- Recommendations from the Socioeconomic Research Agenda constitute the necessary elements for addressing gaps in our understanding of the socioeconomic effects of HABs. They include an approach for obtaining an improved national estimate of the economic impacts of HABs; REAs and assessments of social impacts and defining socioeconomic impact thresholds for triggering more detailed impact studies (e.g., in the case of designated HAB events of significance); and sponsoring research on the value of information, HAB policies, risk communication, and the incidence, severity, and costs of human illnesses. Many of these paths forward are included below under the broader themes identified previously in HARRNESS (2005) and HARR-HD (2006).

B. *Assess economic impacts*

- Implement community-level surveys to address the need for an improved national estimate of the economic impacts of HABs that considers the losses associated with HABs and the costs of responding to them. The survey approach would be transferable to other HAB contexts and would generate data for use in benefit transfer to assess losses from HAB events occurring in contexts that were not studied specifically.
- Identify and describe the impact pathways of HABs in communities, and evaluate the costs to all impacted economic sectors.
- Identify the range of human behavioral responses to HABs and their associated changes in economic welfare.
- Evaluate the costs of illnesses and fatalities due to HABs.
- Determine the distribution of HAB economic impacts across communities, demographic groups, and regions.
- Identify and describe the impacts of HABs on communities particularly vulnerable to bloom events, including farmers, ranchers, and fishers using methods such as listening sessions, focus groups, and community-wide discussions.

C. *Assess social and cultural impacts*

- Carry out REAs to understand the sociocultural context for HAB impacts and the effectiveness of HAB response efforts.
- Determine the dependence of communities on natural resources impacted by HABs.
- Identify the community social networks used for sharing resources and information.

- Characterize the effects of HABs on social, psychological, and economic well-being; changes in social cohesion; and uncertainty.
- Assess the information needs of managers, decision-makers, educators, and other stakeholders to guide the development and delivery of mitigation tools to reduce HAB impacts.
- Identify and include TEK and LEK in HAB monitoring, forecasting, risk communication, and adaptation.
- Determine how trust, belief, and perception influence human behavioral responses to HABs and HAB policy.
- Assess the value of scientific information and forecasts.
- Determine the value of information from HAB forecasts and monitoring in terms of damages avoided for existing programs.
- Assess the net benefits of implementing new programs and enhancing existing HAB forecasts and monitoring programs.
- Assess the value of TEK, LEK, and other cognitive constructs for avoiding HAB impacts on communities.
- Include trusted scientists and policymakers from impacted communities in planning and decision-making related to HAB impacts.

D. *Evaluate policy responses*

- Use cost-benefit or cost-effectiveness approaches to analyze the economic tradeoffs involved in the implementation of alternative policies and interventions to reduce HAB impacts.
- Conduct social analyses of alternative policies and interventions to reduce HAB impacts.

E. *Identify vulnerable communities*

- Develop community profiles that identify the socioeconomic characteristics that make communities more vulnerable to HABs, including underserved communities, and how those characteristics vary across communities and for different HABs.
- Evaluate communities' abilities to withstand the socioeconomic effects of HABs, including the cumulative effects of HAB events and of HAB events combined with other disturbances.

F. *Assess and build resilience*

- Measure resilience in communities impacted by HABs and identify practical and effective ways to build resilience.

- Identify critical thresholds that would cause socio-ecological systems to shift to new states, as well as indicators to provide early warning of approaching those thresholds.
- Identify and include TEK and LEK into adaptation strategies.
- Address vulnerable communities' hesitancies to changes in subsistence harvesting due to HAB activity and work with community policy makers to build resilience.

G. *Programmatic*

- Ensure federal interagency coordination to maximize current levels of HAB socioeconomic research investments.
- Establish federal research programs dedicated to evaluating the socioeconomic effects of HABs.

4.3. Tribal Impacts

4.3.1. CURRENT STATE OF KNOWLEDGE AND SIGNIFICANT ADVANCES

A. *Community and Regional Efforts*

- Localized/regional consistent phytoplankton monitoring at key subsistence harvest sites provides "early warning" of HAB events.
- Depending on the region, there is community involvement and tribal awareness of the risks associated with HABs and toxins, but this is limited.
- There is a need to link regional programs together, expanding tribal efforts nationally.

B. *Subsistence Shellfish Toxin Analysis*

- Increased knowledge and expertise to perform toxin analysis on subsistence and commercial shellfish.
- Subsistence shellfish testing for marine biotoxins can provide tribal citizens the information necessary to develop shellfish harvest management plans, providing harvest opportunities when the risk of human health impacts is low.
- Tribal laboratories support tribal subsistence efforts and build capacity.
- Tribal governments that are actively leading monitoring efforts increase the capacity of the region and expand the communities' involvement while developing localized climate adaptation strategies.

C. *Marine Mammals*

- There is increased regional awareness of domoic acid (DA) and paralytic shellfish toxins (PSTs) in marine mammals in some communities in Alaska (see Fig. 2.4).

D. *Community Outreach*

- Increased outreach is available through databases, the Integrated Ocean Observing System (IOOS), and regional networks.

E. *Traditional Ecological Knowledge (TEK) and Public Awareness/Risk Assessment*

- Due to climate changes and warming ocean conditions, HAB events are starting earlier and lasting longer into the early winter months.
- There is TEK knowledge of HAB timing and harvest opportunity. For example, Tlingit people stop harvesting clams in the spring once herring arrive because HABs develop.
- Some outreach material and databases are used to inform tribal citizens of current HAB events and risks associated with shellfish harvest.

F. *Freshwater HABs*

- Minimal regional tribally-led programs are set up to monitor and test for freshwater toxins.

4.3.2. KNOWLEDGE GAPS AND UNDERDEVELOPED CAPABILITIES

A. *Community and Regional Efforts*

- A limited number of tribal agencies and tribal nations actively collect weekly phytoplankton samples.
- There are funding limitations to implement consistent monitoring programs.
- Efforts by state and federal managers to include community input in monitoring programs is necessary.

