WORKSHOP ON THE SOCIO-ECONOMIC EFFECTS OF MARINE AND FRESH WATER HARMFUL ALGAL BLOOMS IN THE UNITED STATES

PROCEEDINGS AND RECOMMENDATIONS FOR AN ASSESSMENT FRAMEWORK AND RESEARCH AGENDA
JULY 27 TO AUGUST 5, 2020

U.S. NATIONAL OFFICE FOR HARMFUL ALGAL BLOOMS

Proceedings of the Workshop on the Socio-economic Effects of Harmful Algal Blooms in the United States

U.S. National Office for Harmful Algal Blooms
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The views expressed in these proceedings are those of participating scientists under their responsibilities.

Front cover:

Image of western Lake Erie taken with the Landsat-8 satellite on September 26, 2017. (Credit: NOAA/NCCOS). In late September, the Lake Erie cyanobacteria bloom was reported in the Maumee River in Toledo, Ohio. It was unusual for such a bloom to intensify so late into September and the bloom rarely enters the Maumee River. Historical satellite data, used in monitoring and forecasting harmful algal blooms, assisted NOAA scientists in accurately predicting this bloom two months ahead of its occurrence in July 2017. During the week following September 20, 2017, the bloom covered an area of 1000 square miles from Toledo to the Ontario coast, reaching the mouth of the Detroit River, making it one of the four largest on record since 2002. Concentrations of the cyanotoxin microcystins, produced by cyanobacterium *Microcystis*, prompted the county health departments to issue a recreational public health advisory. These actions helped safeguard a popular rowing regatta and supported monitoring of the Lake Erie central basin to protect the drinking water supply for almost 3 million people in the region. Three years earlier (August 2014), Toledo was forced to shut down its water system for half a million residents for two days after bloom waters entered its intake pipes.

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Marc Suddleson (NOAA) and Porter Hoagland (WHOI), Workshop Co-Chairs[1]

[July 27 to August 5, 2020]

Summary

The US National Office for Harmful Algal Blooms at the Woods Hole Oceanographic Institution (WHOI) and the NOAA National Centers for Coastal Ocean Science (NCCOS) held a virtual workshop comprising four sessions between July 27 and August 5, 2020. This report summarizes the workshop proceedings and presents recommendations developed by participants during the discussion. The recommendations advance an assessment framework and a national research agenda that will lead to comprehensive evaluations of the socio-economic effects of harmful algal blooms (HABs) in fresh water (primarily the Great Lakes) and marine waters of the United States.

The Workshop participants 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 socio-economic effects of HABs.

Introduction

Harmful algal blooms (HABs) can lead to significant negative socio-economic consequences (Hoagland *et al.* 2002; Adams *et al.* 2018; Jin *et al.* 2020). Adverse effects include losses of commercial fish harvests and recreational fishing opportunities and catches, costs of healthcare to treat human illnesses, especially shellfish poisoning and

1 The Co-Chairs are indebted to the members of the Workshop Planning Team including: Dr. Don Anderson (WHOI); Dr. Maggie Broadwater (NOAA); Dr. Thomas Burke (Johns Hopkins U.); Dr. Timothy Davis (Bowling Green U.); Dr. Di Jin (WHOI); Dr. Sherry Larkin (U. of Florida), Dr. Frank Lupi (Michigan State U.), Dr. Stephanie Moore (NOAA); Dr. Carrie Pomeroy (UC Santa Cruz); Dr. Mary Kate Rogener (NOAA); and Mr. Chris Ellis (NOAA). The Team was instrumental in developing the workshop format, identifying participants and case studies, organizing the agenda, engaging during the Workshop, and contributing to the content of the recommendations and proceedings. The Team was also instrumental in reorienting from a traditional, in-person format to a virtual format in a relatively short period of time due to the COVID19 pandemic. The Co-chairs also acknowledge the significant efforts of Claire Anacreon, Dr. Mindy Richlen, and Victoria Uva from the US National Office for HABs at WHOI in providing both substantive content and technical assistance in organizing and running the workshop, designing the web page, and building the Zotero database. We also recognize the important contributions of Chris Ellis (NOAA), Shannan Lewinski (NOAA), and Dr. Felix Martinez (NCCOS) in facilitating and moderating Workshop discussions. The efforts of everyone were critical to success of the Workshop.

respiratory and neurological ailments, reductions in the welfare of coastal residents and visitors, reduced profits for local businesses, and a diminished sense-of-place in affected regions. These effects can be impactful to individuals, families, firms, or communities and persistent at local levels. They can also be measurable and significant at national or even international levels.

Interventions or responses can reduce HAB impacts, but they can be costly too. These interventions have been classified as methods to prevent, control, or mitigate HABs (also referred to as "PCM"). Preventive approaches such as reducing or eliminating anthropogenic nutrient inputs seek to avoid the occurrence of some blooms or to reduce their extent. Mitigation, including monitoring and forecasting, risk communication, or the provision of insurance, among other approaches, seeks to reduce HAB impacts on human health, living resources, and coastal economies. Control-type interventions include destroying HAB cells or breaking down toxins, physically removing HAB cells or their toxins from aquatic systems, or limiting the growth and proliferation of harmful algae. Although scientists have advanced some potentially promising control strategies, the challenges of demonstrating environmentally safe, cost-effective, and societally acceptable strategies have limited their implementation.

In the face of the wide array of hazards arising from HABs, policymakers, public health officials, and resource managers have sought to characterize their magnitude using a common metric. Fundamentally, decision makers would benefit from clear information not just about the damages from HABs—as measured by economic impact or degree of social disruption—but also about the costs of responding in ways that might lessen the hazard. Such "policy responses" can be conceptualized even more broadly than the PCM examples cited above, ranging from the conduct of basic scientific research or the physical modification of the environment *ex ante* to the avoidance of bloom areas or the treatment of medical conditions *ex post*. As an example, Fig. 1 depicts the kinds of actual and potential interventions and their timing with respect to blooms of *Karenia brevis* in the Gulf of Mexico.

EARLY STUDIES AND SOME HURDLES

Over the last three decades, a number of studies have attempted to describe the overall scale (size of impacts) and scope (distributions of impacts across individuals, firms, other groups, or communities) of the socio-economic effects of HABs in the United States (Anderson *et al.* 2000; Hoagland *et al.* 2002; Bauer *et al.* 2006; Hoagland and Scatasta 2006; Hoagland 2008; Ralston *et al.* 2011; Adams *et al.* 2018; Moore and Dortch 2019; Jin *et al.* 2020). These studies reviewed results from the extant published literature, which comprised a variety of methodologies and measures of impacts (e.g., Fig. 2 from Adams *et al.* 2018). Some also estimated the expected value of economic impacts based upon aggregations of relative frequencies of estimates over time (Anderson *et al.* 2000; Hoagland *et al.* 2002; Hoagland and Scatasta 2006; Adams *et al.* 2018). Following a "quick, but dirty" approach to estimating economic impacts (*cf.*, Leman and Nelson 1981), these earlier studies described crude national estimates of the economic effects of HABs on the order of 10^7-10^8 USD annually.

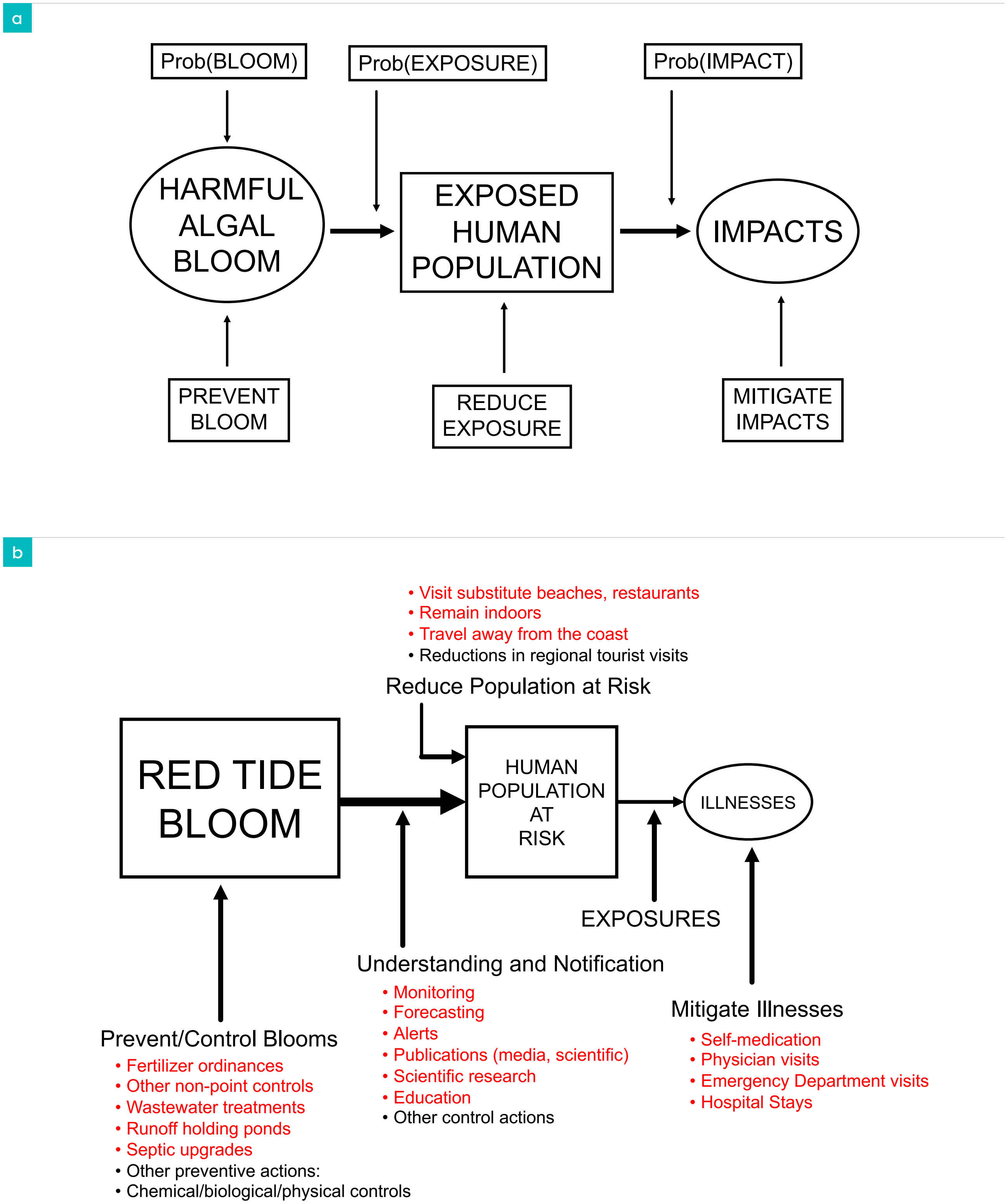

FIG. 1: Potential policy responses to *Karenia brevis* blooms in the Gulf of Mexico: (a) intervention points; (b) some specific examples of interventions. The notation Prob in panel (a) implies that the occurrence of blooms, exposures, or impacts are uncertain; with enough evidence, they may be estimated by probabilities (Pr) of occurrence. Given this uncertainty, the effectiveness of some policy interventions to reduce blooms, exposures, or impacts may be difficult to determine. The red print indicates approaches that have been put in place to prevent, control, or mitigate *Karenia brevis* blooms. Source: Hoagland (2014; Fig. 12).

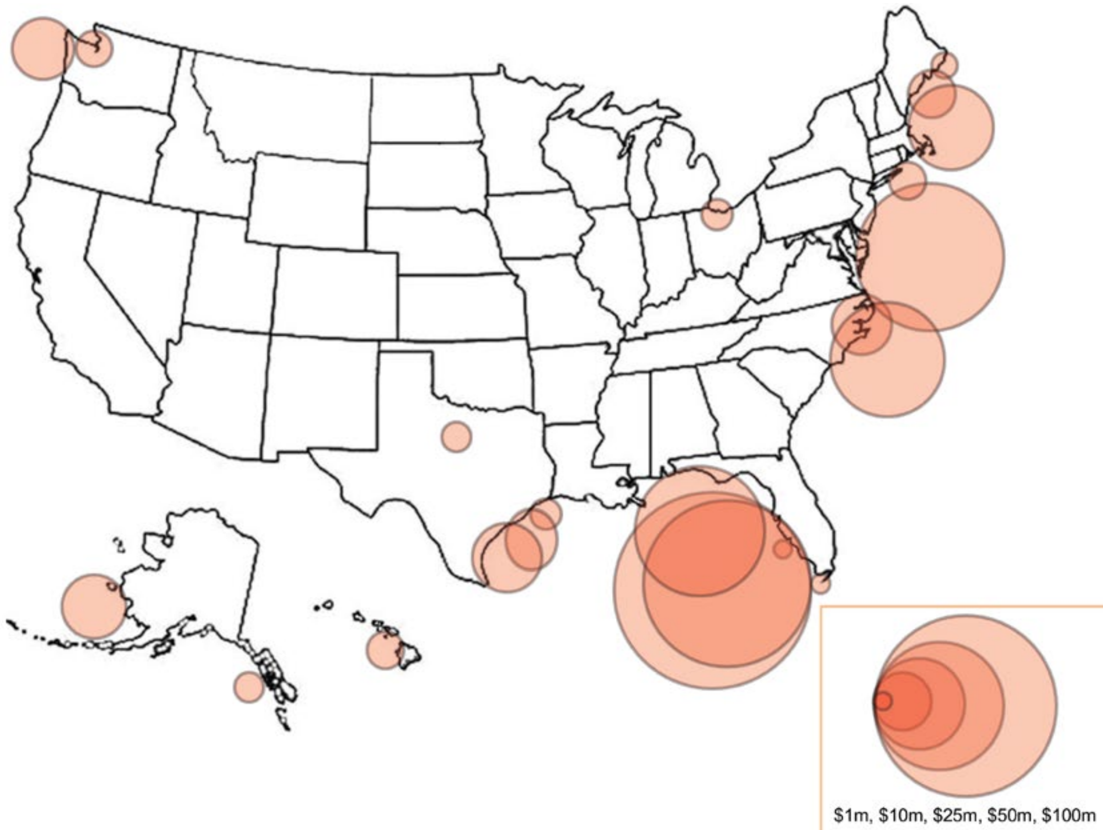

FIG. 2: Some selected historical examples of HABs in the United States for which economic impacts (2015 $m) have been estimated, showing the large range in scales of potential economic impacts. The circles represent estimates of economic (not spatial) scales at different points in time, beginning in the 1970s. Circle size is proportional to estimated economic impact. The maps of Alaska and Hawaii are not drawn to scale (but the circles are comparable). Source: Adams *et al*. (2018). Reprinted with permission.

The hope has always been that the undeniably rough methods used to develop such a national estimate might be refined and made more precise over time. For a number of reasons, however, arriving at a single annual estimate of these effects for the nation has been problematic (Hoagland *et al*. 2002; Adams *et al*. 2018). These problems depend upon the disparate physical characteristics of HABs, including their varying spatial scales, durations, movements and spread, and levels of toxicity (Anderson *et al*. 2000). Further, different algal species produce toxins with different types of effects on humans, marine animals, and the ecosystems they inhabit (HARRNESS 2005). These disparities contribute to inconsistent, uncoordinated, or non-existent reporting mechanisms and a resulting lack of available data on HAB effects. Further, the diversity of human contexts, including values, vulnerabilities, and feasible responses and adaptive capacities of individuals, families, and communities pose challenges to such endeavors.

Importantly, human exposures to HAB toxins can occur in a variety of ways that depend upon how coastal, marine, or freshwater environments are used or enjoyed in any specific location. These exposures can be context- or species-dependent, occurring through the consumption of shellfish or finfish or by drinking water, through contact with bare skin, or by breathing aerosols. Further, when humans intervene to mitigate exposures to HAB toxins, the responses themselves can be costly—either in terms of the direct cost of the intervention (such as through the operation of an environmental monitoring or forecasting program), lost commercial or recreational opportunities (such as through a fishery closure, delayed opening, or abridged season), individual avoidance behavior (*e.g.*, Morgan *et al*. 2009), or unintended consequences (such as spatial or temporal shifts in fishing activity resulting in increased interactions with protected species).

As is the case with other types of natural hazards, including tropical cyclones, floods, earthquakes, forest fires, and tornadoes, the irregular occurrence of many HABs means that estimates of socio-economic effects at any location or time can be highly uncertain. In particular, individual small events may not be evaluated at all. The absence of baseline data on human uses renders problematic the assessment of lost surpluses or economic or community impacts. Further, some individual HAB events can lead to very large effects, and such events have tended to drive the national estimate in any particular year or even when averaged over several years. For example, one of the most costly events (measured in direct economic impacts) occurred nearly 50 years ago in Florida (Habas and Gilbert 1974).

Natural scientists now suggest that HAB events are increasing in frequency and magnitude. Increasing flows of anthropogenic nutrient releases, leading to the build up of nutrients in aquatic environments, and the effects of climate change on coastal ocean environments are seen as common causes, though a major factor has simply been a discovery of the true, historical nature of the national HAB problem, long obscured by inadequate monitoring (Anderson *et al*. in press). Uncertainty over event occurrence and bloom characteristics has led to the development of regional HAB forecasting frameworks, and these approaches now are being analyzed to estimate the economic value of improvements in HAB prediction skill (*e.g.*, Jin and Hoagland 2008; Jin *et al*. 2020).

