Chapter 1: An Overview of the Interagency, International Symposium on Cyanobacterial Harmful Algal Blooms (ISOC-HAB): Advancing the Scientific Understanding of Freshwater Harmful Algal Blooms

H Kenneth Hudnell, Quay Dortch, Harold Zenick

Abstract

There is growing evidence that the spatial and temporal incidence of harmful algal blooms is increasing, posing potential risks to human health and ecosystem sustainability. Currently there are no US Federal guidelines, Water Quality Criteria and Standards, or regulations concerning the management of harmful algal blooms. Algal blooms in freshwater are predominantly cyanobacteria, some of which produce highly potent cyanotoxins. The US Congress mandated a Scientific Assessment of Freshwater Harmful Algal Blooms in the 2004 reauthorization of the Harmful Algal Blooms and Hypoxia Research and Control Act. To further the scientific understanding of freshwater harmful algal blooms, the US Environmental Protection Agency (EPA) established an interagency committee to organize the Interagency, International Symposium on Cyanobacterial Harmful Algal Blooms (ISOC-HAB). A theoretical framework to define scientific issues and a systems approach to implement the assessment and management of cyanobacterial harmful algal blooms were developed as organizing themes for the symposium. Seven major topic areas and 23 subtopics were addressed in Workgroups and platform sessions during the symposium. The primary charge given to platform presenters was to describe the state of the science in the subtopic areas, whereas the Workgroups were charged with identifying research that could be accomplished in the short- and long-term to reduce scientific uncertainties. The proceedings of the symposium, published in this monograph, are intended to inform policy determinations and the mandated Scientific Assessment by describing the scien-

tific knowledge and areas of uncertainty concerning freshwater harmful algal blooms.

Background

There is growing concurrence among scientists, risk assessors, and risk managers that the incidence of harmful algal blooms (HABs) is increasing in spatial and temporal extent in the US and worldwide. HABs occur in marine, estuarine, and freshwater ecosystems. A National Plan that primarily targets HABs and their toxins in marine and estuarine waters has been developed, Harmful Algal Research and Response: A National Environmental Science Strategy 2005-2015, (HARNESS 2005), but an analogous plan for freshwater HABs has not been developed. Although many algal groups form HABs within a range of salinity levels, dinoflagellates comprise the majority of marine and estuarine HABs, whereas cyanobacteria are the predominant source of freshwater HABs. The Interagency, International Symposium on Cyanobacterial Harmful Algal Blooms (ISOC-HAB) focused on cyanobacterial HABs (CHABs) because characterization of the state of the science and identification of research needs is essential for the development of a freshwater research and response plan. CHABs and their highly potent toxins, collectively known as cyanotoxins, pose a potential risk to human health. Ecosystem sustainability is compromised by CHABs due to toxicity, pressures from extreme biomass levels, and the hypoxic conditions that develop during CHAB die offs and decay. Some of these risks are described in the World Health Organization's guidelines for CHABS (WHO 1999). However, current data in the US are insufficient to unequivocally confirm an increased incidence or to fully assess the risks of CHABs, thereby complicating Federal regulatory determinations and the development of guidelines, Water Quality Criteria and Standards, and regulations. As a result, state, local, and tribal authorities are placed in the quandary of responding to CHAB events by developing and implementing risk management procedures without comprehensive information or Federal guidance. This dilemma was recognized by the US Congress and expressed in the 2004 reauthorization and expansion of the 1998 Harmful Algal Blooms and Hypoxia Research and Control Act (HABHRCA). Whereas HABHRCA originally targeted harmful algal blooms in the oceans, estuaries and the Great Lakes, the reauthorized Act mandated a Scientific Assessment of Freshwater Harmful Algal Blooms, which will: 1) examine the causes, consequences, and economic costs of freshwater HABs throughout the US; 2) establish priorities and guidelines for a research program on freshwater HABs; and 3) improve coordination among Federal agencies with respect to research on HABs in freshwater environments.