B. *Subsistence Toxin Analysis*

- There are limited testing laboratories that support tribal subsistence shellfish testing.
- Few states run programs that provide subsistence and recreational shellfish testing.
- Subsistence harvesters need 'real-time' data.

- There are funding limitations for setting up tribal laboratories.
- US EPA/NOAA support is required for technology transfer of analytical methods to increase tribal capacity.

C. *Marine Mammals*

- There are limited tissue toxin analysis resources for subsistence harvesters.
- Some tribal communities rely on marine mammal food sources for subsistence; there are thus potential long-term exposure risks from DA and PSTs from marine mammal tissue.
- There is a need for monitoring programs to collect marine mammal tissue for analysis.
- A detailed outreach plan is needed to inform communities of risks associated with toxins in marine mammals.
- Incorporating toxin and monitoring efforts into management plans would improve risk assessments and provide outreach to subsistence communities.

D. *Community Outreach*

- Partnerships with state health and resource managers are needed to share data and impacts of HAB events.
- Regional tribal networks are needed to disseminate critical HAB updates.
- Engagement of tribal youth and schools is lacking.

E. *Traditional Ecological Knowledge (TEK)*

- TEK can be integrated with monitoring and toxin analysis to provide updated information to tribal citizens.

F. *Public Awareness/Risk Assessment*

- State, regional, and community support to provide tribal citizens with concise outreach material is limited.
- "Real-time" data that can be used to better determine when to collect subsistence resources is needed.

G. *Freshwater HABs*

- Few regional tribal laboratories are available to analyze freshwater toxins.
- Tribes are concerned about freshwater toxins accumulated by freshwater mollusks in brackish estuaries.

- Freshwater and marine subsistence resources (clams, plants, fish) could be impacted by freshwater toxins.
- Funding for implementing long-term monitoring is limited.

4.3.3. PATHS FORWARD AND RECOMMENDATIONS FOR THE FUTURE

A. *Community and Regional Efforts*

- Develop regional and community-based phytoplankton monitoring networks that perform phytoplankton identification and quantification; determine salinity, sea and air temperature; sample whole water for cellular toxin analysis; and sample shellfish for biotoxins.
- Undertake training programs that support building regional tribal capacity for long-term monitoring.
- Support development of rapid field testing to evaluate shellfish.

B. *Subsistence Shellfish Toxin Analysis*

- Build tribal environmental program capacity by establishing tribal biotoxin laboratories to support subsistence and commercial fisheries.
- Develop regional tribal laboratories that support freshwater and marine toxin analysis for local tribal governments.

C. *Marine Mammals*

- Develop monitoring programs that include marine mammal tissue sampling.
- Build community resilience with regional networks and training on toxins in marine mammals.
- Develop traditional food programs that support community harvest and distribution.

D. *Community Outreach*

- Create platforms where tribal HAB data can be stored, displayed, and made available for subsistence harvesters and managers.
- Generate outreach material that links TEK with Western science.

E. *Traditional Ecological Knowledge*

- Develop HAB mitigation and adaptation strategies using TEK and Western science.

F. *Public Awareness/Risk Assessment*

- Develop regional databases and outreach methods (e.g., social media and websites) to engage tribal citizens and share toxin data.
- Assess the vulnerability of regions or communities that would allow monitoring, or mitigation of resource losses at specific sites.

G. *Freshwater HABs*

- Work with tribal representatives and US EPA to develop regional tribal monitoring programs.
- Develop regional tribal laboratories that provide toxin analysis on and off reservation lands.
- Transfer US EPA methods of cyanotoxin analysis detection to tribal laboratories.
- Integrate freshwater HAB sampling into existing monitoring programs where applicable.
- Provide support to tribes who can implement a freshwater HAB program.
- Link tribes together to develop regional networks to provide support and consistency with monitoring.

4.4. Outreach and Education

4.4.1. CURRENT STATE OF KNOWLEDGE AND SIGNIFICANT ADVANCES

- US Environmental Protection Agency (US EPA) guidance is available at https://www.epa.gov/cyanohabs;
- Centers for Disease Control and Prevention (CDC)'s guidance is available at https://www.cdc.gov/habs/index.html;
- Interstate Technology and Regulatory Council (ITRC) guidance is available at: (https://rct-1.itrcweb.org/;
- National Oceanic and Atmospheric Administration (NOAA) guidance is available at https://oceanservice.noaa.gov/hazards/hab/.
- The primary sources of harmful algal bloom (HAB) information have been websites, peer-reviewed journals, and scientific conferences. Journals and conferences primarily serve the science community, yet HAB knowledge is needed across many sectors, including healthcare, tourism, and affected communities. Communication materials have been developed by state, tribal, local, territorial, and federal agencies to inform the public about the occurrence and associated risks of HABs. Some states, such as Ohio, Washington, and Wisconsin, have developed targeted outreach materials for physicians, veterinarians, and the public. Many other states, such as California, Florida, and Vermont, have

increased access to HAB monitoring data through state-specific electronic dashboards.