Socio-Economic Research Approaches

Social scientists have applied a wide range of analytical approaches to estimate the size and scale of the socio-economic effects of natural hazards like HABs. These methods have yielded new insights into the changes and impacts wrought by HABs, but variation across methodological approaches means that their results may not be strictly additive. For example:

- Sociologists and anthropologists have utilized qualitative descriptions, statistical demographic methods, or interviews based upon local ecological knowledge (LEK), such as those embodied in rapid ethnographic assessments (REAs), to characterize the effects on communities and the vulnerability or resilience of individuals or larger groups (e.g., Ritzman *et al*. 2018; Karnauskas *et al*. 2019).

- Economists have employed quantitative analytical approaches to estimate changes in consumer or producer surpluses (net economic benefits) in established markets, such as seafood markets, real estate, or coastal tourist industries, or where markets do not exist, such as for recreation or the passive appreciation of nature (e.g., Kahn and Rockel 1988; Wessells *et al*. 1995; Whitehead *et al*. 2003; Parsons *et al*. 2006; Bingham *et al*. 2015; Alvarez *et al*. 2019).

- Economists also have applied methods to account for industrial linkages and changes in the values of product flows, but these so-called regional economic impact approaches (comprising estimates generated by input-output [IO] models) measure changes in gross revenues or income (direct, indirect, or induced output impacts) and the strength of inter-industry connections that differ markedly from measures of surplus changes (e.g., Dodds *et al*. 2008; Dyson and Huppert 2009).

- In public health contexts, such as is the case for many HABs, policy analysts have developed estimates of the cost-of-illness that depend upon lost incomes or the costs of emergency care or hospitalization (e.g., Hoagland *et al.* 2009, 2014). These differ too from measures of surplus changes or output impacts, and they tend to omit estimates of the difficult to measure losses due to pain and suffering when HAB-related illnesses occur.
- Other analytical approaches have involved estimates of the value of scientific information or predictions, the costs of inadequate risk communication, or changes in summary indicators, such as market prices (Jin *et al.* 2008; Jin and Hoagland 2008; Bauer *et al.* 2009; Jardine *et al.* 2020).

While there can be synergies in using multiple socio-economic research methods to characterize the effects of HABs (Bauer *et al.* 2009), some methods can be costly to implement, straining the resources of relevant agencies or interested stakeholders. Such situations may require a regional or national approach to the problem.

Importantly, the application of any particular approach or set of approaches will depend upon the nature of the human context affected by HABs, the availability of relevant data, the technical capabilities and intellectual interests of the analysts, and the financial resources available to undertake a study. Consequently, not only do HAB events occur irregularly, but the conduct of a study of the socio-economic effects in any particular case is not assured, and any measurement of effects is not guaranteed to be commensurate with the measurement of effects from other studies.

These concerns motivated the convening of a national workshop on the socio-economic effects of HABs, supported by the US National HAB Office at the Woods Hole Oceanographic Institution, sponsored by NOAA's NCCOS, and held virtually over two weeks during July-August 2020. This report summarizes the meeting proceedings and presents a set of recommendations concerning the establishment of an institutional ("assessment") framework and development of a socio-economic research agenda.

EXTANT RESEARCH SUPPORT

NCCOS has supported economic research on HABs via competitive HAB research funding programs, specifically through the Prevention, Control, and Mitigation of Harmful Algal Blooms (PCMHAB) and Ecology and Oceanography of Harmful Algal Bloom (ECOHAB) programs, but this support has had limited success to date in stimulating the many high quality proposals needed to obtain better regional and national estimates for several reasons:

- Federal funding opportunities requesting socio-economic research have been very general; the lack of specificity has led to proposals that did not necessarily address needs for damage estimates or social impacts;
- The availability of funding was not communicated well to the larger economic or social science research community;
- Few social scientists had an interest in or knowledge of HAB events and their impacts; and
- Proposals received did not demonstrate effective integration of social scientists into interdisciplinary project teams.

NCCOS has begun to execute a strategy that will lead to a better assessment of the national economic and social impacts from HABs. This strategy includes support for a series of high quality competitive research studies that would begin to provide the necessary building blocks for an updated national assessment. As part of this strategy, NCCOS engaged the

US National Office for HABs to convene a workshop with the purpose of developing an assessment framework for a national research agenda that would lead to comprehensive evaluations of the social and economic effects of HABs in the Great Lakes and marine waters of the United States, including the costs of responding to and mitigating those effects.

Recent NCCOS competitive research investments in HAB socio-economics focus on specific species, impacted sectors, and the costs and benefits of mitigation strategies in specific regions. These efforts include:

- NCCOS and its partner, Gulf of Mexico Coastal Ocean Observing System (GCOOS)—a regional component of the US Integrated Ocean Observing System (IOOS)—funded two studies (see Appendix 4) in Fiscal Year 2019 designed to estimate the costs of the 2017-2019 Florida red tide event across numerous sectors, ranging from tourism to seafood to industries where impacts are less visible, such as healthcare and construction. These two-year projects will evaluate the socio-economic impacts of this extensive event, and will develop a framework to inform future socio-economic assessments of HAB events.
- The NCCOS PCMHAB program supports socio-economic research to assess the societal impacts of HAB events and the costs and benefits of mitigation strategies. Apparent recent increases in number, frequency, and types of HABs have heightened concerns about the safety of seafood, drinking water, the health of endangered species, fish, and other animals, the sustainability of coastal communities, aquaculture enterprises, constraints on state and local financial resources, and long-term aquatic ecosystem changes. In Fiscal Year 2020, NCCOS has funded PCMHAB socio-economic projects (see Appendix 4) that investigate the economic impacts of HABs in the Caribbean and the Pacific Northwest.

COMPLEMENTARY EFFORTS

Two additional complementary efforts are a recent international workshop that focused on the economic impacts of HABs on wild and farmed fisheries, and an initiative to update a US HAB response and research strategic decadal plan. These efforts are briefly described here:

PICES 2019: In October 2019, international experts on the economics and science of marine HABs convened to discuss case studies focused on characterizing the economic impacts of HABs on both farm-raised salmon and shellfish operations, wild-caught and reef-based commercial fisheries, and recreational fisheries (Trainer (ed.) 2020). Participants discussed the net impacts of HABs, their costs, and the resilience of commercial fisheries to a subset of HABs across the world. Five white papers were produced that documented case studies and made recommendations for: *Pseudo-nitzschia* blooms on the US west coast and impacts of that algal bloom on shellfish and marine mammals; impacts of *Margalefidinium polykrikoides* on wild and aquacultured fish kills in the Republic of Korea; ciguatera poisoning (CP) impacts on tropical or subtropical islands; fish aquaculture in the European Union, Canada and Chile; and shellfish aquaculture losses. A peer-reviewed summary report titled, "GlobalHAB. Evaluating, Reducing and Mitigating the Cost of Harmful Algal Blooms: A Compendium of Case Studies," can be found on the North Pacific Marine Science Organization (PICES Report No. 59) and Global Harmful Algal Blooms Program (GlobalHAB) websites. The report provides examples to guide future research on the economic impacts of HABs on fisheries. A related publication (PICES Report No. 47) can also be found on the PICES website. Members of the HAB Socio-economics Planning Committee also assisted with planning the PICES workshop. These connections enabled the sharing of ideas and findings across agencies and among stakeholders.

HARRNESS Update 2020: The US HAB community, with leadership from the National HAB Committee, is updating the 2005 Harmful Algal Research & Response National Environmental Science Strategy (HARRNESS) report. HARRNESS was a decadal plan (2005-2015) designed to facilitate coordination of national, regional, state and local HAB research and management activities by identifying priority needs within several focus areas and suggesting strategies to address them. A subsequent plan, the Harmful Algal Bloom Research, Development, Demonstration, & Technology Transfer (HAB RDDTT) put forth programs and initiatives centered around the HARRNESS recommendations (Prevention, Control, Mitigation; Event Response; Core Infrastructure).

The effort to review and update these reports will identify new research and management priorities. It will also focus on addressing underdeveloped research topics such as social and economic research to understand HAB impacts on individuals, communities, and society. Workshop findings will help inform the HARRNESS Update and may encourage greater investments in social sciences across the HAB community.

Workshop Overview

The US National Office for Harmful Algae at the Woods Hole Oceanographic Institution and the NOAA National Centers for Coastal Ocean Science (NCCOS) held a virtual online workshop in four sessions between July 27, 2020 and August 5, 2020. The aim was to develop an assessment framework for a national research agenda that would lead to comprehensive evaluations of the social and economic effects of HABs in fresh and marine waters of the United States, including the costs of responding to and mitigating those effects.

The workshop was held virtually over four half-day sessions (See Appendix 3 for the agenda and Appendix 2 for a list of participants). Day 1 (July 27), featured presentations on marine and freshwater HABs, basic economic and social science principles, and relevant methodologies. This provided a baseline understanding for the 40 participants comprising largely university and federal economists and social scientists representing a range of institutions, agencies, and US regions. Day 2 (July 29), provided an opportunity for in-depth breakout discussions focused on five regions that experience significant HAB impacts on a regular basis. Topics discussed were the socio-economic impacts of dominant toxic HAB species, responses to prevent, control, or mitigate these HABs, and information gaps hampering impact estimates or evaluation of the benefits of responses. The case studies focused on the following regions and dominant HAB species:

- Great Lakes – cyanobacteria species (blue-green algae)
- Gulf of Maine - *Alexandrium* species
- Gulf of Mexico - *Karenia brevis*
- US West Coast - *Pseudo-nitzschia* species
- US Tropical regions - *Gambierdiscus* species (ciguatera)

To stimulate new approaches and to broaden the field, participants engaged in socio-economic research on other types of natural disasters (e.g., wildfires) as well as HABs were invited to attend. Further, the Planning Team sought to engage both established and early career scientists in the workshop, especially those likely to be actively engaged in HAB socio-economics research and interested in advancing the field. The Planning Team also tried to draw experts from each US region to better represent the range of US HAB issues and to engage social scientists from academia and government.

HAB Challenges and Needs

To help prepare the participants to engage in substantive discussions during breakouts, the first session featured a series of four presentations designed to raise the awareness of key HAB challenges from both natural and social science perspectives.

Two introductory talks by Dr. Quay Dortch and Dr. Timothy Davis provided natural science overviews of marine harmful algal blooms and cyanobacterial blooms, focusing on the distribution of algal species and causes and impacts of related bloom events. Presenters also broadly covered efforts to mitigate and control blooms and their impacts. The second set of talks by Dr. Michael Downs and Dr. Sunny Jardine provided overviews for non-social scientists of the nature of economic and social impact analyses, and discussed various methodological approaches to estimate HAB impacts.

Oral Presentations

***Many HABs, Many Impacts*: Dr. Quay Dortch** (Dortch Presentation)

HABs result from excessive numbers of a few algal or cyanobacterial species that are toxic to humans and/or other organisms or have other deleterious effects on ecosystems. All coastal areas and the Great Lakes experience HABs (Fig. 3a) and there have been many recent HAB events that received considerable press coverage (Fig. 3b). The five HABs considered at this workshop have diverse impacts through multiple mechanisms (Table 1).

HAB impacts can be reduced by prevention, control, and mitigation approaches. Prevention requires that bloom causes be known and amenable to manipulation. Freshwater blooms can often be attributed to nutrient enrichment, so reduction of nutrient runoff may be a successful prevention method. In contrast, eutrophication is the cause or a contributing factor for only some marine HABs. There are many methods for controlling freshwater HABs, although most are effective only on small scales. For marine HABs, the only methods in the late phases of development in the US are clay dispersal and taxa-specific algaecides. Clay dispersal is widely and effectively used in Asia. Most helpful for mitigating impacts are HAB prediction and monitoring, which can provide early warning and protect public health. Other mitigation approaches include public outreach and education.

Financial assistance to impacted communities has been provided through Small Business Administration loans and Congressional appropriations after NOAA declarations of Fisheries Failures. The Harmful Algal Bloom and Hypoxia Research and Control Act (HABHRCA) 2017/2019 mandates the declaration of HAB and Hypoxia Events of National Significance and funding for assessment and financial mitigation; NOAA and EPA are in the process of developing implementation policies.

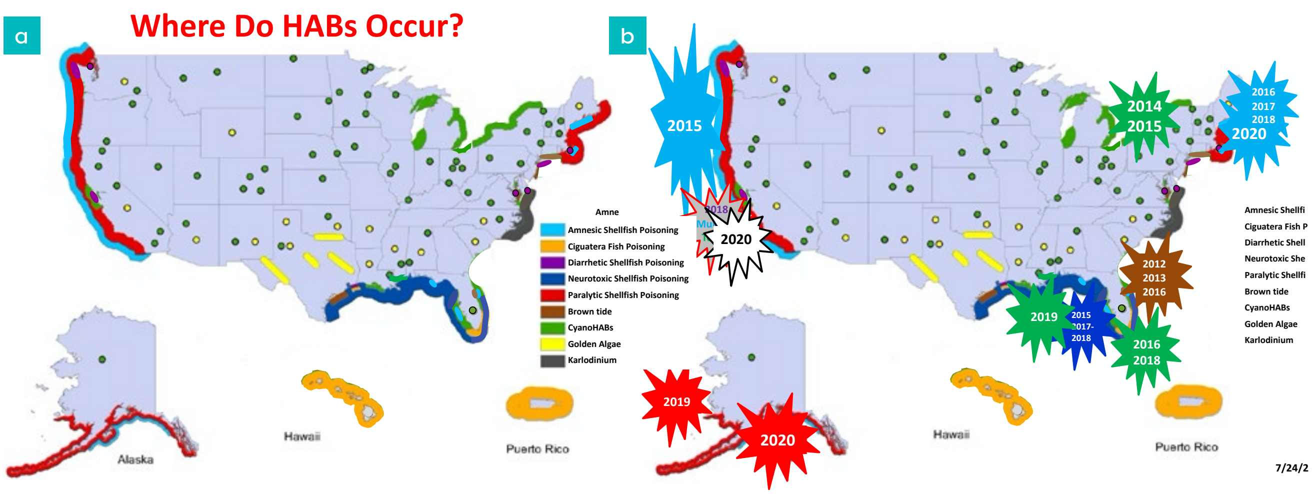

FIG. 3. Schematic maps of HAB occurrences in the U.S.: a) Ranges of common (not all) HABs. (b) Recent newsworthy HABs.

	Case Study	Syndrome	Acute Extreme Symptoms	Other US Locations	Taxa	Toxins	Routes Human Exposure					Animal Mortality	Other Ecosystem Impacts
							Shellfish	Fish	Aerosol	Drinking Water	Contact		
	Great Lakes		depends on toxins	Inland water bodies, low salinity estuaries	*Microcystis Dolichospermum Cylindrospermopsis* others	hepatoxins neurotoxins dermotoxins		Y?	Y?	**Y**	**Y**	Fish kills? Birds?	Hypoxia, water discoloration, taste & odor
	Gulf of Maine	Paralytic Shellfish Poisoning **PSP**	paralysis, death	AK, WA, OR CA, FL, NY	*Alexandrium catenella*, others	saxitoxins	**Y**					Marine mammals, birds, terrapins, fish	Water discoloration
	Gulf of Mexico	Neurotoxic Shellfish Poisoning **NSP**	respiratory illness, gastric distress, headache		*Karenia brevis*, others	brevetoxins	**Y**	Y?	**Y**			Marine mammals, birds, sea turtles, fish	Water discoloration, hypoxia
	US West Coast	Amnesic Shellfish Poisoning **ASP**	seizures, memory loss, death	Many	*Pseudo-nitzschia*	domoic acid	**Y**	Y?				Marine mammals, birds	
	US Tropical Areas	Ciguatera Poisoning **CP**	gastric distress, neurological dysfunction		*Gambierdiscus*	ciguatoxins	Y?	**Y**				?	

TABLE 1. Impacts of case study HABs events, indicated by colored shapes. More information about impacts of individual HABs. A ? indicates some evidence but more study needed.

In summary, harmful algal blooms encompass such a diverse array of ecologically and socially disruptive events that it makes generalizations about impacts difficult. Extreme HAB events, which recently have been occurring annually, prompt the greatest interest in economic impacts. Congress desires a single national estimate of the economic impact of HAB events without appreciating the complexity and lack of information, or considering the social impacts. The US does an excellent job of protecting consumers of commercial seafood from death and acute illness, but the impacts of long-term, low level exposure, especially to multiple toxins is unknown. The impacts of extreme events on coastal recreation, tourism and real estate values are mostly uncharacterized. Also, the focus has been primarily on HABs that impact human health, while other HABs, for example those that may impact aquaculture, have not been adequately recognized or investigated. At present, the options for mitigation are much greater than are those for either control or prevention.

CyanoHABS: A Global Problem with Regional Impacts: **Dr. Timothy Davis** (Davis Presentation)

Cyanobacteria, commonly referred to as blue-green algae, can grow to dense concentrations in fresh waters across the globe forming what are known as cyanobacterial harmful algal blooms (cyanoHABs). CyanoHABs are a visual manifestation of poor water quality caused by anthropogenic nutrient (nitrogen and phosphorus) pollution. Furthermore, many cyanoHABs can produce toxins that can sicken or kill humans, cattle, domestic pets, and marine mammals.

CyanoHABs occur in all 50 states and over the last decade have been increasing in prevalence across the country causing disruptions to drinking water supplies (Toledo, OH, 2014; Salem, OR, 2018) and causing other significant socio-economic impacts (Lake Okeechobee, FL 2016 and 2018; Gulf of Mexico/Lake Pontchartrain, LA, 2019). CyanoHABs occur in all five of the Laurentian Great Lakes but are most prevalent in western Lake Erie, Green Bay, Lake Michigan (WI), Saginaw Bay, Lake Huron (MI). Due to climate change, cyanoHABs in the Great Lakes and elsewhere will increase in intensity, duration and potentially have higher toxin concentrations.