The US Environmental Protection Agency (EPA) is authorized to protect human health and the environment from contaminants in drinking and recreational waters through the mandates of the Safe Drinking Water Act, last amended in 1996 (SDWA 1996), and the Clean Water Act, last amended in 2002 (CWA 2002). The National Oceanographic and Atmospheric Administration (NOAA), EPA and other Federal agencies recognize that cyanotoxins in freshwaters may present a risk to human health through the potential for exposure from recreational waters, drinking water, fish and shellfish consumption, and other vectors. The Federal agencies also recognize that cyanobacteria and cyanotoxins threaten the viability of aquatic ecosystems through alteration of the habitats that sustain plants, invertebrates and vertebrates. EPA's Office of Water listed cyanobacteria and cyanotoxins on the first drinking water Contaminant Candidate List (CCL) of 1998 and the second, CCL2, of 2005 (CCL 2006). Risk assessments, regulatory determinations, and risk management procedures can be informed by research that further clarifies: 1) the spatial extent and temporal frequency of freshwater CHABs, both toxic and non-toxic; 2) dose-response relationships describing the effects of individual cyanotoxins and commonly occurring cyanotoxin mixtures in humans and other species at risk; and 3) cost effective means to prevent, control, and mitigate CHABs in surface waters.

EPA's National Health and Environmental Effects Research Laboratory, a component of the Office of Research and Development, invited other Federal and state entities to co-sponsor a CHAB symposium, ISOC-HAB. The purpose of the Symposium was to characterize the state of the science and to identify research needs, thereby informing EPA's Office of Water and the HABHRCA-mandated Scientific Assessment of Freshwater Harmful Algal Blooms. NOAA and seven other Federal entities, the Food and Drug Administration, Department of Agriculture, Centers for Disease Control and Prevention, Army Corps of Engineers, US Geological Survey, National Institutes of Health, and National Institute of Environmental Health Sciences, as well as the University of North Carolina Institute of Marine Sciences joined EPA in co-sponsoring ISOC-HAB. An interagency organizing committee of 32 members and a five member executive advisory committee (see Organizing Committee page) were assembled to develop an operational structure for ISOC-HAB.

Theoretical Framework for Cyanobacterial Harmful Algal Blooms

The ISOC-HAB Organizing Committee developed a theoretical framework of interrelationships between factors that may influence the development of CHABs and be impacted by CHABs to help identify the major topic areas and subtopics of the symposium (Fig. 1). Both natural forces and human activities may be promoting CHABs through habitat alteration (Causes, Prevention and Mitigation Workgroup Report this volume). The natural forces may include an upswing in temperature cycles that allow tropical genera of cyanobacteria to flourish in subtropical regions, the evolution of new strains of cyanobacteria that can better compete for survival and dominance, a decline in predatory populations that limit cyanobacteria growth, and age-related eutrophication of surface waters. Anthropogenic pressures may be major sources of ecological change that promote CHABs. There is evidence that greenhouse gasses are increasing global temperatures, thereby allowing temperature limited genera and species to expand spatially and temporally (Paul this volume). Excessive levels of nitrogen and phosphorus in surface waters from point and non-point sources promote the development of CHABs, and their ratios may determine which species dominate blooms (Paerl this volume). Waters that are high in phosphorus and relatively low in nitrogen are typically dominated by species that contain heterocysts, specialized cells to collect and fix nitrogen into useable forms. Non-heterocyst containing species often dominate blooms in waters that are high in nitrogen. The incidence of CHABs may be increased by pollutants, such as pesticides and metals in storm-water runoff and other sources that disrupt the balance between cyanobacteria and their predators, or lead to the rise of more resilient strains of cyanobacteria through natural selection. The introduction of non-native organisms into surface waters also may promote CHABs. The recent resurgence of CHABs in the Great Lakes is associated with the invasion of Asiatic Zebra muscles, *Dreissena polymorpha,* that may selectively filter-feed non-toxic phytoplankton (Occurrence Workgroup Report this volume). The combined pressures from natural forces and human activities on surface waters may provide a competitive advantage to cyanobacteria over their predators, leading to an increase in the spatial and temporal extent of CHABs.