- The influence of anthropogenic (human-induced) factors on HAB events was cited in HARRNESS (2005); much more information is available since its publication.
- US EPA, in coordination with partners, has taken several actions to protect public health from HABs, including the development of tools and activities to improve communications and expand stakeholder engagement. These include:
    - Development in 2012 of the US EPA's Cyanobacterial HABs in Water Bodies website which provides information for states, tribes, and communities to protect public health during cyanobacterial HAB events in drinking and recreational waters, and
    - Publication since 2014 of the monthly Freshwater HABs Newsletter with information for states and local governments on events, webinars, beach closures and health advisories, and new journal articles.
- US EPA has also conducted webinars and campaigns to increase awareness and knowledge about HABs. In 2014, for example, US EPA conducted a HAB awareness campaign in coordination with other federal agencies, such as CDC and NOAA, some states, non-governmental organizations, and academia. This campaign included four national webinars on HABs, nutrient pollution, and federal collaboration. US EPA also developed videos (e.g., Nutrient Pollution 101; When in Doubt, Stay Out; and Protect Your Pooch from HABs), conducted an algal bloom photo contest with the National Environmental Education Foundation, and partnered with the Humane Society, the American Kennel Club, and CDC to alert pet owners about HAB risks.
- US EPA provided several tools and resources to states and primacy agencies and local communities to help effectively communicate the risks from cyanotoxins in drinking and recreational waters. These resources include the Cyanotoxin Management Plan Template and Example Plans, the Drinking Water Cyanotoxin Risk Communication Toolbox, the Recreational Water Communication Toolbox for Cyanobacterial Blooms, and the HABs Infographic to inform the public about HABs. US EPA also developed a quick reference guide for financing resources to aid in managing HABs, a factsheet summarizing opportunities for using the Drinking Water State Revolving Fund programs to address HABs, a factsheet for drinking water operators on cyanobacteria and their toxins, and an overview video of the tools to assist states, tribes, and operators of drinking water facilities in managing cyanotoxins in drinking water.
- US EPA facilitated HAB workshops across the country to build relationships and identify shared HAB-related goals, needs, and barriers among federal, state, and Tribal Clean Water Act (CWA) and Safe Drinking Water Act (SDWA) programs.

- The workshops, held from 2015 to 2018 in nine US EPA regions, provided information on the risks from exposure to HABs, strategies for the prevention and management of blooms in surface water, and effective cyanotoxin treatment techniques in drinking water. The workshops also provided a forum for state and tribal health and environmental agencies to exchange information about their HAB programs, individual experiences, and needs for the protection of public health from HABs and their toxins in drinking, fresh and marine waters.
- US EPA hosted two additional workshops in regions 10 and 7 to address specific topics related to HABs. The US EPA Office of Water and Region 10 hosted a Regional Cyanobacterial HAB Workshop and Tabletop Exercise (TTX) in October 2019 to help states and tribes enhance the ability of drinking water utilities and water managers to prepare for, manage, and respond to cyanobacterial blooms and their toxins in drinking and recreational waters. During the TTX, a hypothetical HAB scenario was presented for participants to discuss in small groups. Participants could respond by drawing on their individual experiences from previous events and their roles and responsibilities in their own organizations. After the TTX, participants engaged in a "hotwash" session to discuss key issues raised during the TTX section and opportunities for program improvements.
- In February 2020, a multi-regional HAB workshop was hosted in partnership with the Office of Water; Office of Research and Development; Regions 5, 7, and 8; and the University of Kansas. The focus was to discuss common issues and solutions for managing HABs and excess nutrients in Regions 5, 7, and 8. More than 140 people attended the workshop, including water quality professionals from federal, state, and local governments; drinking water systems; regional watershed associations; the agricultural community; and academic institutions.

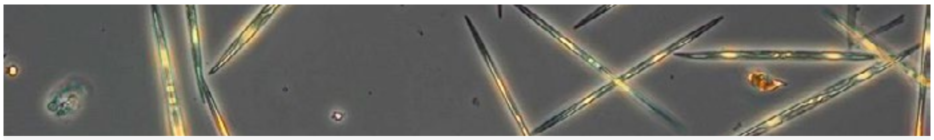
- CDC maintains the One Health Harmful Algal Bloom System (OHHABS), which collects data on human and non-human animal illnesses caused by HABs and on environmental data about HABs. Health departments in US states and territories are the primary reporters to OHHABS, and they work with additional partners to identify HABs and human and other animal illnesses caused by HABs. OHHABS can collect reports about HABs in freshwater or seawater and any associated human or other animal illnesses. HABs can be reported even if no such illnesses are identified.
- In 2016, in concert with the launch of OHHABS, the CDC launched the HAB-associated illnesses website. This website consolidated and expanded upon existing public health information and resources available to educate the public, medical providers, and other stakeholders in HAB-associated illness prevention. Outreach materials on the website currently include fact sheets, posters, social media graphics, and reference cards (Figs. 4.5 and 4.6), many of which are available in Spanish and English. These are designed for use by health department staff, continuing education units for healthcare professionals,

physicians, poison control center staff, veterinarians, and the public, with specific resources available for animal owners.

- As a partner of state, tribal, local, territorial, and federal agencies, CDC participates in workshops and conferences to share information about public health considerations related to HABs. CDC hosts the Drinking Water Advisory Communications Toolbox, (Drinking Water Advisory Communication Toolbox Drinking Water Advisory Communications Toolbox, CDC), a practical guide to help water systems operators effectively communicate with partners and the public about water emergencies. It includes information specific to cyanobacterial bloom-related advisories. This project was a collaborative effort among CDC, US EPA, American Waterworks Association (AWWA), the Association of State and Territorial Health Officials (ASTHO), the Association of State Drinking Water Administrators (ASDWA), and the National Environmental Health Association (NEHA). Additionally, CDC has partnered with national organizations, such as ASTHO, to support the development of educational content, such as a podcast featuring the Oregon Health Authority titled "Communicating During an Emergency: Cyanotoxin Lessons from Oregon."
- To assess the status of cyanobacterial HAB outreach and monitoring efforts, two questionnaires were distributed to health and environmental departments in 50 states and the District of Columbia (DC). One questionnaire focused on cyanobacteria HAB exposure to humans from drinking water and the second targeted exposure through recreational activities. All states plus DC responded to the recreational survey; 46 states plus DC responded to the drinking water survey (Hardy et al., 2021).
  - All states except Alaska answered that microcystins (MCs) were the cyanotoxins of greatest concern for recreational exposure; they were also of greatest concern for drinking water except for Utah (anatoxin-a in reservoirs was the greatest concern) and Rhode Island (MCs and anatoxin-a in reservoirs/ponds were the greatest concern).
  - Regional comparisons disclosed a lack of cyanobacteria HAB programs in southern relative to northern states that may be related to the higher percentage of water surface area in the latter. Recreational outreach is more extensive than drinking water outreach (only 16 states reported having some type of drinking water outreach program, compared with 35 states with recreational outreach), and preferred outreach methods are websites and press releases. Additionally, respondents reported very limited funding for outreach and monitoring programs. These results establish baseline information to help determine the future direction of cyanobacterial HAB outreach and monitoring programs at local, regional, and national levels.