Current in-lake control treatments and technologies are not economically feasible in large lakes (e.g. western Lake Erie), although they can be effective in smaller systems. As such, the only viable long-term management strategy, especially in large lakes, is to reduce the nitrogen and phosphorus loads entering from the surrounding watersheds. If the status-quo remains, future cyanoHABs will continue to cause significant socio-economic harm to communities across the country.

HABs Social Science Overview: **Dr. Michael Downs** (Downs Presentation)

Identifying and describing the potential impact pathways of HABs in communities is challenging, especially in real time, but there is an accessible body of existing work by social scientists engaged in research for the NOAA National Marine Fisheries Service (NMFS) and regional fishery management councils that can help inform this process. This existing work focuses on the engagement and dependency of fishing communities to foster management directed toward the sustained participation of those communities. Typically, impact pathways are described with respect to commercial, sport/charter, and subsistence fishing. In the commercial and sport/charter sectors, data gaps are common for vessel and processing crew members, fishing support service sector businesses, and markets. With subsistence fisheries, common data gaps include retention practices during commercial fishing activities, the use of "joint production platforms," and the sociocultural context and webs of relationships in subsistence resource harvesting, sharing, and use.

One continuing challenge is integrating human dimensions in marine ecosystem level analyses that are routinely useful at key points in ongoing fishery management decision-making processes and useful for the analysis of events such as HABs that are variable in their location, timing, intensity, and duration, if not their nature. Researchers in the North Pacific region are building out ecosystem and socio-economic profiles, creating a standardized framework that facilitates the integration of ecosystem and socio-economic factors within the stock assessment process. Key to this effort is a communications loop involving researchers and analysts across multiple disciplines involved in fishery management, stock assessment, and ecosystem/socio-economic assessment tasks that have overlapping ecosystems and human dimensions data needs. On the human dimensions side, vulnerability and resilience of communities in the context of adverse developments in the marine ecosystem depends in part on the nature of marine resource dependence and in part on the socio-cultural and socio-economic structure of the involved communities and nature of the web of human relationships within and across communities. The development of this type of information takes time but is critical for understanding the potential differential distribution of impacts. It is also critical for understanding how the cumulative impacts of adverse events (i.e. HABs) may challenge the sustained participation of a community in a marine resource related activity (i.e. commercial fishing).

Ultimately, social science research necessarily involves establishing and maintaining relationships between researchers and resource users. Fieldwork must also involve a two-way flow of information where information from researchers may help minimize adverse economic consequences of an event and local or traditional knowledge from those routinely on the water may provide insights useful for improving resource management. Fieldwork is resource intensive, both from a staffing and funding perspective, and producing the highest quality data depends on establishing trust, all of which is challenging in studying dynamic HAB events. On the other hand, HAB events have proven to be a valuable opportunity to conduct interdisciplinary fieldwork involving social and biological scientists that can improve analytic products in both areas and serve as a model for integration of analysis undertaken for ongoing management processes that, done well, allow a more agile and comprehensive response to acute adverse events.

The Economics of HABs: **Dr. Sunny Jardine** (Jardine Presentation)

HABs, and policies for managing HABs, can impact both the economic benefits and the economic costs associated with human use and appreciation of coastal and marine environments. Benefits are defined as the maximum amount that people are willing to pay for something. Costs are defined as the maximum value that people give up in order to have something. Consider the example of an oyster farm. The benefits include the maximum amount that consumers are willing to pay for the oysters. The costs include expenditures on labor and equipment but also on the other things that are given up, such as the foregone value of the farm owner's time.

Market demand represents consumers' maximum willingness to pay for each unit of a market good and market supply represents producers' cost of bringing each unit of the good to market. Thus, market demand and supply curves can be used to measure the economic value, or the net benefits, of a particular good that accrue to the consumers and producers of that good, i.e., consumer and producer surplus respectively.

One way to measure the economic impacts of HABs is to measure any changes in economic value (e.g. consumer and producer surpluses) caused by a HAB event. For example, in order to determine the impact of a HAB event on consumer and producer surpluses in the aquaculture industry, one must measure the economic value generated with the HAB event and compare this to the counterfactual of what the economic value would have been without the HAB event. Note that the economic value generated in a year preceding the HAB event is not necessarily a good counterfactual because factors that determine economic value, such as growing conditions and market demand, can change over time.

Cost-benefit analyses, based on the concept of economic value, can be used to evaluate the tradeoffs of adopting alternative strategies to manage HABs, or can be used retrospectively to evaluate the economic impacts of a management change. Economic impact analysis is another tool, which considers multiplier effects, but is not closely related to the concept of economic value. Whatever tool is used, it is important to construct a defensible counterfactual scenario of what would have happened without the HAB or the management change related to HABs.

Regional Case Studies

Workshop participants were assigned to one of the five regional case study teams led by at least one social science expert and one HAB expert from the HAB Socio-economics Planning Committee. To enable participants to focus their time on discussing social and economic aspects of each case study, information about each HAB species, its impacts, mitigation efforts, and any promising control methods was prepared and shared with participants in advance. These background materials and the expertise from the leaders of the breakout sessions provided workshop attendees sufficient information on bloom dynamics and impacts (e.g., public health, ecosystems, and socio-economics) to begin discussions on methods used to measure social and economic impacts of the specific bloom species in that region. These Bloom Characteristic and Impacts background documents can be found in Appendix I. Further, a simplified quick reference guide of impacts (Table 1) was provided to each case study team.

The following causal loop diagram (Fig. 4) demonstrating the links between the natural and socio-economic system was developed by the Planning Team and shared with case study teams as an optional aide to guide discussions.

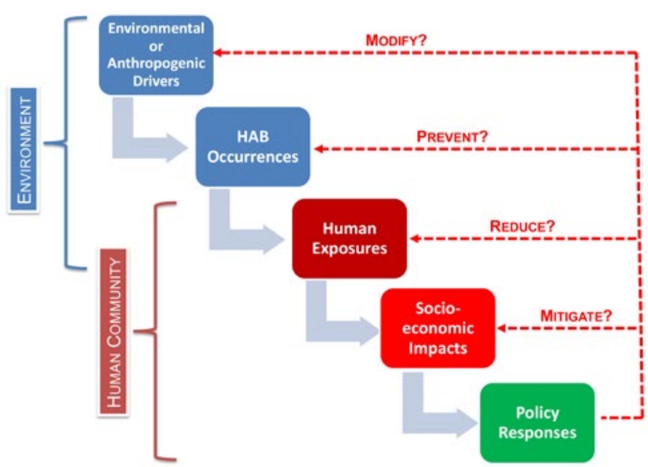

FIG. 4: Causal loop diagram illustrating the interactions between humans and the environment, including human exposures to impacts, assessments of socio-economic effects, and choices of policy responses. The latter feeds back at various points in the process.

The main focus of each case study was to discuss and capture information about each of the following four case study elements:

- **Social and economic consequences** of the HAB: impacts to human communities, firms, or individuals; social and economic structures and organization; quantitative or qualitative measures of impacts; and accounting stances. Identify who is impacted, how are they impacted, has it been measured, how was it measured, what data were used, what data are needed to evaluate direct impacts.
- Actual and potential **human responses** to prevent, control, or mitigate the HAB (costs of responses, including implications for communities, firms, or individuals). Has it been measured, how was it measured, what data were used, what data are needed to evaluate cost of responses. Where in the pathway do these measures take place (i.e., are they designed to prevent, control, or mitigate?), who implements them, how do you determine how effective they are (i.e., can you measure costs avoided?), who benefits?
- **Gaps in information** about the above elements.
- **Recommended methodological approaches and any relevant examples of** economic and social science assessment.

Each case study team lead reported out key points from their discussion during the plenary session on Day 3. Links to these plenary presentations can be found in Appendix I. Write-ups summarizing each breakout session findings are provided below.

Breakout Session Summaries

GREAT LAKES: CYANOBACTERIAL BLOOMS: DR. FRANK LUPI

Many species of cyanobacteria (blue-green algae) occur naturally in freshwater ponds, lakes, and rivers, estuarine environments, where fresh and salt waters mix, and in the ocean. In freshwater environments, the addition of nutrients (P or N) can cause cyanobacteria species to bloom excessively, and many of these blooms involve the production and release of toxins.

The Workshop's cyanobacterial blooms case study focused primarily on blooms in Lake Erie, one of the Laurentian Great Lakes, although the participants recognized that blooms of toxic cyanobacteria are an issue of widespread importance across the United States. In recent years, the city of Toledo, Ohio has experienced blooms of toxic cyanobacteria which resulted in temporary discontinuation of drinking water withdrawals from the lake or operation of special equipment for filtering the algae and toxins in order to continue withdrawals. Other adverse effects are felt in human uses, such as recreation, tourism, real estate values, and in nonmarket passive values, such as diminutions in individual or community sense-of-place.

Some of the key drivers of cyanobacterial blooms are environmental (high rainfall) and anthropogenic (agricultural nutrient loads). In particular, it is well-recognized that agricultural runoffs of dissolved reactive phosphorus drive bloom extent and runoffs (combined with atmospheric deposition) of nitrogen drive toxicity. Currently, it is possible to forecast P loads and bloom extent, but it is not yet possible to forecast N loads and bloom toxicity.

Human exposures to cyanobacterial toxins can be reduced by changes in human behavior, taken independently or when encouraged by management actions or required by regulation. The former occur when commercial or recreational users avoid Lake Erie or go to another beach (in an unaffected part of Lake Erie or on another lake). Consumers can also switch to drinking bottled water. Policies can include the issuance of beach warnings and changes to Toledo's water supply, the latter involving capital and operating costs.

Economic impacts from cyanobacterial blooms include increased costs of water supply, declines in property values along and near Lake Erie, reduced recreational experiences from beach going, boating, or fishing, and diminished coastal tourism more generally. Cyanobacterial blooms also can result in potential impacts to fish and aquatic ecosystems (e.g., reduced fish harvests from declines in fish stocks or changes in consumer demand). Further, there can be losses to businesses that are linked to tourist activity, recreational uses, and commercial fishing.

There exist potential impacts from cyanobacterial blooms to non-use values for Lake Erie, including social impacts and perceptions of unsafe water supplies. Among the former, freshwater HABs can lead to environmental injustices when communities experience varying levels of impacts or when communities have different capacities to respond to HAB events. Cyanobacterial blooms also can affect humans indirectly when their pets (dogs especially) become sick from drinking the water. Further, freshwater HABs can adversely affect a "sense of place" in and near Lake Erie. Finally, there may be as-yet-unknown impacts on mental health from either ingesting (through drinking the water or eating fish) or breathing aerosolized cyanobacterial toxins.

Policy responses to reduce the occurrence, extent, and toxicity of cyanobacterial HABs in Lake Erie comprise chiefly changes to agricultural nutrient loads.

There are two main categories of research gaps for Great Lakes cyanobacteria blooms. The first category includes natural science and social science questions relating to: bloom toxicity forecasting, the consequences of altering N loads, agricultural costs, and the effectiveness of policy responses. Some work has been focused on these questions, but more is needed. In particular, a deeper understanding of the economic drivers of agricultural nutrient uses, such as prices, costs, risks, constraints on labor or equipment, is critical. Research also is needed on taxing nutrients, soil testing requirements, legal liabilities, nutrient trading, best management practices, and targeting based upon loads or farmer attitudes. Other gaps include those relating to human attitudes, understanding of environmental impacts, and the scale of changes to recreational boating, which comprises about half of all boating on the Great Lakes.

A second category of research gaps comprise environmental justice issues. The central question is whether some groups may be disproportionately affected or less able to avert harm. While the direct effects of HAB toxins on human behavior and economic activity receive much attention, there are questions about whether blooms cause so-called "halo effects" (widespread effects on other sectors due to the miscommunication of risks) or other persistent effects. There may be key differences across communities in awareness or concern, and this may vary as a function of proximity to HAB events or to areas or sectors adversely affected by the events. Specifically, research is needed on how much tourism declines due to previous HABs or due to perceived HAB effects.

GULF OF MAINE: PSP (*ALEXANDRIUM CATENELLA*): DR. DI JIN AND DR. TIM HAAB

Discussions during the Gulf of Maine breakout session covered bloom characteristics, bloom impacts, current understanding of relevant social and economic consequences, and human responses, as detailed in Appendix I.

Existing economic studies on Gulf of Maine PSP blooms address only lost revenues in the commercial shellfishing industry using data on shellfish landings and closures as well as broader economic impacts associated with the lost revenues on regional economy using input-output models. Significant information gaps exist on social and economic consequences of HABs in the region. The group identified four specific areas:

1. There have been no social and economic studies of several economic sectors that are potentially affected by HABs, such as the growing shellfish aquaculture industry, recreational shellfishing activities, and coastal tourism.
2. There is a lack of understanding of the full range of behavioral changes that may occur during HAB events in different sectors and communities, and the resulting welfare changes. Studies utilizing potentially useful economic valuation methods (e.g., non-market valuation techniques) have not been developed in the region.
3. There has been no community impact study. HAB impacts on individual wellbeing and vulnerable social groups or communities have not been examined. Relevant community stories have not been documented by anthropological studies.
4. There has been no study to jointly assess the diversity and distribution of economic impacts across communities, demographic groups, regions, and policy interventions.

The group recognized:

1. The need to separate cases where retrospective studies are feasible vs. where Rapid Needs Assessments are essential during or right after a HAB event.
2. General surveys by a multidisciplinary group, including economists and anthropologists are desirable for case studies.
3. There are no significant anthropogenic causes for the blooms in the Gulf of Maine, and nutrient sources are all natural. Primary mitigation is through shellfish harvesting area closures and HAB forecasts. It is important to improve HAB forecast accuracy to help fishers cope with HABs and to allow for more selective and precise closures of shellfish beds, in time and space, to minimize damages.

GULF OF MEXICO: NSP (*KARENIA BREVIS*): DR. SHERRY LARKIN

Discussions during the Gulf of Mexico breakout session focused on categorizing the groups impacted and how they are impacted by *Karenia brevis*, which were broadly divided into two types of anthropogenic effects: economic and social. The underlying goal was to focus on studies and approaches that can be used to assess whether a HAB is a bloom of "national significance."

The economic impacts can be measured at three scales: individuals, businesses, and government. Impacts on individuals from red tides include losses to their "utility" such as impacts on health from poor air quality, reduced marine recreational activities, diminished aesthetics from discolored water, harm to pets/mammals, lost income and reduced property values (i.e., 'use' and 'non-use' economic values). Businesses and governments are affected similarly and that is by changes in revenues and costs as a result of a bloom (i.e., market information is used to estimate lower gross sales due to reduced coastal recreation that also reduces tax revenue, and there are expenses associated with removing dead fish from coastal waters). If the affected region is heavily dependent on tourism from outside the region, a formal economic impact analysis (e.g., IMPLAN or REMI) should be considered. A more cross-cutting issue is the effect on the labor market and particularly the service sector; acute and prolonged blooms such as was experienced in Southwest Florida throughout 2018 can result in job losses that reduce household income and the ability of businesses to maintain a workforce. A compounding factor is the uncertain effect on human health that discourages workers from returning to HAB-affected jobs. Unstable working conditions can also cause employees to move out of the area when blooms are prolonged, further compromising the coastal communities' ability to maintain economic activity.

Socio-economic impacts can be similarly categorized for purposes of measurement. At the most basic level, service sector employees can lose their jobs with ramifications for the housing and transportation sectors, as well as food security for the dependent families and communities. Since this type of impact may be unique to *Karenia brevis* blooms, it should be noted that it may not be an issue for other states or regions. Non-governmental organizations (NGOs) can help address the food security issue through organizing food banks, and perhaps mental health issues. As mentioned previously, governments must address unemployment and vulnerable communities while communities themselves must face ramifications for their identity and reputation that are dependent (in part) on fast-moving social media.

The group discussed new and ongoing research including studies that are using novel sources of secondary data aimed at estimating specific types of losses in well-defined regions. The group concluded that the key information gaps associated with red tide blooms in the Gulf of Mexico are: (1) the unknown value to the public of addressing red tide events (in total compared to other types of events and which type of impacts are the most important), (2) the undocumented social ramifications of HABs to individuals and communities, and (3) the role of social media (and communications in general) in both amplifying and mitigating economic and social losses caused by red tides.

As a result of these discussions, the group recognized that – as a premise – HABs are important to society, and will be more so as waterfront populations continue to grow; yet, the existing estimates of socio-economic impacts (especially economic effects) do not capture the value of addressing the issue because they were not intended to do so. The paucity of studies addressing the nation-wide relevance should not imply that such studies are not possible. As many group members have experience in using specific methodologies to estimate impacts commissioned by invested sponsors, there is interest in collaboration in order to jointly provide information that is useful to estimating nation-wide impacts (and GCOOS is interested in helping facilitate that interaction and goal). A few nuances of estimating socio-economic impacts of HABs were raised, including that:

- HABs share similarities in terms of estimating impacts with oil spills and natural disasters, with the possible exception that red tides can be prolonged (i.e., last more than a year). These include methods used, how impacts are messaged, and what funding is available.

- HABs are a water quality issue but the measure of impacts must net out or account for other factors that impair coastal waters in general. Similarly, there could be cumulative effects from different types of events (e.g., cyanoHABs, tropical storms and hurricanes).
- Estimates of impacts need to address the current actions (expenditures) being taken to prevent, control and mitigate blooms (i.e., account for the baseline).