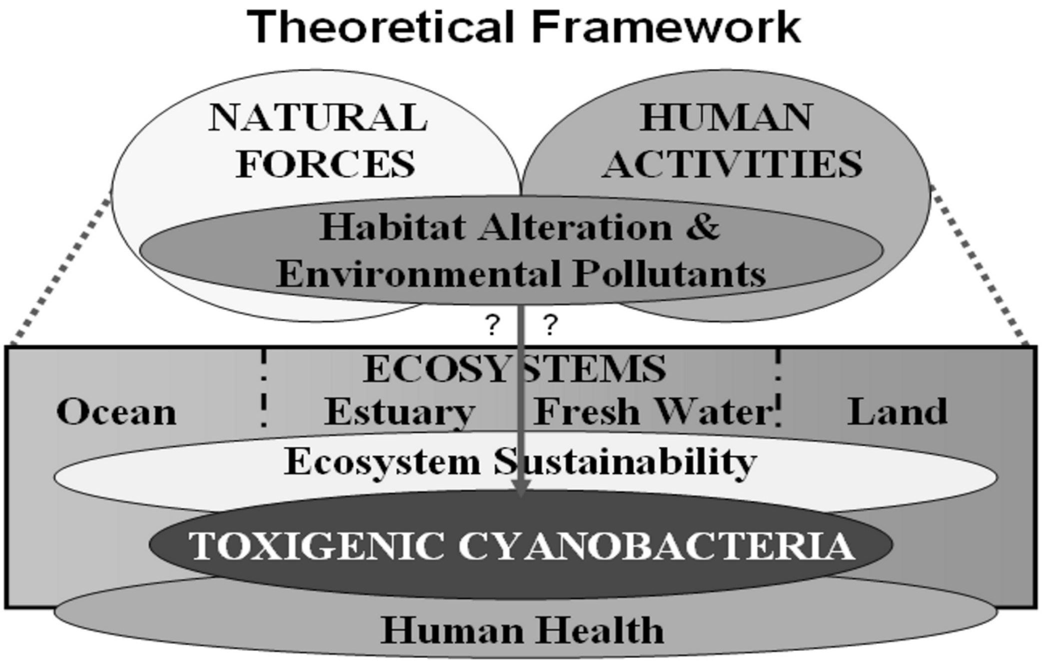

Fig. 1. Both natural forces and human activities may alter habitats in ways that promote the occurrence of cyanobacterial harmful algal blooms, increasing the potential for adverse effects on ecosystem sustainability and human health.

Although CHABs primarily occur in fresh and estuarine waters, there is increasing recognition that cyanobacteria blooms in oceans are threatening the sustainability of some marine ecosystems (Ecosystem Effects Workgroup Report this volume). The recent and unprecedented decline in viable coral reefs worldwide is due in part to marine CHABs (Paul this volume). Species of toxigenic *Lyngbya* adapted to high salinity environments can form benthic mats that expand over an area equivalent to a football field within an hour, causing ecological damage and endangering human health (Australian Environmental Protection Agency 2003).

Cyanotoxins also are found in terrestrial environments where they may pose a risk to human and animal health. Surface waters are increasingly used for field irrigation in agricultural production. Water drawn from sources experiencing toxigenic CHABs is sprayed on crops, producing cyanotoxin-containing aerosols that may be inhaled by humans and other animals, and absorbed by crops. Cyanobacteria can form a symbiotic relationship with terrestrial plants which may biomagnify cyanotoxins. Cyanobacteria of the genus *Nostoc* form colonies on the roots of cycad plants in Guam where for more than 30 years scientists have tried to unravel the genesis of the mysterious neurodegenerative disease that afflicts the native Chamorro population. An amino acid cyanotoxin produced by *Nostoc*, beta methylamino-alanine (BMAA), accumulates in cycad seeds. The seeds are eaten by a species of bat that accumulates high levels of BMAA in its tissues. The bat is a traditional food source for the Chamorro. Analyses detected BMAA in brain tissues of Chamorro victims, leading to the hypothesis that BMAA causes neurodegeneration that may manifest with features of amyotrophic lateral sclerosis, Parkinson's disease, and Alzheimer's dementia. Recent evidence indicates that BMAA is produced by most types of cyanobacteria, and that it may be associated with neurodegenerative diseases elsewhere (Human Health Effects Workgroup Report this volume).