Fig. 4.5. Examples of Centers for Disease Control and Prevention (CDC) communication vehicles used to alert and inform the public of the health threat of freshwater cyanobacterial blooms to their pets and livestock. *Outreach material courtesy of CDC. See* www.cdc.gov/habs

Fig. 4.6. **"Deadly Myths" included in a fact sheet distributed in Alaska on amnesic shellfish poisoning (ASP),** the syndrome (permanent memory loss) caused by ingestion of marine diatom species of the genus *Pseudo-nitszchia*. This alga produces the neurotoxin domoic acid and often forms long chains of single cells (photo credit: Associated Press). *Outreach material courtesy of C. Whitehead.*



Deadly Myths

- Shellfish are safe to eat during months containing the letter "r". In November 2015, the entire California crab fishery was shut down due to high levels of domoic acid.
- If the water is clear, there is no danger of shellfish poisoning. Many harmful algal blooms are colorless, including most *Pseudo-nitzchia* blooms. Some shellfish can also retain their toxins for months after a bloom.
- If wildlife has been eating the shellfish, it must be safe. Every animal has a different tolerance to ASP toxins. Do not assume shellfish is safe on the basis of animal observations.
- If shellfish has been tested for Paralytic Shellfish Poisoning (PSP) toxins, it's safe from ASP toxins as well. Multi-species harmful algal blooms are becoming increasingly common. ASP and PSP toxins could be present in the same samples.
- Domoic acid can be cooked or frozen out of shellfish. This toxin is heat stable and cannot be removed.

- Background information and education are valuable tools to inform the public about HABs. Most states and federal agencies have developed communications materials and programs focused on specific types of HABs for different regions, stakeholders, and types of impacts. Tools for outreach include web sites, brochures, fact sheets, education programs, training sessions, etc. These materials are often shared among jurisdictions.
- Comprehensive information about freshwater cyanobacteria and cyanotoxins, their management in recreational and drinking water, monitoring and analysis, and information about ongoing research in prevention, management, and control is available on the following US EPA CyanoHAB websites (https://www.epa.gov/cyanohabs; https://storymaps.arcgis.com/stories/d4a87e6cdfd44d6ea7b97477969cb1dd). In addition, the US EPA uses the same websites to disseminate information about HABs news, upcoming events, conferences, and

webinars, beach closures and health advisories, and recently published journal articles and other resources.

- The NOAA-funded US National Office for HABs provides news and information to managers, researchers, and the public about marine and coastal HABs through multiple channels:
    - *Harmful Algae Facebook page* (https://www.facebook.com/pages/Harmful-Algae/210160985681846) - updated weekly with news articles and alerts about HABs,
    - *Harmful Algae website* (https://hab.whoi.edu) - organizes information about HABs and their distribution in the US, research developments and strategies, workshop reports and conference proceedings, and related data and information,
    - National and regional e-mail listservs - the primary mechanism for disseminating information about opportunities and announcements of interest to the US HAB community or specific regional communities.
- During HAB events, managers work to communicate complex and often unsettling information effectively and quickly to a wide range of stakeholders with varying knowledge levels. Some states, tribes, and IOOS Regional Associations (RAs) use interactive mapping web sites, press releases, email listservs, and social media content to provide current information about HAB distributions, toxin concentrations in seafood, recreational and subsistence seafood harvesting closures, or beach conditions.
- Community HAB monitoring programs have been started in many states that provide both early warning and public education opportunities.

4.4.2. KNOWLEDGE GAPS AND UNDERDEVELOPED CAPABILITIES

- Although many websites, one-pagers and infographics have been created, very few of these have had formal evaluations of their effectiveness to allow their modification and improvement.
- Social media is now an everyday outlet that many people use as their source of information. The effects of social media on human behavioral responses to HABs have not been evaluated.
- Websites need routine updating to include new information and must be written in multiple languages.
- A coordinated implementation plan needs to be developed for outreach to the medical community.
- General public awareness of HABs and their impacts, and factors that influence both awareness and perception of risk are necessary.

- Unified messaging, encompassing both regional and national outreach, for communicating information to target audiences about HAB events and exposures is desirable.
- Understanding the effectiveness of current outreach methods and messages is needed, e.g., requires reaching the target audiences and communicating the intended information.
- US EPA and NOAA agency websites are designed to address their mandates for HABs. Clearly explaining these would be helpful to the user. For example, US EPA covers freshwater HABs while NOAA covers marine HABs.
- Limited information is available about populations most at risk to support developing more targeted outreach and education efforts. Regional variation of anthropogenic influences on HAB event occurrence needs to be further addressed in this effort.
- Information is lacking about the best methods of communicating risk to different groups of affected stakeholders.
- Training and educational resources for communication of information on HABs and their toxins is lacking.

4.4.3. PATHS FORWARD AND RECOMMENDATIONS FOR THE FUTURE

- Communication training programs are needed for HAB scientists and communicators to effectively message on social media platforms, phone, and in-person interviews. HAB scientists can also work with communicators with expertise in translating scientific information and concepts for other audiences.
- As websites are created and updated, they need to be accessible on all types of computers, tablets, and cell phones.
- An increase in the number of trained taxonomists currently remains a critical need. Additionally, an established plan for workforce training for in situ observation platforms would support improved HAB monitoring.
- Community science phytoplankton monitoring programs need to increase their spatial and temporal observations. Those observations will also provide needed validation data for forecasts.
- Risk communication workshops should be included at national and/or international HAB meetings.
- Provide training and tailor outreach programs to specific groups such as the medical community, shellfish growers, subsistence and recreational shellfish harvesters, and tourism officials to address their needs.
- Determine whether there are gaps in knowledge, translation, understanding, or access.

