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Cyanobacterial Harmful Algal Blooms: Chapter 9: Causes, Prevention, and Mitigation Workgroup Report

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Chapter 9: Causes, Prevention, and Mitigation Workgroup Report

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Introduction

Cyanobacteria (blue-green algae) are estimated to have evolved 3.5 billion years ago, at which time they began to add oxygen to the existing anaerobic atmosphere, actually changing the chemistry of the planet and allowing new life forms to evolve. These ubiquitous microbes are capable of tolerating desiccation, hypersalinity, hyperthermal conditions, and high ultraviolet radiation, often for extensive periods of time. Recently, cyanobacteria have responded to human alterations of aquatic environments, most notably nutrient-enhanced primary production, or eutrophication. In fact, cyanobacterial blooms are now viewed as widespread indicators of freshwater, brackish and marine eutrophication.

Due to the complex interactions between physical and ecological processes, it is difficult to point to any single, definitive ***cause*** for the development and proliferation of these blooms. In reality, cyanobacterial harmful algal blooms (CHABs) likely result from a combination of factors, including hydrology, available nutrients, sunlight, temperature, and ecosystem disturbance; any number of which must interact in precisely the right combination to create optimal conditions for growth. Thus, it should come as no surprise that successful ***prevention*** (inhibiting bloom formation

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Causes, Prevention, and Mitigation

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through the manipulation of causative factors) and ***mitigation*** (ameliorating the effects of and/or controlling the blooms themselves) strategies for dealing with CHABs, may require correspondingly complex approaches.

This document examines possible causative factors that have been implicated in the initiation and maintenance of cyanobacterial blooms, methods for bloom prevention, and techniques for managing the risks posed by cyanobacterial blooms and their toxins. The material presented reflects the views of the workgroup participants about the current state of CHAB knowledge and identifies the research needs and priorities necessary for addressing the problem. All identified research needs are considered to be “high-priority”, and are classified as “near-term” and “long-term” because the completion of certain research tasks is dependent upon the completion of other. Therefore, the numerical ordering of research goals below does not indicate prioritization, but is for ease of reference only. This product is a direct response to the charges that were received by the workgroup, and it is organized according to four topic areas as shown below:

- **Causes -** Identify and prioritize research needed to better describe factors contributing to CHAB initiation, maintenance, and termination in fresh, estuarine and marine waters, recognizing the interconnectivity of systems.

- **Prevention (pre-bloom efforts)** - What are the best prevention options available right now for use by managers? Are there easily identifiable factors that will improve their efficacy? Identify and prioritize research to improve land and water management strategies for preventing or minimizing CHABS, focusing both on techniques that are currently available and emerging approaches in fresh, estuarine, and marine water environments with the intent of providing guidelines to managers.

- **Control/Mitigation (post-bloom efforts)** - Can draft guidelines for controlling and mitigating CHABs be developed now for use by managers? If not, identify and prioritize research to improve processes for removing cells and toxins from fresh, estuarine, and marine water bodies and drinking water, focusing both on current and emerging techniques with the intent of providing guidelines to managers.

- **Economic Analysis** - What ecological factors should be included in models used to predict the relative costs and benefits of processes used to prevent or reduce the occurrence of CHABS in water bodies and cyanotoxins in drinking water?

Overarching Themes

In this workgroup's initial discussions, it quickly became evident that there were a number of overarching issues - areas of concern that were necessary to take into account when addressing the CHAB problem, but that did not fit neatly into the four categories of charges above. Instead, these issues extend across the topics and charges, such that they are a vital part of the entire framework for examining the causes, prevention, and mitigation of CHABs.

The Freshwater – Marine Continuum

There is general agreement that CHABs are a world-wide, rapidly-expanding water quality, human health, and ecosystem problem (Paerl, 1988; Chorus and Bertram, 1999). Furthermore, planktonic and benthic CHAB proliferation is not necessarily confined to any particular type of aquatic habitat, with recent expansions noted across a spectrum of ecosystems ranging from previously pristine mountain streams and springs to large lakes, estuaries and coastal seas (Paerl and Fulton, in press). One commonality of systems impacted by CHAB expansion is that their water and air-sheds are experiencing accelerating human population growth accompanied by increased nutrient and other pollutant loadings, as well as hydrologic modifications. There is little doubt that there is strong linkage between human use and modification of water and air-sheds and CHAB dynamics. In addition, climatic changes, including changes in large storm (i.e., hurricane), flood and drought frequencies and intensities have impacted nutrient and hydrologic regimes of these systems. Identifying causes and formulating prevention and mitigation strategies must take human and climatic factors and drivers into consideration. Because the impacted aquatic ecosystems and their drainage basins are inextricably linked, research, monitoring and management approaches must address the CHAB issue across the freshwater-marine continuum. In most instances, CHAB dynamics are not confined to a single component system and often cross a salinity gradient. Thus, causes and effects must also be traced and addressed across this continuum. Accordingly, the operational scale at which CHAB issues should be assessed and ultimately managed is that of this continuum, which, depending on the specific problem may include habitat, ecosystem, and regional levels.