As the overall goal of this workshop is to recommend approaches that would help develop more comprehensive estimates of HAB socio-economic impacts that are commensurate with the perceived cost to society of ongoing blooms, this workgroup recommended the following three-pronged research approach:

- Qualitative studies to identify key impacts (e.g., anthropology-driven topic-oriented focus groups to support a rank-ordering of impacts for use in quantitative assessments that follow);
- Quantitative studies, perhaps regionally by species, to obtain an estimate of the value of public concern for HABs (e.g., using stated preference/CVM of individuals on their willingness-to-pay), with the goal of showing the conservative level of national public expenditures that is justified; and
- Quantitative studies to obtain estimates of impact/cost/loss by bloom and sector (e.g., using revealed preference/secondary data, potentially incorporating stated preference methods) to help formulate local programs, response and policy).

This approach could be best depicted with a decision tree that includes methods and impacts measured, akin to a best practices document that can support the aggregation of loss estimates and avoid double counting. And once these values are estimated they need to be communicated effectively. User-friendly information tools and infographics should be pursued in common across HABs, including messaging, since communications can reduce risk of impacts (or at least mitigate some impacts). The group was sensitive to the use of or comparison with blooms being considered "natural" and or a "disaster" even though it could make federal funds available. The group also emphasized the ongoing need for studies on human health impacts (e.g., timely aerosol toxin forecasts), environmental data and associated bloom dynamics to learn the life cycle of a bloom that can hold the key to effective prevention, mitigation and or control measures. In sum, the group saw value and expressed interest in helping to foster communication among researchers to advance complementary analysis and raise the profile of ongoing efforts.

US WEST COAST: ASP/DA POISONING (*PSEUDO-NITZSCHIA SPECIES PLURALIS*): DR. CARRIE POMEROY

Domoic acid (DA)-producing *Pseudo-nitzschia* blooms primarily impact human communities by contaminating marine species commonly caught or cultivated and consumed by people. To protect public health, state agencies have implemented seafood consumption advisories and fishery season delays and/or closures. The measures taken appear to have been effective in mitigating acute exposure to DA and associated adverse health impacts, although timely and definitive detection of DA poisoning (i.e., amnesic shellfish poisoning (ASP)) is challenging for several reasons. Moreover, the efficacy of such measures for mitigating adverse health impacts of chronic, low-level exposure (e.g., through frequent consumption of shellfish with DA levels below the US Food and Drug Administration action level) is less clear. At the same time, the policy actions taken (seafood consumption advisories, fishery delays/closures) have economic, social, cultural and psychological consequences – as well as regulatory and management costs.

Group discussion addressed both the direct and indirect consequences of these HAB events which are influenced by feedbacks and interactions within and across parts of the human system, via policy responses/actions and "user" responses. Directly affected users include those engaged in or associated with commercial, recreational, and subsistence fisheries and aquaculture, with responses by and implications for individuals, households and communities (and extending to tourism and other activities).

To ground and guide relevant social science research, the group identified several general topics for investigation to provide a foundation for better understanding the social, cultural and economic consequences of HABs and inform policy responses to mitigate their adverse impacts. These include: 1) context, i.e., the environmental, social, economic and regulatory conditions and events in relevant sectors, activities and groups; 2) beliefs and perceptions; 3) social, cultural, economic and nutritional dependence on affected species; and 4) capacities of individuals, groups and communities to adapt to these events – and to policy actions taken to protect public health.

The group used an "ecosystem service endpoints" approach to identify and organize relevant topics for social science research, guided by the question, "What ecosystem services (provisioning, regulating, supporting, cultural) matter to various actors in the context of HABs?" The discussion then focused on understanding (the avoidance of) adverse health outcomes, not only from eating contaminated seafood but also from foregoing its nutritional value – and the health care costs of each. More directly related to fishery closures and advisories, the group highlighted needs for economic information such as lost income throughout the fishery system and lost consumer surplus, and social and cultural information such as lost fishing and seafood access (also an economic impact), diminished (or changes in) social, psychological and economic well-being, changes in social cohesion, and uncertainty, among others.

Group discussion also focused on the question of scale and scope of relevant research, from the individual to the community level on up, and including not only fishermen, growers (aquaculturists) and seafood consumers, but also fishery support businesses (provide inputs and/or handle outputs), families, households and larger kin groups; communities of interest and of place, socially/economically vulnerable and fishery-dependent populations; health care providers; resource, public health, coastal community/port infrastructure managers; and others indirectly affected by seafood supply and ecosystem health (e.g., tourists).

The group identified myriad social, cultural and economic data gaps and needs to assess the consequences of HABs per se and management responses. These include baseline data to characterize the importance of fisheries and seafood to people and communities, social networks (of catch, distribution, consumption; information sharing and use) and sources of livelihood and well-being. Information also is needed on how people perceive, understand and act (or not) on advisories and trust (or not) in government policy. More information also is needed on the health, social, cultural economic impacts of management decisions, including temporal/spatial shifts in activity and access due to HABs and policy responses, and the distributional impacts of and trade-offs among policy options.

A variety of methodological approaches was suggested for addressing these information gaps, each with its particular applications, strengths and limitations for addressing the information needs highlighted. Methods suggested for economic analysis included cost-benefit analysis, input-output analysis, computable general equilibrium models, and the use of choice experiments to measure non-market value and responses to information. To address social, cultural and some economic information needs, especially acute or immediate term needs, rapid assessment process or rapid appraisal (participatory/ collaborative research) can be used. These are especially useful for characterizing the human (and social ecological) system, identifying variables and relationships for assessment, and identifying valued ecosystem services and viable policy options. Focused studies (e.g., surveys, focus groups) can be used to evaluate perceptions, valuation, and use of information to minimize risk of exposure to toxins. Comparative qualitative and/or quantitative assessment of social and economic impacts and trade-offs among policy scenarios at varying scale and scope also was suggested.

US TROPICAL AREAS: CIGUATERA POISONING (CP): DR. MINDY RICHLEN AND DR. PORTER HOAGLAND

Ciguatera is a poisoning syndrome ("CP") caused by human consumption of fish or shellfish associated with coral reef systems that are contaminated with one or more of a suite of toxins known as ciguatoxins, which are produced by certain microalgal (dinoflagellate) species in the genus *Gambierdiscus*. Symptoms of ciguatera can be debilitating, and include gastrointestinal, cardiovascular, and neurological disturbances, the latter of which may last from days to years. Medical diagnosis is based on the recent seafood-eating history of the patient(s), clinical presentation, and, if possible, results from analytical testing of meal remnants. There is no cure for CP, and treatment is supportive in nature.

The socio-economic and human health impacts of ciguatera are expanding globally, due to the spread of *Gambierdiscus* into temperate and non-endemic areas (e.g., the northern Gulf of Mexico, West African coastal waters, the Eastern Mediterranean Sea) and increased international trade in seafood. Global expansion may be fostered also by ocean warming, expanding the geographic range of *Gambierdiscus* spp. beyond tropical locations. In the United States, range expansion could mean an increased incidence of CP in Florida and in the northern Gulf of Mexico.

Group discussion of the CP case study focused on reviewing the **social and economic consequences** of ciguatera, identifying **actual and potential human responses** to prevent, control, or mitigate illness, describing **challenges or information gaps** unique to ciguatera that hinder economic and social science assessments, and **recommending methodological approaches** for producing better assessments of the costs and social impacts of this HAB syndrome to economies and communities. Brief summaries of these discussions are summarized below.

Social and economic consequences: Ciguatera differs from other HABs in that outbreaks are not associated with planktonic blooms, but are often an ongoing and chronic problem in endemic regions. Consequences of ciguatera outbreaks include economic losses associated with health impacts due to seafood consumption, which include costs associated with acute poisoning (e.g., medical treatments, lost wages) and chronic recurrence of symptoms. Local tourism losses occur as a consequence of the public reporting of an outbreak, including revenue lost by hotels, charter fishing operations, and other downstream impacts, including negative impacts to the "destination image" of a particular location. Examples of estimated socioeconomic impacts associated with CP can be found in Appendix I, Table A1.

There are economic impacts to commercial fishers, which can include net revenues if hotels and consumers avoid purchasing reef seafood or proximate shellfish due to the perception of risk. Additional costs can be associated with the avoidance of fishing in identified hotspots, resulting in additional time and expenses associated with changing fishing locations (e.g., extra fuel). Economic impacts to subsistence fishers are associated with dietary shifts (avoidance of a readily accessible protein source), which can include the nutritional consequences of dietary shifts.

Lawsuits brought by seafood consumers who have suffered from CP can affect fishers, restaurants, hotels, and other market participants comprising the relevant seafood supply chains. There are also social impacts to subsistence fishing communities to whom local fishing is culturally important and disruption of other forms of the social capital associated with seafood production in remote communities or developing economies.

Potential human responses: Potential responses include a variety of approaches encompassing actions taken at the ecosystem level to utilization of existing public health channels. At the ecosystem level, local ecological knowledge (LEK) held by fishing communities can result in an informal type of "closure," in which high risk locations are avoided by subsistence, artisanal, or commercial fishers. Switching from an informal LEK-based areas-to-be-avoided approach to more formal fishery regulations comprising closures would incur costs associated with testing and implementation. Such shifts could be evaluated through cost-benefit analyses, and would likely be dependent on the availability of cost-effective analytical approaches to toxin screening (see below). LEK relating to seafood consumption may contribute to the mitigation of CP, but effectiveness likely varies across different communities comprising varying cultural preferences.

Coral reef conservation and promotion of reef health could help to prevent ciguatera risk by preventing coral dominated reefs from transitioning to algal dominated reefs (thus providing habitat for toxin-producing *Gambierdiscus*). The benefits of improved reef conservation could be integrated into ecosystem assessments and associated models.

Technological breakthroughs leading to the development of rapid ciguatoxin assays for screening seafood in the field would expand existing capacities for monitoring and testing. This is a critical step in preventing CP and its impacts. In addition, improving messaging to communicate seafood consumption risks and increasing the utilization of poison control hotlines could mitigate the miscommunication of risks. Risk communication could comprise multiple formats, including online media, social networks, and messaging through restaurants (e.g., placemat communications), hotels, airports, cruise ships, etc.

Challenges or information gaps: Further assessment of human health impacts from *chronic low-level* cumulative exposure issues and *long-term* impacts from acute or chronic exposure is needed. Studies of the economic costs of health impacts over and above "cost-of-illness" approaches are also required (such as impacts to the quality of life). Economic willingness-to-pay (WTP) for safe seafood consumption and benefits from the safe production of seafood needs to be quantified. Further study of the economic consequences to commercial and subsistence fishers of informal or formal management responses, such as restrictions on certain species, size limits, or even losses of fishing grounds is needed.

Additionally, there is a need for evaluation of the effectiveness of LEK or other cognitive constructs for impacted local communities. Further assessments of the net benefits of implementing new programs for formal monitoring, testing, and closure of fishing locations in comparison with the less formal status quo would allow communities to make more informed policy decisions. The lack of assessments of the economic value of information to reduce uncertainty about the prevalence of ciguatoxins in the environment and their uptake by marine animals, incidence of CP and treatment of illnesses, and effective responses to CP outbreaks is also a critical problem.

Finally, more complete spatial and temporal data is needed on ciguatera prevalence and incidence, especially in areas where CP is expected but does not commonly occur. Strategies to address this gap could include efforts to improve the reportability of illness and educating physicians on symptoms and context of exposure. The environmental drivers of CP also need to be better defined in order to identify management or mitigation actions.

Recommended methodological approaches include:

- Development of rapid and cost-effective toxin screening methods for testing seafood;
- Design of frameworks to improve CP illness reporting by physicians, including improved diagnoses and coding of cases;
- Implementation of experiments to assess the effectiveness of risk communication strategies and messaging;
- Applications of methods of network analysis to evaluate the pathways by which LEK responds to CP outbreaks;
- Implementation of reduced-form regression models to assess hurricane impacts on reef health and potential relationships to the spread of ciguatera;
- Evaluations of stated preference estimates for the willingness-to-pay for safe seafood consumption;
- Development of estimates of valuing information using preference structure models and survey data;
- Applications of rapid ethnographic assessments (REAs) of LEK.

In addition, the CP case study participants recommend development of:

- Qualitative cognitive construct models to understand impacts on markets and other institutions;
- Estimates of the economic losses due to mortalities or morbidities (applying innovative methods for the value of a statistical life or quality adjusted life-years [QALYs]);
- Estimates of the increased costs to seafood producers of displacement from traditionally productive fishing areas; and
- Applications of cost-benefit analyses for assessing the net benefits or cost-effectiveness of alternative ways to mitigate CP exposures.

Workshop Recommendations

After a first round of plenary discussions, consensus recommendations were captured and grouped into two main types: a Socio-Economic Assessment Framework and a Socio-Economic Research Agenda. Recommendations across both types were regrouped, and further refined in a second round of plenary discussions. The Workshop participants recognized that many of these recommendations would need further elaboration as academics, managers, funding agencies, and stakeholders interested in HAB issues (aka, the US HAB Community) advance their implementation. The following briefly describes each set of recommendations and how they relate to each other.

The first set of recommendations relating to a Socio-Economic Assessment Framework constitute institutional arrangements deemed necessary to implement the more specific socio-economic research approaches in the second set. Among these arrangements were recommendations to enhance interagency coordination; adopt modern electronic approaches for communication; establish formal networks to enable interdisciplinary research coordination; formalize regional HAB monitoring, forecasting, and socio-economic impact assessments; construct open-access databases comprising data on socio-economic baselines and departures from baselines; implement rapid response studies of HAB impacts and policy interventions; improve the national reporting of HAB-related public health outcomes; develop medical curricula to raise the visibility of HAB illnesses; explore and foster the use of local ecological knowledge concerning HAB responses; engage citizens in participatory action research; and establish graduate student fellowships focused on HAB socio-economics research questions and needs.

The second set of recommendations constitute the necessary elements of a Socio-Economic Research Agenda. The Workshop expert participants engaged in discussion about the relevance and need for a national estimate of the economic damages associated with occurrences of HABs. (This discussion has been summarized in part in the introduction to this report). It was recognized by the expert participants that such an estimate should consider both the losses associated with HABs and the costs of responding to them in order to mitigate the losses. One suggested approach to a national estimate would entail the fielding of regional (or local) stated preference surveys to assess HAB losses associated with different types of toxins, affecting different categories of human uses, and occurring in different locations. These survey approaches would serve two purposes: first, they would be designed to be utilized in other HAB contexts; namely, the methodology would be transferable. Second, estimates from these studies would constitute reference values that might subsequently serve as data for use in benefit transfers to assess losses from HAB events occurring in contexts that had not been studied specifically.

The first three Research Agenda recommendations pertain to the survey approach and to the transferability of survey methodologies and results. Other specific research recommendations include carrying out rapid ethnographic assessments and assessments of social impacts; designing and characterizing the existence of potential impact thresholds and their measurement and scale; sponsoring studies of the value of natural scientific research on HAB occurrences, including the ambient environmental conditions that lead to these occurrences; sponsoring research on policies that respond to HABs in ways that prevent, control, or mitigate the adverse effects on direct and passive human uses, including cost-benefit analyses comparing the implementation of such policies; sponsoring research on risk communication, the potential benefits of using social media, or novel electronic technologies for communicating risks or tracking the occurrence of events; and sponsoring research on the incidence, severity, and costs of human illnesses.

The following two sets of recommendations were agreed to by the Workshop participants. Although recommendations are numbered for easy reference, this ordering is not meant to imply any prioritization.

I. SOCIO-ECONOMIC ASSESSMENT FRAMEWORK

1. **Federal Agency Coordination**. Encourage coordination among the NOAA line offices (Chief Economist, NOS, NMFS, NWS, others) and across other federal agencies (EPA, USGS, USACE, CDC, USDA, FWS, NPS, OMB, others) on setting priorities for HAB economic and social science research and on the sponsorship of research, including the impacts of and responses to HABs in coastal and marine, Great Lakes, and inland, freshwater environments. To formalize this coordination, explore the potential for establishing a permanent Interagency Working Group on the Socio-economic Impacts of HABs and the drafting of interagency memoranda of understanding (MOUs). Cross-NOAA coordination might be achieved via the NOAA Social Science Committee or facilitated via the temporary HABHRCA Interagency Working Group.

2. **Research Communications**. Facilitate communications among economic and social science researchers working on HABs, including implementing innovative platforms for data file sharing and interactive communications, such as Slack, GitHub, Zotero, or others. Coordinate with existing platforms focusing on facilitating scientific communications concerning the natural science aspects of HABs, including those hosted through the US Office for National Harmful Algal Blooms, at the Woods Hole Oceanographic Institution.

3. **Research Coordination Networks**. Identify active socio-economic research groups at local or regional levels and establish a regional Research Coordination Network following the example of NSF's Dynamics of Integrated Socio-Environmental Systems (DISES) program to collaborate and conduct socio-economic research on HABs. Explore the potential for developing an interdisciplinary science team under the sponsorship of the National Socio-Environmental Synthesis Center (SESYNC). Encourage the participation of natural scientists who work on HABs in these research coordination networks. Consider organizing these networks under the umbrella of Sea Grant programs or consortia at the national, regional, or individual state levels.

4. **Regional Forecasts and Observations**. Develop and implement economic and social measures of the impacts of HAB events as components of existing and expanding regional forecasts and observing networks, such as estimates of public health benefits, reduced shellfish or fishery landings, lost resource rents in the fisheries, reductions in tourism or recreation, increased unemployment, changes to the tax base, increased community vulnerability, reduced community resilience, among others.

5. **Data Commons**. Establish a national (or regional) Data Commons for HAB baseline information, changes to baseline information as a consequence of HAB events, and the data and results of socio-economic research. Require primary data and research results from sponsored research to be entered into the Data Commons using consistent ways of presenting data and results. Explore a means for sustainable financial support for the Data Commons.