- Evaluate existing scientific terminology, prevention messages, platforms, and approaches to outreach to improve resources and methods used. Undertake ongoing evaluation to continually adapt to changing needs.
- Engage multidisciplinary and multisectoral stakeholders to increase health and scientific literacy related to HABs, including awareness of the interconnected impacts on humans, other animals, and the environment.
- Fund social sciences research to develop improved educational materials and risk communication strategies tailored specifically for the diversity of HABs, their impacts, and the locations where they occur.
- Hold regional and national workshops between communications experts and federal, state, local, and tribal HAB managers and communications staff to develop best practices for use during events. These workshops should target a variety of stakeholder groups, e.g., the public, press, recreational or commercial fishers, seafood processing plant operators, and legislators.

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GLOSSARY

Algorithm: in mathematics and computer science, a finite sequence of rigorous well-defined instructions or set of rules, to be used in performing calculations or other problem-solving operations.

Allelopathy: the production of metabolites that can inhibit growth of other co-occurring microorganisms

Anatoxin: secondary, water-soluble, bicyclic amine toxin produced by multiple genera of freshwater cyanobacteria (e.g., *Dolichospermum*). It binds to acetylcholine receptors in nerves and at neuromuscular junctions, inhibits the enzyme acetylcholesterase, and can cause human and other animal poisoning by incapacitating nerve and muscle function.

Aptamers: synthetic antibodies, i.e., stable short strands of nucleotides (DNA or RNA), or peptides that bind with high affinity and specificity to target molecules or antigens. Aptamers offer advantages over antibodies as they can be engineered completely in vitro, are readily produced by chemical synthesis, and elicit little or no immune response.

Autecology: a subdivision of ecology which studies the individual organism or species.

Azaspiracids: fat-soluble, polyether amino acid toxins produced by the marine dinoflagellates, *Azadinium* spp., that can accumulate in shellfish and thereby cause azaspiracid shellfish poisoning (AZP) in humans. They inhibit voltage-gated potassium channels causing gastrointestinal illness.

Bayesian model: statistical model based on the Bayesian interpretation of probability where probability expresses a *degree of belief* in an event that may be based on prior knowledge about the event such as the results of previous experiments.

Benthic: existing on bottom surfaces or in the sediment vs. existing in the water column (pelagic).

Benthos: the community of organisms living on bottom surfaces or in sediments of a body of water (such as an ocean, river or lake).

Bioassay: standardized test that provides a measure of total toxicity based upon a biological response of the whole live organism (in vivo), or specific cells, tissues, functions or reactions (in vitro).

Biogeochemical cycling: the natural cycling of compounds among the living and nonliving components of an ecosystem.

Biomagnification (= bioamplification): increase in the concentration of a toxin or pollutant in the tissues of an organism at successively higher levels in the food chain.

Bloom: proliferation of phytoplankton and macroalgae in the environment, may or may not have harmful effects (see also, Harmful Algal Bloom).

Brevetoxins: a suite of lipid-soluble, neurotoxic cyclic polyether compounds produced by dinoflagellates of the genus *Karenia*. These toxins bind to voltage-gated sodium channels in nerve cells, with an excitatory effect, causing the illness referred to as neurotoxic shellfish poisoning (NSP).

Capsid: nanometer-sized protein shell whose main function is to encapsulate the viral genome in one host, to transport it and subsequently release it inside another host cell.

Certified reference materials: "controls" or standards used to check the quality of a product, validate analytical measurement methods, and/or calibrate instruments. A certificate provides information on measurement uncertainty and traceability (relating a reference standard to national or international standard).

Ciguatera poisoning (CP) and Ciguatera fish poisoning (CFP): a human syndrome or form of food poisoning caused by eating fish or shellfish contaminated with ciguatoxins (CTX), that are produced by benthic microalgae endemic to tropical regions.

Cylindrospermopsin: a water-soluble polycyclic uracil toxin produced by a variety of freshwater cyanobacteria. It causes protein synthesis inhibition and is hepatotoxic (toxic to the liver).

Cloud computing: the delivery and use of computing resources (servers, databases, storage) over the Internet.

Coccolithophores: single-celled, spherical microalgae typically $< 30\ \mu m$ in diameter, that are enclosed in calcium carbonate ($CaCO_3$) plates (coccoliths). Sinking of coccoliths after cell death plays an important role in storing carbon dioxide in oligotrophic open ocean sediments and thus in carbon cycling.

Congeners: one of many variants/configurations of a toxin structure.

Cyanobacteria: a phylum of bacteria, formerly known as blue-green algae. Most species within the phylum can perform photosynthesis.

Cyanophages: bacteriophage (viruses) that are specific to cyanobacteria.

Diatoms: single-cell or chain-forming microalgae, members of the Class Bacillariophyceae, characterized by cell walls made of overlapping silica valves (called frustules).

Dinoflagellates: single-celled microalgae of the Class Dinophyceae, characterized by two dissimilar swimming flagella; possess a rigid cell wall composed of cellulose plates forming a theca (thecated or armored cells), or naked (unarmored) cells. Single cells may form chains of varying length.

DNA sequencing: determination of the nucleic acid sequence, i.e., the order of the four nucleotide bases (adenine, guanine, cytosine, thymidine) in deoxyribonucleic acid (DNA).

Domoic acid: water soluble, neuroexcitatory amino acid produced by some algae (e.g., diatoms of the genus *Pseudo-nitzschia*), and that causes amnesic shellfish poisoning (ASP). It is structurally similar to kainic acid.

Downwelling: in the open or coastal ocean where Eckman transport causes surface waters to converge or impinge on the coast such that surface water is carried down beneath the surface.