Cyanobacteria and cyanotoxins are clearly hazardous to human health and ecosystem sustainability, but the degree of risk they present is unclear (Risk Assessment Workgroup Report, this volume). Research is needed to accurately assess the risks and provide risk managers with cost effective options for reducing the risks as warranted. A Scientific Assessment of Freshwater HABs can describe a comprehensive approach toward understanding the interconnections between the causes of blooms and toxin production, the characteristics and magnitude of the risks they pose, and the means for reducing the risks through prevention and mitigation strategies. Meeting these objectives requires that relationships between CHABs, humans, and the environment be viewed as a system of interconnected components.

A Systems Approach to Cyanobacterial Harmful Algal Blooms

The concept of a systems approach can be traced back to ancient Greece when Aristotle proclaimed that “The whole is more than the sum of its parts.” A system is generally defined today as a dynamic process that provides the functionality required by users of the system. In engineering, a systems approach integrates multidisciplinary groups into a unified team that develops and implements a process from concept to operation. The application of a systems approach to risk assessment and management issues requires several fundamental components.

- Integration of discovery (i.e., descriptive) science with hypothesis-driven science
- A cross-disciplinary team to develop and implement the system
- Development of new approaches and technologies coupled with tools for data acquisition, storage, integration, and analysis

Whereas a systems approach to CHABs is appropriate, a broad perspective is required to accommodate the stochastic nature of biological and ecological processes. That is, the causes, occurrences, production of hazardous materials, routes of exposure, dosage of hazardous materials, and effects of a CHAB can be viewed as an ordered collection of random variables whose values change over space and time. These components and their interconnections, the processes by which one component at least partially determines the qualities of the next component, form the CHAB pathway. The combination of the CHAB pathway, risk assessment, policy determination, and risk management forms a systems approach to CHABs. A systems approach to CHABs provides the perspective that ecosystems partially determine human well-being, and that humans partially determine ecosystem well-being. To produce the tools required to manage the risks that CHABs impose on humans and ecosystems, it is necessary to characterize the components and their interconnections. Successful risk management tools may target the components and interconnections of the CAHB pathway for disruption to reduce risk.

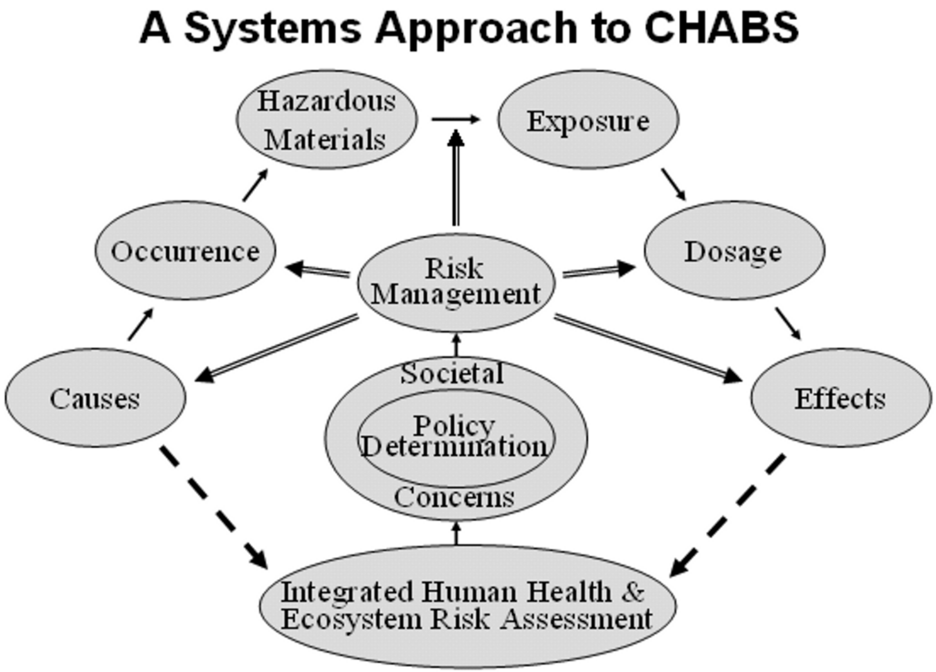

Fig. 2. A systems approach to Cyanobacterial Harmful Algal Blooms. This diagram illustrates the system's components (ovals), their interconnections (thin arrows), the consideration of the entire CHAB pathway during integrated risk assessment (dashed arrows), and some of the intervention targets that, if disrupted, could reduce risk (thick arrows).