6. **Baseline Information**. Encourage the development of baseline information in local areas or regions where HABs have occurred. Encourage the development of innovative approaches to aggregate baseline data to the national level. Baseline information would comprise compilations of measures of environmental condition; measures of: human uses (residential housing, short-term property rentals, tourist visits, recreational uses, commercial, recreational or subsistence fishing, seafood supply chains and consumption; instances of animal illness (e.g. pets or livestock); estimates of passive values; governance of natural resources and hazards; individual, household, business, or community vulnerability and resilience; anthologies of local ecological knowl-

edge (LEK) and practices; and libraries of published (including grey and refereed) or unpublished, research efforts. Some relevant examples are provided in Table 2.

7. **Rapid Response Studies**. Develop and field stated preference surveys or revealed preference approaches to estimate the economic damages associated with HAB events in pre-selected "pocket" communities. Utilize benefits transfer approaches based upon the results in these studied areas to estimate damages in unstudied areas where blooms may occur irregularly or unexpectedly. Establish rapid-response funding for social science research, especially rapid ethnographic assessments (REAs), to characterize vulnerability, resilience, and adaptation to HAB impacts of individuals, businesses, and communities.

8. **Public Health Advances**. Engage health care communities, including state departments of health and physician groups, to improve medical curricula regarding HAB poisoning diagnoses and treatment. Encourage the national reporting of HAB-related illnesses to improve incidence estimates (OHHABS, NORS or CASPER).

9. **Local and Traditional Knowledge**. Engage local groups and communities in thinking about ways in which to incorporate local and traditional ecological and social knowledge into HAB monitoring, forecasting, risk communication, and adaptation.

10. **Citizen Science**. Engage citizens using "participatory action research (PAR)" approaches in local communities impacted by HABs. PAR approaches could utilize modern technologies (cell phones) or social media to identify bloom formation, scale the physical effects, characterize human health impacts, update and refine local ecological and social knowledge, and suggest ways of responding to bloom events. Communities could be linked to regional forecasting and monitoring efforts.

11. **Graduate Student Fellowships**: Establish graduate student fellowships for economic and social science research on HAB impacts and responses. Relevant examples include the NOAA Fisheries-Sea Grant Joint Fellowship and State Sea Grant Program Fellowships and the University of Florida's Water Institute

TABLE 2: Sources of baseline information (n.b., these comprise varying accounting stances, levels of spatial granularity, and frequencies of reporting)

Integrated Ocean Observing Systems (IOOS)	national and regional data portals	https://ioos.noaa.gov/data/
Bureau of Ocean Energy Management (BOEM)	marine cadastre data registry	https://marinecadastre.gov/data/
NOAA Fisheries	commercial fishery statistics	https://www.fisheries.noaa.gov/national/sustainable-fisheries/commercial-fisheries-landings
NOAA Fisheries	Marine Recreational Information Program (MRIP) [marine recreational fishing]	https://www.fisheries.noaa.gov/topic/recreational-fishing-data
NOAA Fisheries	Community Social Vulnerability Indicators (CSVIs)	https://www.fisheries.noaa.gov/inport/item/52041
Northeast Regional Ocean Commission (NROC)	Northeast Ocean Data	https://www.northeastoceancouncil.org/quick-links/
Mid-Atlantic Region Ocean (MARCO)	data portal	https://portal.midatlanticocean.org/
Gulf of Mexico Alliance (GOMA)	Data & Monitoring Team	https://gulfofmexicoalliance.org/our-priorities/priority-issue-teams/data-and-monitoring-team/
Caribbean Regional Ocean Planning (CROP)	data portal	{No web presence.}
West Coast Ocean Alliance (WCOA)	West Coast Ocean Data Portal	https://portal.westcoastoceans.org/
Pacific Regional Ocean Partnership (PROP)	{Under development.}	{No web presence.}
US Forest Service	National Survey of Recreation and the Environment (NSRE)	https://www.srs.fs.usda.gov/trends/nsre-directory/
US Forest Service	National Visitor Use Monitoring Program (NVUM)	https://www.fs.fed.us/recreation/programs/nvum/
National Park Service	visitor use statistics	https://irma.nps.gov/STATS/
State-level coastal zone management programs, ocean planning efforts	coastal atlases, ocean observing systems (OOS), including data on shellfish harvesting and closures, beach uses, state park visitations and uses, health outcomes	{Specific programs and policies are too numerous to include here.}
Municipal	property assessments; beach, fishery, aquaculture permits or leases; cultural practices; and social norms	{Specific programs and policies are too numerous to include here.}
Tribal lands	property assessments; beach, fishery, aquaculture permits or leases; cultural practices; and social norms	{Specific programs and policies are too numerous to include here.}
U.S. Centers for Disease Control	Data on HAB-related human and animal illnesses and food or waterborne outbreaks	https://www.cdc.gov/habs/ohhabs.html https://www.cdc.gov/nors/index.html

II. SOCIO-ECONOMIC RESEARCH AGENDA

1. **Community-Level Surveys**. Implement surveys at the community level to estimate economic consumer surplus changes in a variety of HAB contexts such as commonly impacted sectors (e.g. shellfisheries, tourism) and waterbodies (e.g. lakes, coastal waters). Local communities would need to be identified, and ideally they would be distributed nationally. Design and implement the surveys in a coordinated fashion using transferable survey instruments (#2 below). Consider the pros and cons of internet-based survey approaches.

2. **Transferable Research Approaches**. Encourage the use of transferable research approaches (e.g., transferable economic or social science survey instruments) that can be applied in different HAB contexts. The community-level surveys should be designed with an eye toward facilitating eventual economic benefit transfers (#3 below), but they could also incorporate questions that would help develop deeper ethnographic understandings.

3. **Benefit Transfers**. Encourage the reporting of the quantitative results of the community-level surveys in ways that facilitate benefit transfers to understudied areas that experience HAB events and to facilitate "rapid" evaluations of economic losses in such areas. Investigate the feasibility of utilizing benefit transfer approaches to aggregate the results of community-level surveys to regional or national levels.

4. **Rapid Ethnographic Assessments**. Carry out rapid ethnographic assessments (REAs) to understand the social, economic, and policy factors that can influence HAB impacts and the effectiveness of HAB response efforts. Encourage cross-disciplinary collaboration involving social scientists, economists, and natural scientists in carrying out REAs.

5. **Social Impacts**. Sponsor in-depth research on the social impacts of HAB events, including both immediate and cumulative impacts, the distribution of impacts and the effects of policy responses on affected individuals, communities and other groups, and the measurement and evaluation of community vulnerabilities, resilience, and adaptation to HAB events. Such research may be based on the results of scientific research and regional forecasts or applications of LEK. This research also may be useful in the design and implementation of the community-level surveys mentioned in recommendation 1 above. Encourage the interpretation and reporting of qualitative social science results in ways that are generalizable to other HAB contexts or at regional or national scales.

6. **Impact Thresholds**. Define regional socio-economic impact thresholds that might trigger more detailed and focused (but likely higher cost) studies of economic welfare losses or community impacts. HAB impact thresholds would comprise measures of economic impacts or community vulnerabilities, applied to the effects of discrete bloom events or to the cumulative effects of a series of blooms. Relevant thresholds would be based upon the results of community-level surveys, benefit transfers, ethnographic assessments, or other economic and social science measures of the impacts of HAB events as components of the regional forecasts, such as estimates of public health effects, reduced shellfish or fishery landings, lost resource rents in the fisheries, reductions in tourism or recreation, increased unemployment, changes to tax bases, increased community vulnerabilities, or reduced community resilience.

7. **Value of Scientific Information and Forecasts**. Sponsor research on the value of scientific information and forecasts relating to the frequencies, intensities, and duration of HABs of specific types and the costs of developing that information through scientific research, environmental monitoring, and other types of testing, such as the sampling of fish and shellfish or in situ observations of beach conditions.

8. **Policy Responses**. Sponsor research to inform choices between alternative types of human responses to prevent, control, or mitigate HABs. Such research would comprise the effectiveness of alternatives in reducing human exposures (or in reducing passive value losses), the marginal costs of alternative responses, and the information needs of policy-makers, decision-makers, and other stakeholders. See also the research agenda item on cost-benefit analysis (#13 below).

9. **Risk Communication**. Sponsor research to characterize effective methods of risk communication that increase the level of trust in information providers or decision-makers, minimize so-called "halo effects," and identify governance structures that facilitate effective assessments of risks and communications of risks to the public.

10. **Social Media**. Sponsor research on the effects of efforts to communicate risks through social media on human behavioral responses to HABs.

11. **Novel Methodologies**: Sponsor research to advance applications of new and novel methodologies such as social media analytics and human mobility data from personal communication devices (e.g., smartphones) to collect baseline information or measure behavioral responses.

12. **Costs of Illness**. Sponsor research on the incidence and severity of illnesses arising from exposure to the different HABs. Apply recent advances in the economic valuation of morbidity and mortality (such as stated preference approaches or quality adjusted life years (QALYs)) to scale the direct effects of human exposures to HAB toxins (e.g. aerosolized brevetoxin or cyanotoxin and ciguatoxin).

13. **Cost-Benefit Analysis**. Encourage the analysis of tradeoffs involved in the implementation of policies and interventions to reduce HAB impacts by utilizing cost-benefit or cost-effectiveness approaches. Such analyses would rely upon estimates of lost surpluses generated through the community-level surveys or benefit transfers, and they could comprise the aforementioned recommendations to analyze the value of information and cost of illness, including consideration of the full array of feasible responses to prevent, control, or mitigate the relevant HABs. Some examples of relevant responses include:

    a. Commercial shellfish or fishery closures;

    b. Drinking water bans or treatment;

    c. Restrictions on recreational uses, such as fishing, beachgoing, swimming, boating;

    d. Limits on fertilizer applications;

    e. Forecasts and observing systems;

    f. Risk assessments, management, and communication;

    g. Other context-dependent responses.

Resources

A library of publications was compiled by the HAB Socio-economics Planning Committee. This library is available to researchers and students by request. A bibliography (including abstracts and digital object identifiers) of the library holdings can be found here. PDFs (including those for resources without DOIs) are available in this library.

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Appendices

1. Regional Case Study Materials (Bloom Characteristics and Impacts and Presentation to the Plenary)
2. Participants
3. Agenda
4. NCCOS Socio-economic project descriptions
5. Keywords

Appendix 1: Regional Case Study Materials

GREAT LAKES: CYANOBACTERIAL BLOOMS

Bloom Characteristics and Impacts [2]

WHEN AND WHERE:

- HABs occur in all five Laurentian Great Lakes
  - Primary regions are western Lake Erie and Sandusky Bay; Saginaw Bay, Lake Huron; Green Bay, Lake Michigan, western Lake Superior; Sodus Bay and other embayments in Lake Ontario.
- HABs can be formed by non-nitrogen fixing cyanobacteria such as *Microcystis* and *Planktothrix* as well as nitrogen fixing genera such as *Aphanizomenon*, *Dolichospermum/Anabaena*, *Cylindrospermopsis/Raphidiopsis.*
- Main toxins of concern are the liver toxins, microcystins (caused the 2014 Toledo water crisis). Other toxins that have been detected are the liver toxins, cylindrospermopsins as well as the neurotoxins saxitoxins and anatoxin-a.
- Primary drivers are non-point source nitrogen and phosphorus (mainly from agriculture)
- Duration can last from weeks (e.g. western Lake Superior) to months (western Lake Erie/Sandusky Bay).

EXCEPTIONAL EVENTS: WHAT MAKES THESE EXCEPTIONAL?

- Lake Erie blooms in 2011, 2014, 2015
- In 2011 and 2015, heavy Spring rains led to increased nutrients (phosphorus and nitrogen) loads to the western basin leading to the Lake, the second and first largest blooms since 2002.
- In 2014, microcystin concentrations exceeded the World Health Organization threshold level for safe drinking water in Toledo water treatment plan finished drinking water, resulting in the water supply in Toledo, Ohio being shut down for just over 2 days.

2 Tim Davis, Ph.D., Bowling Green State University; Frank Lupi, Ph.D., Michigan State University; Quay Dortch, Ph.D., NCCOS; Mary Kate Rogener, Ph.D., NCCOS.

IMPACTS:

Mechanisms of exposure and public health

- Primary human interactions are through coastal use, drinking water and health risk to humans and pets
- The presence of high levels of cyanotoxins in drinking water can cause gastrointestinal complications, liver damage, neurological symptoms, and potentially even death.
- In 2014, Toledo, Ohio officials issued a two-day ban on drinking and cooking with tap water for more than 400,000 residents due to toxin concentrations that exceeded the World Health Organizations guideline level for safe drinking water.

Ecosystem Impacts

- These blooms may cause fish kills and discolored or foul-smelling water.
- Blooms are linked to deaths of both wild and domesticated animals.

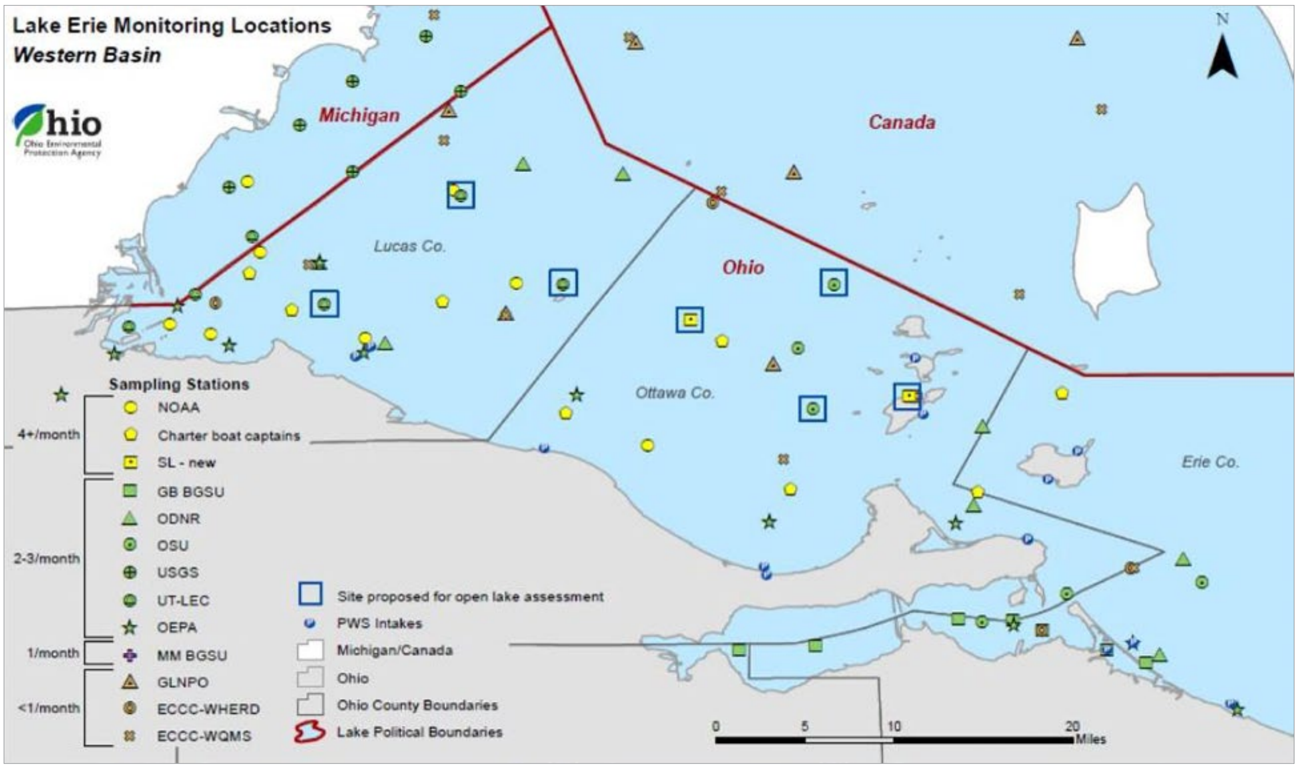
Socio-economic Impacts

- Crude estimates suggest the 2011 and the 2014 Lake Erie HAB events cost over $70 million each (Bingham *et al*. 2015), and estimates for annual damages to Canada exceed $270 million (Smith *et al* 2019).
- Besides water supply, other potential economic impacts include beach warnings and amenities, water based recreation (beaches, boating and fishing), fishery harvests, coastal tourism outside of recreation, coastal business income, property value, non-use values.

MONITORING: CURRENT & POSSIBILITIES FOR FUTURE

- State:
  - Recreation: Ohio conducts monitoring for cyanoHAB toxins and species in recreational waters and issues two levels of advisories:
    - Recreational Public Health Advisory -- HAB is visually confirmed and/or when cyanotoxin toxin levels are equal to or exceed Recreational Public Health Advisory threshold (6 ppb microcystin, 80 ppb anatoxin-a, 5 ppb cylindrospermopsin, 0.8ppb saxitoxin)
    - Elevated Recreational Public Health Advisory -- HAB toxin levels are equal to or exceed the Elevated Recreational Public Health Advisory threshold (20 ppb microcystin, 300 ppb anatoxin-a, 20 ppb cylindrospermopsin, 3 ppb saxitoxin)
  - Drinking water: Ohio conducts qPCR screening and weekly or biweekly toxin concentration screenings at specific public water system locations throughout Lake Erie. Increased sampling frequency or advisory notification to the public might be required depending on the presence and concentration of toxins or toxin-producing genes.

- Great Lakes Observing System (GLOS) partners with federal, academic, and NGOs to monitor and provide an early warning system for HABs in Lake Erie. Monitoring equipment utilized includes:
    - Sondes distributed at at-risk areas to measure dissolved oxygen, blue green algae, chlorophyll, turbidity, pH, and water temperature
        - most of the near real-time buoys can be found on this site
    - Environmental Sample Processors (ESPs) -- autonomous, *in situ*, sampling and analysis unit that employs DNA-based and toxin detecting technology to confirm species and toxin presence.