Driver: any natural or human-induced factor that directly or indirectly causes a change in a system.

Ecosystem: a functional unit consisting of living organisms, their non-living environment and the interactions within and between them. The components included in a given ecosystem and its spatial boundaries depend on the purpose for which the ecosystem is defined.

El Niño/La Niña: periodic sea surface temperature changes in the Pacific Ocean that lead to global weather pattern alterations. **El Niño** results in movement of warm water toward the coasts of the Americas, so-called because it generally develops just after Christmas. **La Niña** results in colder-than-normal surface water in the eastern tropical Pacific.

Encystment: process involved in cyst formation.

Epidemiology: the study and analysis of the spread and patterns of a disease and of the factors affecting the state of health in a defined population.

Epiphytic: mode of life in which an organism (e.g., microalga) attaches and grows on the surface of other organisms (e.g plants, solid surfaces like rocks and sediment) merely for physical support, i.e., not as a parasite.

Etiology: study of the cause, set of causes, or origin of a disease or abnormal condition.

Eukaryotes: cells that possess a nucleus, and other intracellular organelles or membrane-bound bodies such as mitochondria and plastids, and a more complex cell wall as compared to prokaryotic cells.

Excystment: process involved in cyst germination.

Exopolymers: external secretions surrounding the cell that are produced by some microorganisms (mainly algae and bacteria) and can affect their palatability to grazers, allow them to adhere to solid surfaces, and protect them from environmental conditions.

Exposome: the totality of exposures to stressors over a lifetime, which predispose and predict health effects in an individual, which is a complement to the genetic material contained within an organism.

Euphotic (or photic) zone: the top, surface layer of the ocean or other body of water, variable in depth, that is illuminated by sunlight thus allowing photosynthesis by algae to occur.

Eutrophic (vs. oligotrophic): characterized by an abundance of nutrients.

Eutrophication: the process/es that allow an enrichment in nutrients in a body of water, marine or freshwater.

Flux: the amount of a substance (e.g., heat, salt, nutrient) that flows through a unit area perpendicular to the flow per unit time.

Genomic: relating to the complete set of genes within the genome of an organism.

Greenhouse gases: gases, primarily carbon dioxide (CO_2) but also methane, nitrous oxide, and chlorofluorocarbons (CFCs), emitted through human activities (e.g., burning of fossil fuels, agricultural practices, decay and burning of organic waste), and that trap heat in the Earth's atmosphere.

Flocculation: physico-chemical process that allows individual particles (e.g., clay sediment particles) to aggregate forming a floc, and thus come out of suspension and be more rapidly deposited on the bottom.

Harmful algae: microalgae or macroalgae that can cause harmful environmental or health effects.

Harmful Algal Bloom (HABs): proliferation of phytoplankton and/or macroalgae that have negative effects on marine or freshwater environments and associated biota. Impacts include water discoloration and foam accumulation, low oxygen (hypoxia) or lack of oxygen (anoxia), contamination of water and/or seafood with toxins, disruption of food webs, and massive large-scale mortality of biota.

HAB resting stage: stage (e.g., cyst) in the life cycle of some algae which allows them to better undergo stressful environmental conditions.

Haemolytic activity: causing rupture (lysis) or destruction of red blood cells (erythrocytes). It is measured in units such as saponin nano-equivalents (SNE; saponins are algal sterols that can cause disruption [pore formation] of cell membranes and thus cell rupture), or the concentration of a harmful alga that causes 50% haemolysis (see Fig. 2.12).

"Halo" effect: indirect effect of HABs in which the contamination of some seafood product affects the demand for, and sale of other seafood product even if it does not pose a risk to human consumers.

Heterotrophic: an organism's dependence on an external food supply vs. **autotrophic**: able to synthesize organic compounds from inorganic nutrients.

Hydrodynamic cavitation: disruption of nuisance cells in the water column using the energy produced by cavity formation technology.

Lysis: the rupture of cell membranes thereby liberating cell contents.

Macronutrients (vs. micronutrients): essential nutrients for the growth of aquatic plants and animals such as nitrogen (N) and phosphorus (P) (and silicon [Si], in the case of diatoms).

Macrophytes: vascular plants (which include both seagrasses and macroalgae) that grow in or near water and are either emergent, submergent, or floating.

Mesocosm: a medium scale (volume ca. 1 to 10,000 m^3) water enclosure or experimental system that examines the effects of the natural environment under controlled conditions, thus providing a link between field studies and controlled laboratory experiments.

Metabolomics (= metabolic profiling): the comprehensive analysis of metabolites, i.e., small molecules, intermediates and products of cell metabolism in a biological sample; a technology used to determine cellular responses to changing environments. The **metabolome** represents the complete set of metabolites in a biological cell, tissue, organ or organism, which are the end products of cellular processes.

Metadata: data that describe other data (e.g., text, image, measurement), but not the content of the data, e.g., descriptive information used for identification such as collection, time, depth, instrument settings.

Metrology: the science of measurement, including the definition of units of measurement.

Microcystins: a class of cyclic peptidic, potent liver toxins produced by some freshwater cyanobacteria or so-called blue-green algae (e.g., *Microcystis*). They pose a severe threat in drinking water for humans, livestock, and pets.

Micronutrients: essential nutrients required in much lower amounts than macronutrients, such as metals and vitamins.

Mixotrophy: the ability of microorganisms to use a mix of different sources of energy and carbon, instead of having a single trophic mode (autotrophy or heterotrophy), i.e., they can photosynthesize, or derive organic carbon by feeding on other organisms. Eukaryotic mixotrophs have their own chloroplasts, have endosymbionts with chloroplasts, or acquire them through kleptoplasty (sequestration from other organisms).

Model initialization: the initial state of a forecasting model (time = 0) that captures initial current conditions and from these conditions, forecasts are made.

Nanoparticles: less than 50 μm in size that cannot be captured in a plankton net.