Relevant Scales for Research and Management

CHAB occurrence is influenced by interacting meteorological, hydrological, physiochemical, and biological factors on a variety of spatiotemporal scales. For example, discernable ecological patterns are often influenced by the specific spatiotemporal resolution associated with the study, and results may change with scale. Additionally, global, regional, and local factors all influence the timing, magnitude, and duration of CHABs. Thus, macro-, meso-, and micro-scale studies, as well as studies involving the incorporation of more than one of these scales, are necessary to adequately describe the regulatory factors driving CHAB formation and to identify the most effective scale at which to implement management efforts. Key spatiotemporal scales include: a) global studies to assess long-term (decadal) changes in climate, environmental patterns, and eutrophication with respect to the apparent increase in CHAB development over the last fifty years; b) ecoregion and air/watershed studies to assess the impacts of moderate to long-term (years) changes in emission of pollutants, land-use practices, and watershed/waterbody management on CHAB formation; and c) ecosystem, community, and population studies to assess the influence of near-term (hours to seasons) changes in the environmental and physiological factors that influence CHAB occurrence, magnitude, and duration.

Monitoring

The first step in understanding the prevalence and severity of CHABs is monitoring. Monitoring includes a variety of techniques that range from collecting discrete water samples that are analyzed for the presence of cyanobacteria, to continuous-flow instruments that measure pigments that are unique to this group of algae. The types and quantities of cyanobacteria are an indicator for the types and quantities of cyanotoxin that may be present. Monitoring also provides early warning so that human health can be protected before serious problems develop. The ultimate aims are to determine: 1) whether toxin-producing cyanobacteria are present; 2) the concentration of organisms of concern; 3) if the population and/or toxin level(s) are increasing or decreasing; 4) the current level of impact; and 5) the development, transport, and dissipation of the bloom and bloom impacts.

The design of a monitoring program should be tailored to the specific issues in a waterbody. For example, monitoring a reservoir used for drinking water should focus on the areas near the water intake structure(s) or the actual raw water brought into the facility. The timing of sampling in reference to the seasonal occurrence of the cyanobacterial bloom should also be considered, with little or no sampling needed in cold months, and more intense sampling during warmer seasons and bloom development. If feasible, information on the conditions that initiate or sustain bloom formation should be collected so that models can be developed to better understand and predict blooms. Understanding the causes of blooms will ultimately lead to better methods of prevention.

For recreational waters, wind-driven currents often cause buoyant cyanobacterial blooms to amass on shorelines. These accumulations contain orders of magnitude more cyanobacterial cells than blooms in open water areas, thus presenting more of a health risk to humans and animals. Monitoring the spatial location of these accumulations is important in determining the maximum potential exposure during a bloom; however, it is difficult to quantify the number of organisms present. Many cyanobacteria are capable of regulating their buoyancy on a diurnal basis as a function of their internal physiology. Thus, integrated water sampling throughout the entire water column may be needed in open waters. For example, *Cylindrospermopsis,* which does not form a surface scum, inhabits mid-water depths at lower light intensities, necessitating integrated water sampling.

At the core of many monitoring systems are the sensors and the platforms on which they are deployed. One of the greatest needs in this field is the development of quantitative, easy-to-use, rapid sensors of CHAB cells and toxins in natural planktonic and benthic assemblages for use across hydrologically and geographically variable ecosystems at multiple scales. Although microscopic identification and counts are needed for verification, they are time consuming, require expertise often not available, and in the case of filamentous and colonial taxa, (e.g. *Microcystis*, *Nodularia*, *Anabaena*, *Aphanizomenon*) lack quantitative rigor. New techniques for monitoring, such as the use of diagnostic photopigments and various molecular approaches, are under development and will provide additional tools for helping to understand the potential health risks associated with cyanobacterial blooms. Satellite images and spectra from airborne radiometers showing ocean color and sea surface temperature have been used for detecting and tracking cyanobacterial blooms. However, there are other potential remote sensing techniques that can be developed and implemented as currently available satellites are phased out. There is a need for sensors that provide additional information about other environmental factors, such as nutrients, in order to understand the role of human activities in causing blooms. There is also a particular need for sensor systems applicable to large lake, estuarine and coastal ecosystems. These environments require large numbers of samples and rapid throughput, necessitating the development and deployment of sensors on unattended monitoring platforms, including buoys, AUVs (automated underwater vehicles), aircraft, ferries, and other "ships of opportunity" as well as satellites.

Modeling

Mathematical models are needed to better understand CHABs and their relationships to the surrounding environment. Models will help to establish a basic framework for relating potential causative factors to the occurrence of CHABs, improve our understanding of the conditions that initiate toxin production, characterize the factors that maintain CHABs under various conditions, and to both develop and measure the efficacy of various management strategies.