The concept of a systems approach for managing the risks of CHABs is illustrated in Figure 2. The nine ovals identify components of a system for characterizing and managing CHABs. The thin arrows between the ovals represent the interconnections between components. The dashed arrows signify the incorporation of all characteristics of the CHAB pathway, from causes to effects, into an integrated approach to the assessment of risks that CHABs pose to human health and ecosystem sustainability. The risk assessment in conjunction with societal concerns such as laws, legal decisions, public values, available technologies, and economic, social, and political factors inform the policy and regulatory process, potentially resulting in the development and implementation of a risk management plan. The thick arrows radiating from the risk management component indicate some of the potential targets for risk management interventions. A system is formed by combining the components and interconnections along the CHAB pathway with the components and interconnections of the risk assessment, policy determination, and risk management processes into a functional unit. Implementation of such a system will provide a dynamic process that helps to prevent, predict, and respond to CHABs to protect human health and the ecosystem.

A starting point for the development of a system to manage CHABs is the identification of areas of uncertainty within the CHAB pathway as shown in Figure 2. Many environmental factors that contribute to the development of CHABs are known (Paerl this volume, Paul this volume). However, the threshold levels of individual factors, the dependence of thresholds on the magnitude of other stressors, and the processes whereby the integration of stressors triggers CHABs are not well characterized. Although actions can be taken to minimize the contribution of known stressors (Piehler this volume), research that better characterizes the interdependence of stressors will enable the development of more targeted and effective risk management tools. Actions also can be taken to terminate CHABs and reduce levels of free toxin in water, but research is needed to more fully characterize the unexpected and untoward environmental impacts of these actions, and to develop interventions that have minimal adverse effects. For example, the use of copper sulfate to terminate CHABs causes high levels of cyanotoxins and potentially toxic levels of copper in water, and the use of flocculants to bind toxins and transport them to the bottom stresses benthic dwellers. Most CHABs produce an extreme biomass associated with hypoxia (Ibelings this volume, Havens this volume), but a CHAB does not necessarily indicate the presence of toxins (Cyanotoxins Workgroup Report this volume, Carmichael this volume). Research that characterizes the processes that trigger toxin production may lead to the development of methods to minimize their production. Field-ready tests that rapidly and inexpensively identify and quantify a broad array of cyanobacteria and cyanotoxins (Analytical Methods Workgroup Report this volume, Meriluoto this volume, Wilhelm this volume, Lawton this volume, Sivonen this volume) are needed to identify the hazardous materials in CHABs to help assess risks so that risk managers can prevent exposure through actions such as public notification. Cyanotoxins occasionally are present in finished drinking water (Burns this volume), indicating the need to develop effective water treatment processes (Westrick this volume). Mathematical models that integrate physical, chemical, and biological variations over space and time are needed to predict the occurrence of CHABs and toxin production to expand the window of time for risk management actions. Medical interventions may reduce the dosage of toxins that reach target sites, and the duration that toxins circulate in exposed humans and animals (Human Health Effects Workgroup Report this volume, Hudnell 2005). Validation of medical interventions to eliminate cyanotoxins and the development of other treatments for affected individuals are needed to supplement the current standard of care in medical practice, supportive therapy. The assessment of risks from toxic exposures requires extensive information on dose-response relationships. CHABs often contain a mixture of cyanotoxins (Humpage this volume), presenting a formidable challenge to cyanotoxin risk assessment (Burch this volume). Equally challenging is the need to quantify CHAB risks to humans and ecosystems holistically, so that risk management actions can be identified that are effective, efficient, and without unintended consequences (Risk Assessment Workgroup Report this volume, Orme-Zavaleta and Munns this volume).