Nitrogen fixation: the use of chemical processes by certain microorganisms to assimilate atmospheric nitrogen into organic compounds, as part of the nitrogen cycle.

Ocean acidification (OA): reduction in the pH of the ocean, accompanied by other chemical changes (primarily in the levels of carbonate and bicarbonate ions), over an extended period, typically decades or longer, which is caused primarily by uptake of carbon dioxide (CO_2) from the atmosphere, but can also be caused by other chemical additions or subtractions from the ocean.

Omics: disciplines in biology whose names end in the suffix -omics such as genomics, proteomics, metabolomics and transcriptomics. (See individual glossary entries for these terms).

Pelagic: the pelagic zone consists of the entire water column of the open ocean (or freshwater body of water). It is subdivided into the 'epipelagic zone' (<200 m, the uppermost part that receives enough sunlight to allow photosynthesis), the "mesopelagic zone" (200–1000 m depth) and the "bathypelagic zone" (>1000 m depth). The term "pelagic" can also refer to organisms that live in the pelagic zone.

Phytoplankton: microalgae that are a constituent of the plankton, i.e., are found suspended or swimming in the euphotic (illuminated) zone of the ocean.

Photosynthesis: the process performed by some organisms (e.g., terrestrial plants, seagrasses, seaweeds, microalgae) whereby they use sunlight as an energy source to synthesize foods from carbon dioxide and water; oxygen is generated as a byproduct.

Picoplankton: planktonic algae and other microorganisms that are less than 2-3 μm in cell size.

Polymerase chain reaction: a technique for amplifying copies of a target DNA or RNA sequence to provide ample material for further study.

Polymorphism: having two or more clearly different forms such as two or more morphologies; or as in genetics, two or more forms of a DNA sequence that can occur among individuals or populations.

Primary production: the amount of organic matter synthesized by an organism from inorganic substances within a given volume of water in a unit of time.

Proteomics: the large-scale study of proteins in a cell, tissue or organism. The **proteome** is the entire set of proteins produced or modified by an organism or system.

Receptor: a protein or other molecule which binds a specific extracellular molecule (ligand) and initiates a cellular response.

Relaying: practice of moving organisms (shellfish or fish) to more pristine waters to allow them to depurate biotoxins or pollutants to acceptable levels for harvest.

Ribotype: determination of differences in an individual's genetic material based on analysis of DNA fragment lengths.

Riparian: the transition zone between land and a river or stream.

Saxitoxins: water-soluble neurotoxins produced by dinoflagellates or cyanobacteria, that cause paralytic shellfish poisoning (PSP) in humans, typically due to the consumption of contaminated shellfish. These toxins block sodium channels in nerve and muscle cells.

Symbiotic: involving a mutually beneficial interaction between different organisms existing in close proximity.

(Protein) Skimmers (= foam fractionators): mechanical systems often used in aquaculture for aeration of the water column, and elimination (skimming) of floating protein and debris that accumulates at the surface.

Prokaryote: a microscopic, single-celled organism that has neither a distinct nucleus with a membrane nor other specialized organelles. Prokaryotes include bacteria and cyanobacteria.

Stakeholders: all parties with a stake in HAB issues. These include: a) industry (such as the aquaculture and fishing industries, the tourism and recreational sector, and desalination and water treatment plants), b) regulators (resource management agencies, water and seafood safety managers, national authorities, and monitoring laboratories), c) health sector, and d) society or the public (including citizens and communities, fishers and tourists) (see Fig. I).

Stratification: the separation of water into layers based on a specific property (e.g., salinity, temperature, density); a process that acts as a barrier for water column mixing.

Synaptic plasticity: in neuroscience, the ability of synapses (the physical gap between nerves, and nerve and muscles, which must be traversed by any nerve impulse) to strengthen or weaken over time, in response to increases or decreases in their activity. It is an important neurochemical foundation of learning and memory since memories are postulated to be represented by vastly interconnected neural circuits in the brain.

Thermocline: a temperature gradient within the water column of a body of water, characterized by a layer above and a layer below that differ in temperature.

Top-down vs. bottom-up control: in the context of HABs, refers to their control by grazers (top-down) and/or by nutrients (bottom-up).

Toxicity Equivalency Factors (TEF): expresses the toxicity of a toxin in terms of the most toxic form of a group of structurally related toxins that share the same mechanism of action. The underlying assumption in computing TEFs is that the doses of these individual toxins in a mixture are additive.

Toxicogenomics: the genetics that underpin toxin expression within an organism or that reveal organismal response to toxic stimuli.

Toxin potency: the relative concentrations of different chemicals or toxins required to reach the same level of effect on a given biological endpoint (e.g., death in a mouse bioassay). It is used to determine the exposure risk to a chemical or toxin.

Transcriptomics: study of all ribonucleic (RNA) transcripts (both protein-coding and non-coding) during gene transcription in a cell, tissue, or organism. Data obtained are used to gain insight on processes such as cell differentiation, disease stage and toxin production. The **transcriptome** can vary with external environmental conditions and with the expression level of RNAs.

Upwelling (vs. downwelling): phenomenon induced by physical forces (usually wind divergence of equatorial currents or coastal winds pushing water away from the coast), whereby deeper water (typically colder and poor in nutrients) is brought up to the surface.

Upregulation vs. downregulation: related to genes that are expressed in high (upregulated) or low (downregulated) abundance in response to cellular processes and physiological changes to stimuli.

Zoonotic/zoonosis: an infectious disease caused by a pathogen (an infectious agent such as a bacterium, virus, or parasite), that has jumped from a non-human animal (usually a vertebrate) to a human. Transmission can be direct (air, saliva) or through an intermediate host.