From OEPA on WLE US (and some Canada) monitoring activities:

FORECASTING: CURRENT & POSSIBILITIES FOR FUTURE

- Lake Erie Bloom Forecast:
    - The Lake Erie early season projection and seasonal forecast estimates bloom severity based on Maumee River discharge and modeled phosphorus loads.
    - Lake Erie Harmful Algal Bloom Forecast is a HAB forecast (nowcast and 5-day forecast) that provides bloom extent and trajectory using *Microcystis* concentrations, and wind and current data.
    - Lake Erie HAB Tracker- combines remote sensing, monitoring, and modeling to produce daily 5-day fore-casts of bloom transport and concentration.

PREVENTION

- The spring total phosphorus load appears sufficient to predict bloom magnitude, permitting a seasonal forecast prior to bloom initiation (Stumpf *et al.*, 2012). Toxin concentrations are strongly dependent on nitrogen concentrations, therefore to reduce the size and toxicity of blooms a dual N and P reduction approach is needed (Davis *et al.*, 2015, Gobler *et al.*, 2016).

CONTROL

- No current cost-effective control for the blooms once they begin.

Great Lakes: Plenary Presentation

The Great Lakes slides are available here: Presentation to the Plenary.

Great Lakes: References

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GULF OF MAINE: PSP (*ALEXANDRIUM CATENELLA*)

Bloom Characteristics and Impacts [3]

WHEN AND WHERE:

- There are two types of blooms in the region.
  - The first consists of localized blooms in small embayments (few km^2) - i.e., in the Nauset Estuary on Cape Cod. These are self-initiating and self-seeding. They are highly seasonal, occurring in April and May.
  - The second category is that of widespread coastal blooms, often covering hundreds of km^2. These initiate from cyst seedbeds in eastern and western Maine, but initial toxicity is in the west, beginning in April

3 Quay Dortch, Ph.D., NCCOS; Mary Kate Rogener, Ph.D., NCCOS; Di Jin, Ph.D., Marine Policy Center, WHOI; Donald Anderson, Ph.D., WHOI.

and extending into June and gradually shifting to the east as waters warm, leading to toxicity in July and August in eastern Maine.

- The coastal blooms mostly impact Maine, NH, sometimes MA, and sometimes Georges Bank.
- Possible decadal periodicity in the extent and magnitude of coastal outbreaks; currently in low phase (Anderson *et al.*, 2014; Kleindinst *et al.*, 2014)
- Same organism causes similar problems around Long Island, NY, on US West coast and AK, Canadian east & west coasts

EXCEPTIONAL EVENTS:

- 1972, 2005, 2006, 2009 based on coast line impacted, levels and duration of toxicity (Anderson *et al.*, 2014; Kleindinst *et al.*, 2014). 2019 exceptional for duration and intensity. 2010 and 2020 are exceptional in terms of extremely low levels of toxicity.

IMPACTS:

Mechanisms of exposure and public health impacts

- *Alexandrium* produce neurotoxins that can accumulate in shellfish, causing paralytic shellfish poisoning in human consumers.
  - Causes a range of neurological symptoms and in severe cases, respiratory arrest and death. Toxins not removed with heating or freezing of contaminated shellfish.
  - Shellfish monitoring program initiated in 1958 in eastern Maine, and then in mid-1970s in other New England states. Georges Bank is operating under Onboard Screening, Dockside testing program.
  - No recent cases in US from commercially available shellfish after establishment of monitoring programs.
  - Maine and other states rapidly expanding shellfish aquaculture.

Ecosystems Impacts

- Toxins accumulate in higher trophic levels and have caused mortalities of multiple species, including protected species, humpback whales (Gerachi *et al.*, 1989), sturgeon (Fire *et al.*, 2012), diamond-back terrapin (Hattenrath-Lehman, 2017)

Socio-economic Impacts

- Harvest losses due to shellfish closures resulting from the 1980 bloom were estimated at $5 million and total economic impacts were estimated to be $15 million (Hoagland *et al.*, 2002).
- Estimates of the lost sales of shellfish in Maine and Massachusetts due to closures imposed as a consequence of the 2005 bloom range from about $2.5 million (Hoagland and Scatasta, 2006; Jin *et al.*, 2008) to $6 million (Athear, K., 2008). The total economic impacts to the Maine economy associated with the $6 million direct economic impact are $14.8 million (Athear, K., 2008).
- The total direct impacts on the commercial shellfish (quahog, softshell clam, mussel) industry in Massachusetts may be as high as $18 million (Jin *et al.* 2008).

- Supply shortage resulting from local closures led to an increase in shellfish imports to New England during the 2005 red tide.
  - Shellfish closures in Maine were the most likely cause of observable price changes on the Fulton Fish Market in New York.
- Ahearn (2009) estimated losses of $1.2M per week in lost harvester sales and an overall loss of $2.9M/week to the Maine economy. Blooms often last 8 weeks or longer.
- Fishery failures declared in 2006 ($4M ME & MA) and 2009 ($5M, ME, MA, NH) due to shellfish harvesting area closures. Funds used to mitigate fisheries losses and improve monitoring.
- Developed Shipboard screening/Dockside testing protocol approach for monitoring shellfish in remote locations on Georges Bank, opened up clam fishery worth $10-15 million/yr.
- Estimates of lost sales of soft-shell clams in Machias Bay, Maine due to red tide closures over a nine year period (2001-2009) are $166 thousands or $18.4 thousands per year (Evans *et al.* 2016).

MONITORING:

- States--see above
- Need to assess the economic impact of routine, coast-wide closures of mussel harvesting from April to October every year in Maine. Implemented in 2013 due to budgetary constraints. Exception areas with valuable shellfish resources are monitored separately. New Hampshire and Massachusetts still use weekly shellfish flesh testing at established stations.
- ESPs (autonomous measurement toxins/cells) & IFCBs (autonomous ID & count cells) demonstrated in Salt Pond, MA, and Gulf of Maine for moored remote, automated monitoring of cell numbers & toxins; research continuing with various moored and mobile platforms. Pilot HAB observing network

FORECASTING:

- NOAA Gulf of Maine Harmful Algal Bloom Forecasting is ongoing using coupled physical/biological models based on many years of lab and field research, cyst map (seed-like cysts produced in the fall, deposited in bottom sediments, initiate bloom in spring when conditions are adequate), and oceanographic conditions.
  - Seasonal forecast of bloom severity
  - Weekly forecasts of cell abundance at different locations and depths
- Future
  - Developing a machine-learning paralytic shellfish forecast for 30+ specific locations along ME coast based on State monitoring of specific toxins
  - Improving Gulf of Maine Forecast to include toxicity estimates derived from ESP data at locations near state shellfish monitoring stations.

- Economic value of forecasting
    - A framework for measuring the value of HAB predictions was developed by Jin and Hoagland (2008). The results indicated that the long-term value of a HAB prediction and tracking system for the Gulf of Maine was sensitive to the frequency of HAB events, the accuracy of predictions, the choice of HAB impact measures, and the effectiveness of public and private responses.

PREVENTION

- Coastal bloom is naturally occurring bloom not impacted by factors (e.g., anthropogenic nutrients) amenable to prevention.
- Exception may be ice melt in the Arctic or other climate-related inputs of fresh water that may be altering water mass characteristics in Gulf of Maine.
- Localized blooms on Cape Cod may be affected by local anthropogenic nutrient inputs.

CONTROL

- Coastal bloom is massive; very difficult to control due to scale issues.
- Clay flocculation tested, found to be ineffective due to low cell concentrations in blooms. New, modified clays may be more effective, but have not been tested.
- Control is more feasible in small embayments like in Nauset Estuary. Localized blooms could be treated with clay or other technology (e.g., ozone nanobubbles) at the end of the bloom, just before the cysts are formed that are the inoculum for the next year's bloom. These methods need to be tested.
- Cyst burial tested and shown to reduce cyst abundance in the surface sediment layer from 4 to 30-fold. This would decrease the bloom inoculum from germinated cysts. The concept needs to be tested at larger scales.

Gulf of Maine: Presentation

The Gulf of Maine slides are available here: Presentation to the Plenary.

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GULF OF MEXICO: NSP (*KARENIA BREVIS*)

Bloom Characteristics and Impacts [4]

WHEN AND WHERE:

- Florida: SW coast most years in fall, Panhandle some years, East coast occasional
- Alabama: Same years as Panhandle
- TX--every 3-5 years, independent of FL
- MS/LA--every 10-15 years, associated with FL bloom and tropical storm hurricane
- NC (1987)

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EXCEPTIONAL EVENTS:

- 2005, 2017-2019, Prolonged blooms that over-winter and spread such that areas of impact vary. Lesser events can be just a few days to a few weeks, and conditions can vary just a few miles apart due to prevailing wind conditions and bloom intensity

IMPACTS:

Mechanisms of exposure and public health impacts

- Mechanisms of human exposure to brevetoxins:
  - Aerosolized by wave action along beaches during blooms, causes respiratory irritation in healthy beach-goers and more severe illness in people with underlying health conditions
  - Accumulate in shellfish (and fish?) and cause Neurotoxic Shellfish Poisoning (NSP) that causes a range of neurological gastrointestinal symptoms that are not removed with heating or freezing of contaminated shellfish (no cases from commercial shellfish sources in U.S. since harvest areas monitored and closed)
- Emergency room admissions increased during red tide events, costs estimated by Hoagland (2009)
  - Gastrointestinal distress up 40% (Kirkpatrick *et al.*, 2010)
  - Respiratory diagnoses up 54% (Kirkpatrick *et al.*, 2006)
  - Significant increase in neurological (headache) illness for individuals ≥55 years (Diaz *et al.* 2019)

Ecosystems Impacts

- Mortality of endangered turtles, marine birds, protected and endangered marine mammals UMME's, and potentially household pets
- Mortality and reduced stock sizes of harvested fish and shellfish, e.g., for red grouper the annual harvest quotas were reduced (commercial and recreational)
- Hypoxia during exceptional events (maybe more often?)
- Water discoloration

Socio-economic Impacts

- Reduced restaurant and lodging revenues (via sales tax data) in coastal counties with concentrated coastal tourism during months with red tide present (Larkin and Adams, 2007).
- Reduced restaurant revenues on days noted by staff as being affected by red tide (Morgan *et al.*, 2008).
- Clean up and response costs for Florida's red tide in four Florida counties and two municipalities for initial assessment, public notification, and removal of dead fish from the coastline (Morgan *et al.*, 2009).
- Lost value to recreational boaters from reduced boating access (Alvarez *et al.*, 2019).

- Reduced property prices during four red tides within 5 miles of the coast (e.g., Bechard, 2020).
- Petrolia *et al.* (2019) determined that the aggregate value of the benefits associated with beach information/forecasts to the public exceeds the estimated cost. https://doi.org/10.1086/706248

MONITORING AND FORECASTING:

- State: State monitors cell counts and closes shellfish harvesting to protect public health, when counts >5,000 cells/liter. Closures can last for months over wide areas.
- HABscope: A citizen scientist collects a water sample, places it under a microscope and uses an iPod to take a video. The video is analyzed by machine learning to automatically identify and count *Karenia brevis* cells in the sample (Hardison *et al.*, 2019).
- Imaging Flow Cytobot (IFCBs; instrument that autonomously identifies & counts cells) being used for *Karenia* mapping on an experimental basis; could be expanded to a HAB observing system with greater temporal and spatial resolution.
- NOAA FL HAB forecast: respiratory impacts on beaches on a county-wide scale, twice a week. SW FL began in 2004, added TX in 2005, then expanded to east coast FL and AL/MS/LA as needed.
- Every Beach Every Day: A Red Tide Respiratory Forecast generated from HABscope that can provide more accurate scientific data on bloom concentrations with the goal of providing information about "every beach, every day" that also will help improve forecast models that predict a toxic bloom's movement patterns (Hardison *et al.* 2019).
- USF seasonal forecast bloom severity based on location of Loop Current, eddy formation, and upwelling intensity (Weisberg *et al.*, 2019).

PREVENTION (STOP BLOOMS BEFORE THEY START, I.E., UNDERSTAND AND INFLUENCE BLOOM INITIATION)

- Blooms initiate at depth offshore and are transported to surface in coastal zone by moderate upwelling. Early studies suggested anthropogenic nutrients not a major factor (Heil *et al.*, 2014), but a large regional ECOHAB study is investigating.
- Policies to improve the public's ability to understand the physical attributes of blooms, specifically risk communication policies, are preferred over physical, chemical, or biological controls (Hoagland *et al.*, 2020).

CONTROL (PUTTING A SUBSTANCE ON THE BLOOM TO STOP IT AND LESSEN NEGATIVE EFFECTS)

- Field tests with clay flocculation (Sengco and Anderson, 2005) and microbubbles with ozone have shown promise and require further demonstration.
- Dinocide from naturally occurring bacterium (*Shewanella*) tested in mesocosms (Pokrzywinski *et al.*, 2012).

Gulf of Mexico: Presentation

The Gulf of Mexico slides are available here: Presentation to the Plenary.

Gulf of Mexico: References

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US WEST COAST: ASP/DA POISONING (*PSEUDO-NITZSCHIA SPECIES PLURALIS*)

Bloom Characteristics and Impacts [5]

BLOOM CHARACTERISTICS

- Blooms are caused by diatoms in the genus *Pseudo-nitzschia* that produce the toxin domoic acid (DA) (not all blooms are toxic).
- Blooms occur seasonally (i.e., spring through fall) off the coast of California, Oregon, Washington (Horner *et al.*, 1997; Horner *et al.*, 2000; Lewitus *et al*, 2012; Smith *et al.*, 2018).
- Exceptional events occurred in 1991, 1998-99, 2002-03, 2005-06, and 2015-16 (Lewitus *et al.*, 2012; Moore *et al.*, 2019).
  - The 2015-16 event was the largest recorded in the region and was caused (in part) by the 2013-2015 North Pacific Marine Heatwave (aka the Blob) (McCabe *et al.*, 2016) .

BLOOM IMPACTS

- *Pseudo-nitzschia* can produce DA, which accumulates primarily in the viscera of shellfish, crustaceans, other invertebrates and sometimes finfish (e.g., anchovies, jacksmelt, sardines; Mazzillo *et al.* (2010)) and can remain in the animal long after blooms have dissipated.
- Consumption of shellfish (bivalves and crustaceans) and finfish contaminated with DA can result in amnesic shellfish poisoning (ASP) in humans or domoic acid poisoning (DAP) in seabirds and marine mammals (Quilliam and Wright, 1989; Lefebvre and Robertson, 2010).
  - ASP/DAP is characterized by gastrointestinal and neurological disorders, with severe cases resulting in seizures, disorientation, memory loss, respiratory difficulty, coma, and death.
  - DAP in seabirds and marine mammals results in increased strandings.

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HUMAN RESPONSES

Monitoring and forecasting

- Federal, tribal, and state agencies, academic partners, and volunteers monitor the water for cells and toxins (e.g., Trainer and Suddleson, 2005), sometimes using advanced, automated technologies -- this provides early warning of blooms to avoid costly recalls of contaminated seafood and potentially inform other mitigating actions.

- When elevated DA levels are indicated in water samples, state agencies monitor DA concentrations in some seafood (marine spp) via dockside sampling of commercial catches or targeted sampling done in collaboration with fishery participants.

- The Pacific Northwest HAB Bulletin utilizes beach (and offshore sampling when available) from state and tribal partners, NOAA, ocean models and ocean buoy data to forecast HAB events impacting Oregon and Washington shellfish (Trainer *et al*. 2020).

- California Harmful Algae Risk Mapping (C-HARM) predicts the spatial likelihood of blooms and dangerous levels of DA using a blend of numeral models, ecological forecast models of *Pseudo-nitzschia*, and satellite ocean color imagery (Anderson *et al*. 2016).

- CA HAB Bulletin synthesizes C-HARM model output, near real-time observations, and public health alerts.

Management

- Federal, state and tribal agencies issue seafood consumption advisories and in some cases fishery season delays or closures when DA concentrations exceed "action levels" established by the FDA for human consumption (see Ekstrom *et al*., 2020 for summary of monitoring and management actions for the 2015 event; see Showalter-Otts 2016 for an overview of the federal and state regulatory context in which these decisions are made).

- Advisories and closures are lifted (by various geographies) based on monitoring results indicating DA levels have dropped to acceptable levels.

Prevention

- Role of human activities has not been explored, but studies suggest warming (McCabe *et al*., 2016; McKibben *et al*., 2017), ocean acidification (Tatters *et al*., 2012), and nutrient speciation (Radan and Cochlan, 2018) may exacerbate blooms and/or bloom toxicity

Control

- No studies investigating control methods.

Mitigation of risk/impact posed a) by HABs and/or b) by government policy/action to address HAB impacts

- Government/public [policy responses] to HABs and to SE impacts of policy responses:

    - Seafood consumption advisories are issued and in some cases fisheries are closed when DA concentrations exceed "action levels" established by the FDA for human consumption (see Ekstrom *et al*., 2020 for summary of monitoring and management actions for the 2015 event; see also Showalter-Otts 2016).

    - Advisories and closures are lifted (by various geographies) based on monitoring results indicating DA levels have dropped to acceptable levels.