Characterization of the CHAB pathway as the interconnections between CHABs, humans, and the environment provides a basis for integrated risk assessment. The characterization of integrated risks and the development of cost effective interventions will support policy determinations and risk management processes. The primary goals of ISOC-HAB, discussed below, were to describe the state of the science of CHAB system components and interconnections, and to identify research needed to reduce scientific uncertainties and improve risk management processes.

ISOC-HAB Organization, Charges to Speakers and Workgroups, and Products

The ISOC-HAB Organizing Committee identified seven major topic areas and 23 subtopics to be addressed during the symposium (Table 1). Each subtopic was addressed by an invited participant during a platform session.

The primary charge given to each speaker was to describe the state of the science in the assigned area. The major topic areas were addressed by Workgroups for which specific charges also were developed. The primary charges for each Workgroup were to identify research needed to reduce scientific uncertainties and to develop processes that ultimately will provide risk managers with cost-effective tools to prevent and mitigate the effects of CHABs.

Table 1. The seven major topic areas and the 23 subtopics addressed at ISOC-HAB.

Occurrence of CHABS • A US & World Overview • The Florida Experience • The Nebraska Experience • The New York & Great Lakes Experience	Analytical Methods • Sample Preparation • Laboratory Methods • Field Methods • Emerging High Throughput Analyses
Causes, Prevention, & Mitigation • Nutrients and Other Causes • Global Climate Change • Watershed Mangement • Drinking Water Treatment	Human Health Effects • Laboratory Exposures • Environmental Exposures • Epidemiology
Cyanotoxin Characteristics • Types, Toxicokinetics & Toxicodynamics • Genomics & Proteomics • Bioterrorism Potential	Ecosystem Effects • Aquatic Vertebrates • Trophic Status & Ecological Conditions
	Risk Assessment • Economic Impact • Toxic Microbes & Mixtures • Human & Ecological Integration

In addition to the primary charge for each topic area, additional charges were given to each Workgroup. The Organizing Committee realized that there was overlap between some of the topic areas, largely due to the interconnections between components on the CHAB pathway. Similarities among some of the charges given to different Workgroups were intended to promote characterization of the interconnections from a broader diversity of perspectives. All Workgroups were asked to identify factors needed in models to predict the occurrence of events along the CHAB pathway, not for the immediate construction of predictive models, but to help identify research needed to reduce scientific uncertainties. Highlights of the Workgroups' charges are described below.

Occurrence of CHABs

The Occurrence Workgroup was charged with identifying trends in: 1) the spatial and temporal incidence of CHABs in the US and worldwide; 2) the prevalence of specific genera and species in fresh, estuarine, and marine water CHABs; 3) the percentage of CHABs that produce cyanotoxins; 4) the types and mixtures of cyanotoxins that most commonly occur in CHABs; (5) the health and ecological risk potentials of CHABs in recreational and drinking water reservoirs; and (6) the development of guidelines and standards by state and local governments. The Workgroup's primary charge was to identify research needed to remove impediments to the collection of CHAB occurrence data in the US, including implementation of the EPA Office of Water's Unregulated Contaminant Monitoring Rule for drinking water (UCMR 1999).

Causes, Prevention, & Mitigation

The Causes, Prevention & Mitigation Workgroup was charged with identifying research needed to better characterize or develop: 1) the natural and anthropogenic causes of CHAB occurrence and toxin production; 2) watershed management and other tools that reduce the probability of CHAB occurrence; 3) methods for terminating CHABs and removing cyanotoxins from source and drinking waters; and 4) methods for potential inclusion in recreational and drinking water risk management guidelines. The Workgroup also considered factors needed in models to predict cost and benefit relationships for methods that prevent CHABs and remove cyanotoxins from water.