APPENDIX I: HARRNESS UPDATE COMMITTEE AND REVIEWERS

Name	Affiliation
Catharina Alves-de-Souza[2]	University of North Carolina Wilmington
Clarissa Anderson[2]	Southern California Coastal Ocean Observing System
Donald Anderson[1]	Woods Hole Oceanographic Institution
Dan Ayres[2]	Washington State Department of Fish and Wildlife
Lorraine C. Backer[1]	Centers for Disease Control and Prevention
David Berthold[3]	University of Florida/IFAS
V. Monica Bricelj[2,4]	TechMar Research, Inc.
John Bratton[2]	LimnoTech
Keith Bouma-Gregson[1]	US Geological Survey, California Water Science Center
Holly A. Bowers[1]	Moss Landing Marine Laboratories
Maggie Broadwater[2]	National Oceanic and Atmospheric Administration
Lesley D'Anglada[1]	US Environmental Protection Agency
Jonathan Deeds[1]	US Food and Drug Administration
Quay Dortch[1]	Consultant to CSS, Inc; contractor to NOAA National Centers for Coastal Ocean Science
Gregory Doucette[1]	National Oceanic and Atmospheric Administration
Leanne Flewelling[2]	Florida Fish and Wildlife Conservation Commission, Fish and Wildlife Research Institute
Rebecca Gorney[2]	New York State Department of Environmental Conservation
Jennifer Graham[1]	US Geological Survey, New York Water Science Center
Matthew Gribble[3]	University of Alabama at Birmingham
Ben Holcomb[2]	Utah Department of Environmental Quality
Miki Hondzo[3]	University of Minnesota
Meredith Howard[1]	Central Valley Regional Water Quality Control Board
Katherine Hubbard[2]	Florida Fish and Wildlife Conservation Commission
Sunny Jardine[2]	University of Washington
Di Jin[2]	Woods Hole Oceanographic Institution
Barbara Kirkpatrick[1]	Texas A&M Gulf of Mexico Coastal Ocean Observing System
Raphael Kudela[1]	University of California at Santa Cruz
Gregg Langlois[2]	California Department of Public Health (retired)
Brian Lapointe[2]	Harbor Branch Oceanographic Institution
Sherry Larkin[2]	University of Florida

Dail Laughinghouse[3]	University of Florida/Institute of Food and Agricultural Sciences (IFAS)
Kathi Lefebvre[1]	NOAA Northwest Fisheries Science Center
Michael Lomas[2]	National Center for Marine Algae and Microbiota, Bigelow Laboratory for Ocean Sciences
Mandy Michalsen[3]	US Army Corps of Engineers
Stephanie Moore[1]	National Oceanic and Atmospheric Administration
David Nobles[2]	Culture Collection of Algae at the University of Texas, Austin
Tenaya Norris[2]	The Marine Mammal Center
Hans Paerl[3]	University of North Carolina at Chapel Hill
Michael Parsons[1]	Florida Gulf Coast University
Valerie Paul[3]	Smithsonian National Museum of Natural History
Melissa Peacock[3]	Northwest Indian College, Salish Sea Research Center
Kaytee Pokrzywinski[1]	NOAA National Centers for Coastal Ocean Science, and US Army Corps of Engineers
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APPENDIX II: SUMMARY LIST OF HAB RESEARCH PROGRAMS AND VARIOUS REPORTS PRODUCED

Establishment of Programs solely devoted to HAB Research and Response

- 1997 NOAA Ecology and Oceanography of Harmful Algal Blooms Program (ECOHAB)
- 2002 NOAA Monitoring and Event Response for Harmful Algal Blooms Program (MERHAB)
- 2003 NOAA HAB Event Response Program
- 2010 NOAA Prevention, Control, and Mitigation of HABs Program (PCMHAB)
- 2022 USACE Harmful Algal Bloom Demonstration Program

Reports Submitted to Congress

- 2000 National Assessment of Harmful Algal Blooms in U.S. Waters
- 2001 Prevention, Control, and Mitigation of Harmful Algal Blooms: A Research Plan
- 2007 National Assessment of Efforts to Predict and Respond to Harmful Algal Blooms in U.S. Waters
- 2008 Scientific Assessment of Marine Harmful Algal Blooms
- 2016 HABs and Hypoxia Comprehensive Research Plan and Action Strategy
- 2017 HABs and Hypoxia Great Lakes Research Plan and Action Strategy
- 2018 HABs and Hypoxia in the United States: An Interagency Progress and Implementation Report
- 2020 HABs and Hypoxia in the Great Lakes: An Interagency Progress and Implementation Report

HAB Federal Agency and Community Reports

- 1993 Marine Biotoxins and Harmful Algae: A National Plan
- 1995 The Ecology and Oceanography of Harmful Algal Blooms: A National Research Agenda
- 1996 Harmful Algal Blooms in Coastal Waters: Options for Prevention, Control, and Mitigation
- 1997 National HAB Research and Monitoring Strategy: An Initial Focus on *Pfiesteria*, Fish Lesions, Fish Kills and Public Health

- 2007 Proceedings of the Interagency, International Symposium on Cyanobacterial Harmful Algal Blooms (ISOC-HAB): State of the Science and Research Needs, also available as 2008 Cyanobacteria Harmful Algal Blooms: State of the Science and Research Needs
- 2008 Research, Development, Demonstration, and Technology Transfer National Workshop Report: A Plan for Reducing HABs and HAB Impacts
- 2020 Framework for the National Harmful Algal Bloom Observing Network: A Workshop Report
- 2020 Harmful Algal Blooms and Ocean Acidification Workshop: Defining a Research Agenda
- 2021 Proceedings of the Workshop on the Socio-economic Effects of Harmful Algal Blooms in the United States
- 2021 Implementation Strategy for a National Harmful Algal Bloom Observing Network (NHABON)
- 2021 Cyanobacteria harmful algal blooms (HABs) and US Army Engineer Research and Development Center (ERDC) : research and services
- 2021 Aligning research and monitoring priorities for benthic cyanobacteria and cyanotoxins: a workshop summary

Back cover photo: Dense euglenoid bloom in 2015 off the coast of Santa Monica, California. *Photo credit: LA city sanitation staffer.*

For additional copies or information, please contact
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