    - Federal fishery disaster assistance
    - Dynamic management (e.g., targeted closures and piecemeal reopening of fisheries)
    - Post-harvest handling requirements (e.g., crab evisceration)
- Private (businesses, individuals, community groups, non-governmental organizations):
    - actions to offset losses (e.g., income diversification, advertising) (Moore *et al.*, 2020b)
    - Pursuit of alternative fisheries, activities or food sources
    - Development or use of alternative products and preparations (e.g., crab evisceration)
    - Fund-raising campaigns and aid efforts (e.g., CCWF GoFundMe campaign)

SOCIAL AND ECONOMIC IMPACTS

Most of the known social and economic impacts of West Coast Pseudo-nitzschia blooms stem from fisheries delays and closures. The information presented is based on published literature and ongoing work by steering committee members and colleagues, and is provided as a starting point for discussion. Impacts include adverse social, cultural, economic, physical and mental health effects affecting individuals and communities (of interest, place), local to national.

Impacts of DA-producing HABs

- Fish kills/shellfish die-offs
- Loss of resource used for commercial, recreational and/or subsistence purposes
- Increased DA levels in valued species, leading to increased risk of ASP in consumers:
- Some ethnic and cultural groups are more likely to prepare affected species and/or consume parts (especially the viscera) where the toxin levels typically are highest/most concentrated (SFEI 2000, Sachena *et al.* 2003, Mazzillo *et al.*, 2010).
- People with high consumption rates of razor clams, lower body weights, and people who consume clams at the upper range of legal DA limits may also be at higher risk for health impacts from DA exposure (Ferriss *et al.* 2017).
- Members of three WA coastal tribes who reported high consumption rates of razor clams had isolated decrements of some measures of memory (Grattan *et al.*, 2016). Link to domoic acid and PNW special issue in Harmful Algae

Impacts of policy responses to DA-producing HABs

Increased/new sampling/testing:

- Financial and human resource costs to state government
- Some social conflict about fishermen collecting samples
- Fishery delays (e.g., Dungeness crab), closures (e.g., rock crab, razor clam) and advisories

Commercial fisheries

- $97.5 million reduction in ex-vessel (dockside) value of West Coast Dungeness crab in 2015 (NMFS 2015) compared to the previous year (NMFS 2015)
- Federal commercial fishery disaster declarations (e.g., $1.5M for WA Quileute Tribe 2015-16 Dungeness crab fishery and $25.8M for CA 2015-16 Dungeness and rock crab fisheries)
- Closures of the commercial razor clam fishery in WA disproportionately impacts members of the Quinault Indian Nation who are responsible for most of the commercial harvest and sales (Crosman *et al.*, 2019)
- Distributional impacts of the 2015 and 2016 commercial Dungeness crab fishery closures include a greater ability of large commercial fishing vessels to mitigate losses, with the proportion of total revenue going to small-vessel operators and the proportion of small-vessel participation in the Dungeness crab fishery falling in several California fishing ports (Jardine *et al.*, 2020)
- Specific requirements for capture, handling, etc., differentially affect subsectors of the fisheries and associate seafood distribution/supply system(s)
- During the 2015-16 DA event, ex-vessel prices in the CA commercial Dungeness crab fishery declined by 9.6% while prices to consumers did not (Mao and Jardine, 2020)
- Rock crab: sudden, unexpected closure of commercial fishery where previously advisories had been used to protect public health adversely affected fishery participants and families
- Dungeness crab: pre-season investments in vessel, gear, equipment followed by lack of income to cover those expenditures
- Both: immediate loss of income, some fishermen (captains and crew) unable to pay (household as well as business) bills; uncertainty about when and how the fisheries would be reopened

Recreational fisheries

- A season-long closure of the recreational razor clam fishery in WA, as occurred in 1998-1999 and 2002-2003, is estimated to result in more than $24 million in annual lost expenditures (2008 dollars; Dyson and Huppert, 2010),

Subsistence fisheries

- Razor clams are an important food source for the Quinault Indian Nation, especially during winter months when other natural resources are unavailable (Crosman *et al.*, 2019)
- Other population subgroups (defined by demographic and other characteristics) rely on access to affected species for sustenance and/or fulfilment of cultural values; closures, delays and/or advisories preclude/limit capture and consumption of culturally valued species and/or animal parts, preparations, etc.

All fisheries/broader seafood system

- Delay/closure of fisheries can cause stress and sadness (Ritzman *et al.*, 2018, Moore *et al.*, 2020a).
- Loss of sense of place, impacts to cultural identity, and inability to participate in and sustain traditions (e.g., holiday meals) (Culver *et al.*, 2016, Ritzman *et al.*, 2018, Moore *et al.*, 2020a, Moore *et al.*, 2020b, Crosman *et al.*, 2019).
- Lack of supply to support community "crab feeds" -- as important social and/or fundraising, and other cultural events.
- Loss of confidence in seafood safety affecting purchases, seafood supply chain and participants, consumption.

Indirect effects

- Temporal (and spatial) shifts in directly affected fisheries have on-the-water and shoreside implications for other fisheries, shoreside receivers, ports, markets, fishery-support businesses.
- Economic hardship resulting from fishery closures extend beyond fishing-related operations to other sectors, such as hospitality (Ritzman *et al.* 2018).
- Delays to the 2015-16 commercial Dungeness crab fishery combined with habitat compression resulted in an increase in whale entanglements (Santora *et al.*, 2020), leading to additional closures/season truncation to reduce risk of whale entanglements; related recreational fishery policy action likely to follow.

US West Coast: Presentation

The West Coast slides are available here: Presentation to the Plenary.

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US TROPICAL AREAS: CIGUATERA POISONING

Bloom Characteristics and Impacts [6]

WHEN AND WHERE:

Ciguatera is prevalent throughout tropical and subtropical areas in the Pacific Ocean, the Indian Ocean, and the Caribbean Sea. US regions where ciguatera occurs include Hawaii, the Gulf of Mexico, the Florida Keys, Puerto Rico, the US Virgin Islands, Guam, and other territories in free association (Marshall Islands, Micronesia, Palau) or in political union (Northern Mariana Islands) (See Fig. A1).

6 Mindy Richlen, Ph.D., US National Office for HABs at WHOI; Porter Hoagland, Ph.D., Marine Policy Center, WHOI.

EXCEPTIONAL EVENTS & OUTBREAKS:

- Ciguatera Poisoning (CP) is caused by eating coral reef fish or proximate shellfish contaminated with a suite of toxins known as ciguatoxins.
- CP is the most common marine toxin disease in the world. Globally, tens of thousands of people are afflicted each year (Fleming *et al.*, 1998); outbreaks have been documented in ciguatera endemic regions, and impacts are most severe to island communities dependent on subsistence fishing.
- In the United States alone, thousands of people are afflicted each year in Florida (Radke *et al.*, 2015), the US Virgin Islands (Radke *et al.*, 2013), and Puerto Rico (Azziz-Baumgartner *et al.*, 2012).
- Due to increasing international trade in seafood (supplying retail markets or restaurants), ciguatera outbreaks have been reported from inland or temperate locations in Canada, Germany, Paris, and the United States

IMPACTS:

Mechanisms of exposure, ecosystem, public health

- Ciguatoxins are produced by certain microalgal (dinoflagellate) species in the genus *Gambierdiscus,* which live on the surfaces of macroalgae and dead coral in coral reef ecosystems. These dinoflagellates are inadvertently consumed by herbivorous reef fish while they graze on macroalgae, and these fish accumulate ciguatoxins in their body tissues. Toxins also may undergo biotransformation and accumulate in the coral reef food web.
- Highest toxin levels are generally found in larger predatory fish, such as barracuda, moray eel, snapper, grouper, mackerel, and amberjack, although herbivorous fishes can also be ciguatoxic. In ciguatera-endemic areas, some of these larger carnivorous fish species can accumulate high levels of ciguatoxins and are dangerous to eat. Some of these fish are those frequently sought by recreational and subsistence fishers (Fig. A2).
- Symptoms of ciguatera are diverse and include gastrointestinal, cardiovascular, and neurological disturbances, the latter of which may last from days to months. Some patients experience neurological symptoms years after initial poisoning. Gastrointestinal symptoms such as diarrhea, vomiting, and abdominal pain generally occur first, followed by neurological dysfunction, including muscular aches and pain, itching, dizziness, sweating, feeling of loose teeth, and numbness and tingling of the mouth and fingers. A distinguishing symptom of ciguatera is temperature reversal, in which cold items feel hot and vice versa.
- Geographic differences in symptoms and progression have been described, possibly due to differences in the chemical structure of ciguatoxins among different geographic regions. In the Caribbean, gastrointestinal symptoms and signs predominate in the acute phase (i.e., first 12 h), followed by neurological symptoms. In the Pacific, neurological symptoms and signs may predominate, and there have been reports of more severe acute effects, including comma. Paralysis and death have been documented in rare instances.
- Neurological symptoms can recur for years and are sometimes severely debilitating. Recurrence of symptoms can be triggered by consumption of fish but also other foods (including chicken, pork, nuts, alcohol, etc.), as well as by over-exertion, stress, and dehydration.

- Medical diagnosis of ciguatera is based on the recent fish-eating history of the patient(s), clinical presentation, and, whenever possible, results from analytical testing of a remnant of the fish consumed by the patient.

- There is no cure; treatment is supportive. Intravenous mannitol has been used with some success in treating symptoms of severe poisoning.

Environmental or anthropogenic drivers

- Unlike many other HAB poisoning syndromes, ciguatera is not associated with large scale blooms of the causative organism.

- *Gambierdiscus* cell densities and toxicity may not track each other in the environment, because the toxin is derived from a few species that are often not very abundant.

- Global expansion of ciguatera may be fostered by ocean warming, expanding the geographic range of *Gambierdiscus* spp. beyond tropical locations. In the US, range expansion could mean increased incidence of ciguatera in Florida and the northern Gulf of Mexico.

SOCIO-ECONOMIC (ALSO SEE TABLE A1)

- Current estimates suggest only 2-10% of cases are reported due to misdiagnosis and under-reporting.

- Hoagland *et al*. (2002) estimated the annual economic impact (costs of illness) of ciguatera in the United States to be $21 million – $30 million in 2016 U.S. dollars – far surpassing public health impacts from other illnesses associated with toxic algae. See Table A1 for additional estimates.

- Socio-economic and human health impacts of ciguatera are expanding globally, due to the spread of *Gambierdiscus* into temperate and non-endemic areas (e.g., northern Gulf of Mexico, West Africa, Eastern Mediterranean) and increased international trade.

- Impacts of ciguatera may be most severe in isolated island communities that are dependent on subsistence fishing for food.

- Risk of ciguatera is a significant impediment to development of shallow water fisheries in the Pacific.

- The Hong Kong market for live reef fish results in significant sales revenues for many small island communities of the South Pacific, but ciguatera outbreaks can jeopardize access to this market.

MONITORING: CURRENT & POSSIBILITIES FOR FUTURE

- Efforts to develop rapid screening methods for toxins in fish have not been successful due to the complex toxin chemistry and the broad array of toxins that may be involved.

- Methods are being developed to identify and monitor for toxic species, but have not yet been implemented widely.

- These challenges underscore the need for accurate and sensitive tools to provide quantitative data on the abundance and identity of the primary toxin-producing species, their distribution and dispersal pathways, and their responses to temperature, given expected trends in ocean warming.

- Until rapid methods for screening fish for ciguatoxins are available, preventative measures appear to be the only safeguards against poisoning.

FORECASTING: CURRENT & POSSIBILITIES FOR FUTURE

- None are operational; ciguatoxin flux model is under development, which incorporates data on growth characteristics of toxic *Gambierdiscus*, information on cellular toxin content, data on toxin uptake/assimilation.

PREVENTION:

- **Difficult to Detect:** Prevention of CP has been hindered by the complex suite of ciguatoxins associated with this syndrome. Ciguatoxins do not affect the taste or odor of fish, and cannot be destroyed or altered by cooking, smoking, freezing, or salting.

- **Avoidance of consumption:** Prevention of CP relies on avoidance of those high-risk carnivorous fish species most commonly associated with poisoning, including warnings to never eat barracuda or moray eel. Parts of fish where ciguatoxins are concentrated should not be consumed: liver, intestines, heads, and roe of smaller reef fish. Fish caught in areas known to be ciguatoxic should be avoided (local fishermen may know which areas to avoid). The consumption of larger reef fish should be avoided (one guideline from the Canary Islands specifies avoiding fish >6 lbs), but smaller fish can be toxic too.

CONTROL:

- **None:** No measures to control or mitigate *Gambierdiscus* spp. or ciguatoxins directly are known to exist.

TABLE A1. Socio-economic impacts of ciguatera outbreaks compiled from the scientific literature (estimates from the US in **bold text**).

Year	Description of event	Economic impacts and estimated $ (if known)	Reference
1998	Contaminated fish imported from Fiji to Hong Kong	Depression of fish retail prices 20-60% (1997: grouper sold for **US$100/kg**).	Sadovy 1998b, 1999
1960s-1980s	Canadian tourists and fish imports	Medical costs and lost-labor productivity **CA$2.7 million per year**	Todd, 1985
1987-1992	US tropical jurisdictions	Lost sales, medical costs, lost productivity, monitoring and management costs **US$19 million per year**	Hoagland *et al.*, 2002
1987-1989	Tahiti, French Polynesia	Lost productivity and banned reef-fish sales **US$1.1 million per year**	Bagnis, 1992b
2000	Kiribati	Closure of export fisheries to Hong Kong AU$250,000 (~$8000 per fisher)	Yeeting, 2009
2004-2006	Survey of households in Culebra, Puerto Rico	Lost productivity Avg. **US$164.80 per case**, 39 cases	Azziz-Baumgartner, 2012
2004-2006	Rarotonga, southern Cook Islands	Monitoring, management, and health-related costs **NZ$750,000 per year**; Costs due to dietary shifts **NZ$1 million per year**	Rongo, 2012
2007-2013	Lagoon fishermen, Moorea, French Polynesia	Hospitalization, medication, loss of productivity for reported and unreported cases; **US$241,847**	Morin, 2016

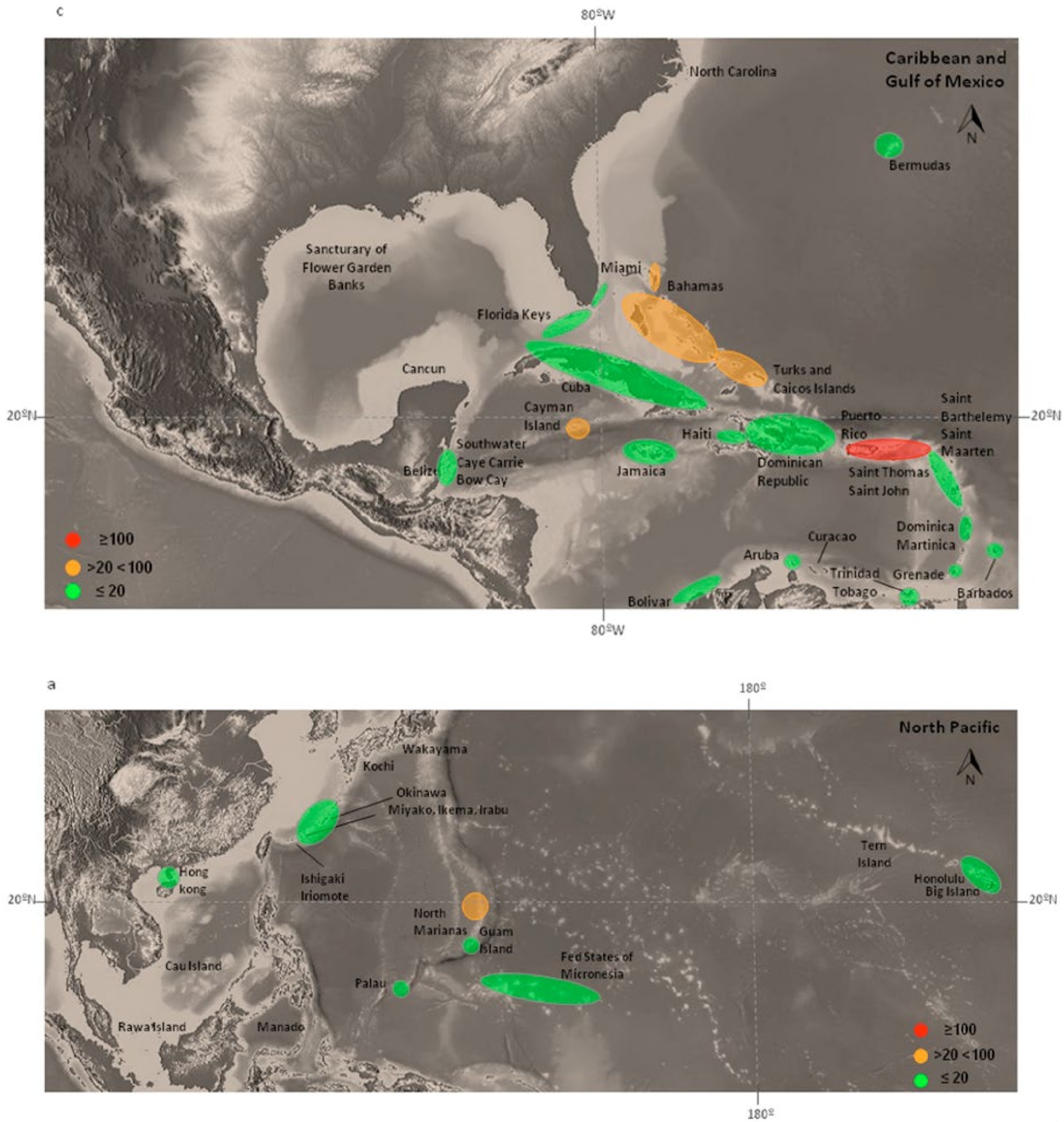

FIG. A1. Geographical distribution of ciguatera fish poisoning incidence. Colors reflect the incidence rate (100,000 persons-year). Location names indicate the spots where *Gambierdiscus* spp. were reported. From Solino *et al*., 2020. Reprinted with permission.