Cyanotoxin Characteristics

Charges for the Cyanotoxin Characteristics Workgroup included identifying research needed to better characterize: 1) methods for rapid and cost effective identification and quantification of known and novel cyanotoxins; 2) the pharmacokinetic properties of cyanotoxin absorption, distribution, and metabolism in animals; 3) the toxicodynamics of cyanotoxin modes of action in the production of adverse health effects; 4) factors that increase and decrease susceptibility to adverse health effects; 5) the genomics and proteomics of cyanobacteria and cyanotoxin production; and 6) methods to reduce the potential risk of cyanotoxin use in bioterrorism. The identification of factors needed in models to predict the production of cyanotoxins during CHABs also was included in the Workgroup's charges.

Analytical Methods

The Analytical Methods Workgroup was charged with identifying and evaluating current methods for detecting and quantifying cyanobacteria, single cyanotoxins, and mixtures of cyanotoxins. The Workgroup's charges also included identifying research needed to develop rapid and cost-effective: 1) field screening kits to identify and quantify cyanobacteria and cyanotoxins; 2) field screening kits to detect genes responsible for cyanotoxin production; 3) laboratory methods to identify and quantify cyanobacteria and cyanotoxins; and 4) laboratory methods to identify the genes responsible for cyanotoxin production. The Workgroup's charges also included the identification of methods needed to produce bulk cyanobacteria and cyanotoxins of known quality, as well as certified toxin standards for use by a broad scientific community.

Human Health Effects

The Human Health Workgroup's charges included the identification of research needed to further characterize: 1) human health effects associated with exposure to particular cyanobacteria genera and species; and 2) human health effects associated with exposure to particular cyanotoxins, individually and in mixtures. The Workgroup's charges also included the identification of existing and needed infrastructure to better assess exposure and effect relationships, including exposure monitoring and health surveillance programs, and internet-based data management and distribution systems. The Workgroup also considered factors needed in models to predict exposure and effect relationships in human populations.

Ecosystem Effects

The Ecosystem Effects Workgroup was charged with identifying research needed to better characterize: 1) effects on biota in land and water ecosystems associated with exposure to particular cyanobacteria genera and species; and 2) effects on biota in land and water ecosystems associated with exposure to particular cyanotoxins, individually and in mixtures. The Workgroup's charges also included the identification of existing and needed infrastructure to better assess exposure-and-effect relationships, including exposure monitoring and surveillance indicators such as sentinel species. The Workgroup also considered factors needed in models to predict exposure-and-effect relationships in aquatic populations, land animals, and ecosystem indicators.

Risk Assessment

The Risk Assessment Workgroup was charged with identifying research needed to: 1) support guideline, criteria and standards, and regulation development; 2) develop tiered monitoring and response systems for fresh, estuarine, and marine waters; 3) develop an integrated human health and ecosystem sustainability risk assessment process; and 4) develop a framework for making policy determinations that encompasses CHAB type, overall risk, and cost/benefit optimization. Also included in the Workgroup's charges were the identification of factors needed in models to predict the cost-and-benefit relationships of risk management tools, and the need to revise or produce new risk management guidelines and regulations.

ISOC-HAB Product & Goals

This monograph contains the proceedings of ISOC-HAB, a series of chapters that describe:

- An overview of ISOC-HAB (this chapter);
- A synthesis of research needed to improve risk assessments and management;
- Seven Workgroup Reports on short- and long-term research needs in the topic areas;
- Twenty-three Speaker Reports on the state of the science in the subtopic areas;
- Fourty-two poster abstracts that describe emerging research in the topic areas.

The monograph is divided into sections corresponding to the major topic areas. Each section contains the Workgroup Report, Speaker Reports, and poster abstracts that address the topic area.

Publication of the ISOC-HAB proceedings in this monograph, and the ongoing publication of materials on the EPA website (http://www.epa.gov /cyano_habs_symposium/) are intended to further the scientific understanding of freshwater harmful algal blooms and provide a resource for:

- Developing the products mandated by Congress through HABHRCA;
- Developing an interagency National Research Plan for CHABs;
- Integrating academic, industrial, local, state, and Federal CHAB research;
- Informing EPA's Office of Water and other Federal institutions;
- Informing states, Indian tribes, and local governments;
- Informing industries, academic institutions, and non-governmental institutions;
- Informing other countries confronting the risks posed by CHABs

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