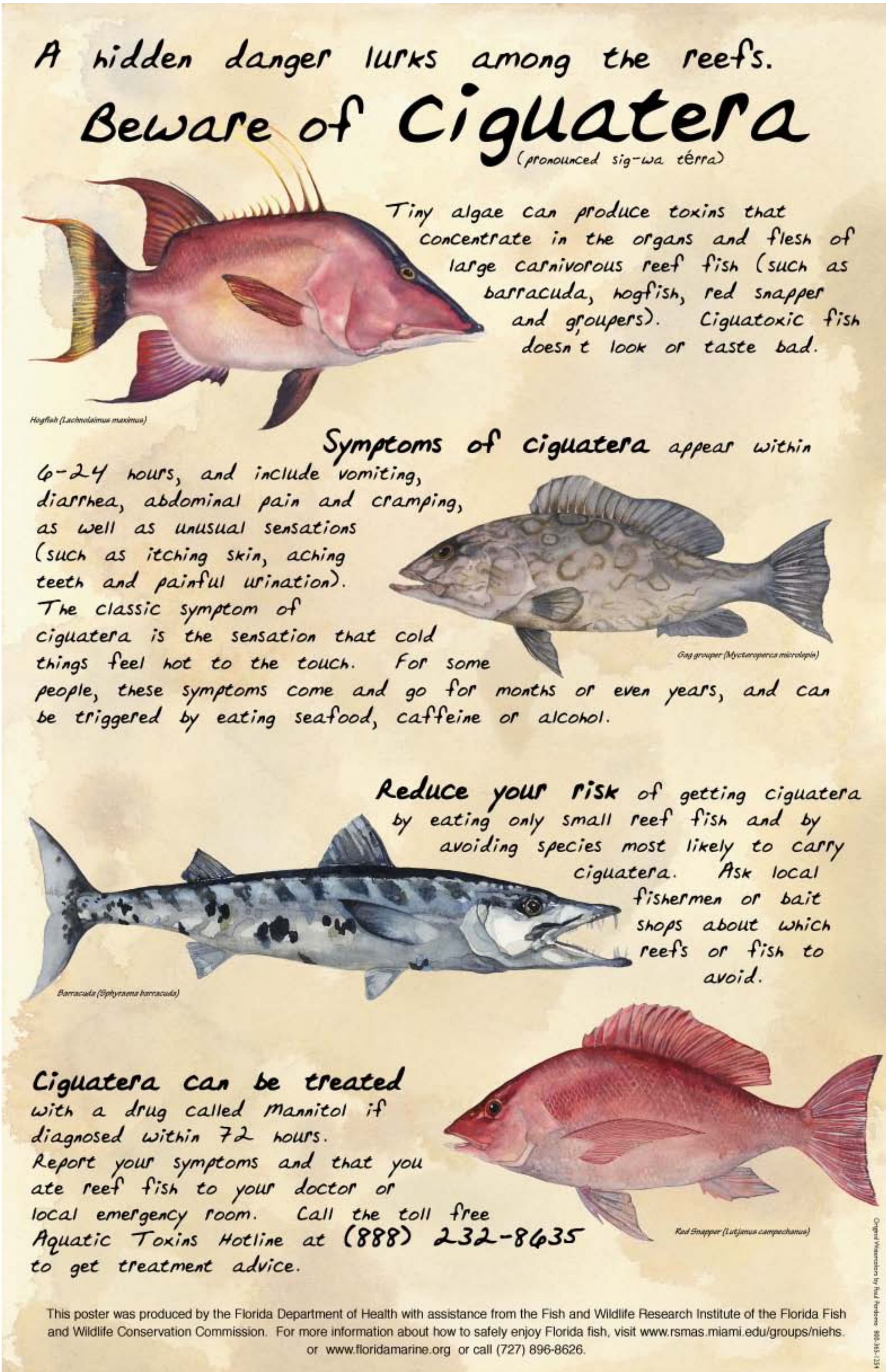

FIG. A2. Outreach poster produced by the Florida Department of Health.

US Tropical Areas: Presentation

The Tropical Area slides are available here: Presentation to the Plenary.

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Appendix 2: Participants

Workshop on Socio-economic Impacts of Harmful Algal Blooms in the US
(listed in alphabetical order by last name)

* HAB Socio-economics Planning Team Member
** HAB Socio-economics Co-Chair

Workshop Participant		Affiliation\Institution	Primary Expertise
Alvarez	Sergio	University of Central Florida	Natural Resource economics
Anderson*	Donald	WHOI	HAB research and mitigation
Anderson	Leif	NMFS/NWFSC	Economics
Backer	Lorraine	CDC	FL red tides
Broadwater *	Maggie	NOAA NCCOS	HABs management
Compton	Jana	EPA	Risk Assessment
Court	Christa	University of Florida	Economic Modeling
Davis *	Timothy	BGSU	HABs management
Dortch *	Quay	NOAA NCCOS	HABs management
Downs	Michael	Northern Economics	Cultural Anthropology
Ellis *	Chris	NOAA OCM	Environmental Sociology
Grasso	Monica	NOAA Office of the Chief Economist	Economics
Haab	Tim	Ohio State University	Environmental Economics
Hoagland **	Porter	WHOI	HAB impacts and responses
Holland	Dan	NOAA NWFSC	Natural Resource economics
Ingles	Palma	Formerly with NMFS & USFWS, now independent	Cultural anthropology
Jardine	Sunny	UW	Natural Resource economics
Jin*	Di	WHOI	Marine Resources Economics
Kirkpatrick	Barbara	GCOOS	Environmental Human Health
Krimsky	Lisa	UF	Education
Landry	Craig	University of Georgia	Economics
Larkin *	Sherry	UF	Natural Resource economics
Lauer	Chris	NOAA Office of the Chief Economist	Economics
Lewinski *	Shannan	NOAA OCM	Facilitator
Lipton	Doug	University of Maryland/NOAA	Economics

Lupi *	Frank	Michigan State	Economics
Marino	Elizabeth	Oregon State University-Cascades	Cultural anthropology
Martinez *	Felix	NOAA NCCOS	Environmental Policy
McIlvaine-Newsad	Heather	Western Illinois University	Social Sciences
McPherson	Matthew	NOAA SEFSC	Social Sciences
Moeltner	Klaus	Virginia Tech	Economics
Moore *	Stephanie	NOAA NWFSC	HABs research
Newbold	Steve	University of Wyoming	Natural Resource Economics
Papenfus	Michael	EPA	Economics
Parthum	Bryan	NCEE/EPA	Environmental Economics
Petrolia	Daniel	Mississippi State University	Natural Resource Economics
Pindilli	Emily	USGS	Natural Resource Economics
Pomeroy *	Carrie	UC Santa Cruz	Socio-economics
Richlen *	Mindy	WHOI	HABs research
Roberts	Virginia	CDC	Human Health Impacts
Rogener *	Mary Kate	NOAA NCCOS	HABs management
Seara	Tarsila	University of New Haven	Socio-economics
Sellner	Kevin	Hood College	HABs research
Sohngen	Brent	Ohio State University	Environmental Economics
Suddleson **	Marc	NOAA NCCOS	HABs management
Trainer	Vera	NOAA NWFSC	HABs Research

Appendix 3: Workshop Agenda

Day 1 - July 27	
11:45 - 12:00	Participants begin logging in and testing equipment Introduction Activity
12:00 - 12:20	**Overview** Objective: Welcome and explanation of meeting goals
12:20 - 1:40	**Natural Science Presentations/Discussions** Objective: Share HAB challenges and needs from a natural scientific perspective Marine Presentation - Quay Dortch Freshwater Presentation - Tim Davis
1:40 -3:00	**Social Science Presentations/Discussions** Objective: Share HAB challenges and needs from a social scientific perspective Social Science Presentation - Michael Downs Economic Presentation - Sunny Jardine
3:00-3:30	**Charge to Case Study Groups and Open Discussion**

Day 2 - July 29	
12:00-12:10	**Welcome Back, Recap of Case Study Charge**
12:10 - 2:50	**Case Studies (concurrent breakout rooms)** Objective: Identify information gaps and recommend social science and economic research priorities to improve documentation and quantification of the impacts of HABs on society and societal responses. • Great Lakes – Cyanobacteria • Gulf of Maine – Alexandrium spp. • Gulf of Mexico – *Karenia brevis* • US West Coast – Pseudo nitzschia spp. • US Tropical regions - Ciguatera spp. Identify information gaps and recommend social science and economic research priorities to improve documentation and quantification of the impacts of HABs on society and societal responses.
2:50 - 3:00	**Return to Plenary and Wrap-Up**

DAY 3 - August 03	
11:45 - 12:00	Participants begin logging in and testing equipment
12:00 - 12:10	**Recap Plan for Day 3**
12:10 - 3:00	**Case Study Presentation/Discussions** Objective: Report out from each case study discussion on social and economic consequences, human responses to the hazard, any gaps, priorities for research. • Great Lakes - Cyanobacteria • Gulf of Maine - Alexandrium spp. • Gulf of Mexico - *Karenia brevis* • US West Coast - *Pseudo-nitzschia spp.* • Tropical - Ciguatera
2:50 - 3:00	**Wrap Up, Charge for Next Day**

DAY 4 - August 05	
11:45 - 12:00	Participants begin logging in and testing equipment
12:00 - 3:00	**Review and Discuss Recommendations and Priorities Identified During Case Studies** Objectives: • **Methodological Approaches**: Identify recommended methodological approaches and any relevant examples of economic and social science assessment. • **Framework for Aggregating Assessments**: Can we create a framework for assessing the social and economic effects of HABs at local, state, regional, and national levels? • **Research Priorities**: Identify economic and social science research priorities.

Appendix 4: NCCOS Funded Socio-economic Projects

NCCOS AND GCOOS FLORIDA HARMFUL ALGAL BLOOM SOCIO-ECONOMIC ASSESSMENT

NCCOS awarded the Gulf of Mexico Coastal Ocean Observing System (GCOOS) funding to run a competition and select grantees to assess the short- and long-term socio-economic impacts of Florida's 2017-2019 Red Tide event. Two projects were selected:

- **From Bloom to Bust: Estimating Economic Losses** and **Impacts of Florida Red Tide (*Karenia brevis*)**

Institutions: University of Central Florida, University of South Florida

Project Period: September 2019 - August 2021

Location: Florida

Total Funding: $277,122

Project Summary: The study will examine the economic impacts of *K. brevi*s events across 80 different sectors, based on varied bloom occurrence and intensity.

- **Assessment of the short- and long-term socio-economic impacts of Florida's 2017-2019 Red Tide even**t

Institutions: University of Florida, Texas A&M University Corpus Christi

Project Period: September 2019 - August 2021

Location: Florida

Total Funding: $279,796

Project Summary: The study will comprehensively quantify and qualify the short- and long-term socioeconomic impacts of the 2017-2019 Florida *K. brevis* event and develop a transferable framework to help inform national-scale efforts focused on quantifying as well as measuring community vulnerability and resiliency.

NCCOS PCMHAB HAB SOCIOECONOMIC (HABSOCIO)

The NCCOS PCMHAB program funds socio-economic research projects to assess the societal impacts of HAB events and the costs and benefits of mitigation strategies. The following are active PCMHAB HABSOCIO projects:

Evaluation of mitigation strategies for harmful algal blooms in the West Coast Dungeness crab fishery

Institutions: Oregon State University, University of Washington, NOAA Northwest Fisheries Science Center, University of California at Davis

Project Period: September 2020 - August 2024

Location: Washington, Oregon, California

FY20 Funding: $292,826

Total Funding: $1,173,193

Project Summary: The Dungeness crab fishery is the most valuable fishery on the US West Coast. Concentrations of domoic acid in crab following harmful algal blooms (HABs) can close areas to commercial and recreational crabbing. Recently HAB events have caused lengthy delays to the start of the commercial season, generating what are believed to be large economic losses and triggering federal fishery disaster assistance. Little is known about the relative economic merits of different potential mitigation strategies. This project will analyze the potential effects of alternative mitigation strategies for HAB impacts on the West Coast Dungeness crab fishery. The primary focus is on regulatory approaches that are flexible and can increase opportunities for the industry amid HAB events while ensuring food safety for consumers.

Value of the SoundToxins partnership: an early warning system for HABs in Puget Sound

Institutions: Washington Sea Grant, NOAA Northwest Fisheries Science Center, Washington Department of Health

Project Period: September 2020 - August 2023

Location: Washington

FY20 Funding: $79,951

Total Funding: $279,926

Project Summary: Washington State is a national leader in farmed bivalve shellfish, with an industry that employs more than 3,200 people in family wage jobs and contributes an estimated $270 million to the economy. The SoundToxins partnership was established in 2006 as a cost-effective monitoring program to provide an early warning of harmful algal bloom (HAB) events through weekly phytoplankton monitoring. The benefits of the SoundToxins partnership to managers include helping the Washington Department of Health prioritize analysis of shellfish samples to areas identified as having the greatest HAB risk (through HAB cell counts), preventing product recall by providing alerts to the Washington Department of Health via the 24/7 communication system, and assisting shellfish growers and managers in avoiding costs associated with HAB events by allowing selective harvest, early harvest and depuration of toxic shellfish prior to harvest. This project will estimate the net economic benefits of the HAB early warnings provided by SoundToxins and evaluate net economic benefits to recreational shellfish harvesters.

Value of the Pacific Northwest HAB Forecast

Institutions: Woods Hole Oceanographic Institution, University of Washington, Washington State Department of Fish and Wildlife, Oregon Department of Fish and Wildlife

Project Period: September 2020 - August 2023

Location: Pacific Northwest

FY20 Funding: $299,948

Total Funding: $899,896

Project Summary: Along the Washington and Oregon coasts, razor clam and Dungeness crab fisheries have been adversely impacted by marine algae that produce the toxin domoic acid. The razor clam fishery is the largest recreational bivalve shellfish fishery in the region and a major source of tourist-related income to small communities along the coast. The Pacific Northwest (PNW) Harmful Algal Blooms (HAB) Bulletin is a forecasting tool that provides information to managers to facilitate their decisions to open and close the shellfisheries, including implementing delayed openings, selective harvests at "safe" beaches, and increasing harvest limits.This project will estimate the economic benefits of the PNW HAB Bulletin, using a methodology for quantifying the value of information.

Assessing Societal Impacts of Harmful Macroalgae Blooms in the Caribbean

Institutions: University of Rhode Island and Woods Hole Oceanographic Institution

Project Period: September 2020 - August 2023

Location: U.S. Virgin Islands, Puerto Rico

FY20 Funding: $318,292

Total Funding: $838,137

Project Summary: In recent years, the number, distribution, and magnitude of macroalgal blooms have increased globally, with consequent impacts on coastal system resilience that have led many to consider them a new type of natural disaster. This is particularly true in the Caribbean and Gulf of Mexico regions, where blooms of free-floating *Sargassum spp.* are resulting in pelagic, nearshore, and onshore accumulations that have become an increasingly persistent and severe nuisance since first appearing in 2011. Management responses to these HAB events vary considerably from place to place. Response techniques can include the erection of floating interception barriers, development of removal technologies in nearshore waters, varying intensities of manual and mechanical removal of beached macroalgae, and transport and disposal of removed biomass, often to unlined landfills or illegal dump sites. This study will use a mixed methods approach to examine how *Sargassum* events and their mitigation in the Caribbean affect multiple dimensions of social resilience, including economic impacts, human wellbeing, local ecological knowledge, and individual attitudes, values, and behaviors.

Appendix 5: List of Acronyms

ASP	Amnesic Shellfish Poisoning
CASPER	CDC Community Assessment for Public Health Emergency Response
CDC	Centers for Disease Control and Prevention
CFP	Ciguatera Fish Poisoning
CP	Ciguatera Poisoning
CVM	Contingent Valuation Method
CyanoHAB	Cyanobacterial Harmful Algal Bloom
DA	Domoic Acid
DISES	NSF Dynamics of Integrated Socio-environmental Synthesis Center
ECOHAB	Ecology and Oceanography of Harmful Algal Blooms
EPA	U.S. Environmental Protection Agency
FDA	U.S. Food and Drug Administration
FWS	Fish and Wildlife Service
GCOOS	Gulf of Mexico Coastal Ocean Observing System
GlobalHAB	Global Harmful Algal Blooms
HAB	Harmful Algal Bloom
HAB RDDTT	Harmful Algal Bloom Research, Development, Demonstration, & Technology Transfer
HARRNESS	Harmful Algal Research and Response: A National Environmental Science Strategy 2005-2015
IOOS	U.S. Integrated Ocean Observing System
LEK	Local Ecological Knowledge

MOU	Memoranda of Understanding
NCCOS	NOAA National Centers for Coastal Ocean Science
NMFS	NOAA National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NORS	CDC National Outbreak Reporting System
NPS	National Park Service
NSP	Neurotoxic Shellfish Poisoning
OHHABS	CDC One Health Harmful Algal Bloom System
OMB	Office of Management and Budget
PAR	Participatory Action Research
PCMHAB	Prevention, Control, and Mitigation of Harmful Algal Blooms
PICES	North Pacific Marine Science Organization (Pacific version of the International Council for the Exploration of the Sea)
PSP	Paralytic Shellfish Poisoning
QALY	Quality Adjusted Life-Years
REA	Rapid Ethnographic Assessments
SESYNC	National Socio-Environmental Synthesis Center
USACE	U.S. Army Corps of Engineers
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
WTP	Willingness-To-Pay