In order to develop these models, whole watershed research projects are needed in which nutrient exports from controlled agricultural watersheds are monitored and compared to those that have methods in place to aggressively reduce nutrient export from non-point source pollution. These should be long-term research/monitoring sites at which hydrology as well as nutrient and sediment export can be studied over decadal time frames, since system response to land use change occurs over many years. This type of critical, watershed-level research would be analogous to the research done at Hubbard Brook which led to improved understanding of the consequences of acid rain and harvest practices on ecosystem biogeochemistry. Such studies could be undertaken in partnership with the National Science Foundation in coordination with targeted funding from other agencies, such as the Environmental Protection Agency, the US Geological Survey, the National Oceanic and Atmospheric Administration, and the National Aeronautics and Space Administration, for important ecosystem-level research such as that proposed for hydrologic observatories and/or national observation networks. Long-term data is crucial to the development, refinement, and validation of explanative and predictive models.

Modeling and mapping of regional risk levels could help target locations for monitoring programs and process-based research on causes and prevention of CHABs. Methodology could include the use of enhanced geodatabases of harmful algal bloom (HAB) occurrence and attributes of the systems in which they occur (developed by water body type) in conjunction with statistical exploratory data analysis methods to assist in initial model development and threshold determination (e.g., CHAID, Chi-squared Automatic Interaction Detector).

Infrastructure Needs

The ability to understand the causes of CHABs, so that they can be predicted, monitored, controlled, and prevented is dependent on the availability of critical infrastructure. These infrastructure needs were laid out in detail for all HABs in HARRNESS (2005). Reference materials and shared-use analytical facilities are needed so that scientists and managers can quickly and easily identify HAB species and toxins in cells, water, air, and other organisms. Certified toxin standards and HAB-specific probes must be readily available for routine use at reasonable cost. Taxonomic training for identifying HABs, using both morphological and new molecular methods, must be widely available at levels suitable for a range of expertise from local managers to expert researchers. Culture collections and tissue banks can be used to archive newly isolated species and samples from exposed animals for later study. Regional observing systems, now in the planning stages, should be developed with the capability of monitoring for CHABs. Platforms for remote sensing of HABs, such as satellites and in situ moorings, equipped with HAB cell or toxin-specific sensors, need to be developed. Finally, old HAB data must be rescued before it is lost; common data management plans must be developed and data repositories must be established so that raw data, as well as associated metadata, can be shared and large scale/long-term analyses can be conducted.

In the long-term, research programs cannot provide funding to support infrastructure. However, as HABs occur more often, and their impacts continue to intensify, the need for national and regional infrastructure support programs with a long-term funding base will also become more urgent (HARRNESS 2005).

Sample Guidelines (modified from the Wisconsin Division of Public Health's fact sheet on cyanobacteria, and their toxins, and health impacts)

Source: http://dhfs.wisconsin.gov/eh/Water/fs/Cyanobacteria.pdf

- Never drink untreated surface water, whether or not algal blooms are present. Boiling the water will not remove toxins. Owners should always provide alternative sources of drinking water for domestic animals and pets, regardless of the presence of algae blooms.
- If washing dishes in untreated surface water is unavoidable, rinsing with bottled water may reduce possible residues.
- People, pets and livestock should avoid contact with water where algae are visible (e.g., pea soup, floating mats, scum layers, etc.) or where the water is discolored. Do not swim, dive, or wade in this water. Do not use the water to fill a pool or for an outdoor shower.
- Always rinse off yourself and your pet after swimming in any ponds, lakes or streams, regardless of the presence of visible algae blooms. Pay close attention to the bathing suit area and pet's fur.
- Contact your local health department or department of natural resources office to report any large algae blooms on public or private lakes, streams or ponds.
- Never allow children or pets to play in or drink scummy water. Do not allow pets to eat dried scum or algae on the shoreline.
- Do not water-ski or jet-ski over algae mats.
- Do not use algaecides to kill the cyanobacteria. When the cyanobacteria cells die, the toxins within the cells are released.
- Obey posted signs for beach closings. Wait at least one to two weeks after the disappearance of cyanobacteria before returning to the water for wading, bathing or other activities.

Outreach/Education

In order to empower individuals and communities to act on environmental issues, it is necessary to increase environmental awareness through coordinated environmental education efforts. The public must be informed about known or potential cyanobacterial problems in their recreational waters or drinking water supplies, as well as the risks associated with them, so that they can make educated decisions based on that information. Some states have produced short informational documents that are available on the internet and/or disseminated via kiosks at or near impacted recreational areas. These informational documents usually explain what cyanobacteria or blue-green algae are, what algal blooms are, how to recognize a bloom, where blooms occur, and what conditions promote bloom development. They also describe the health effects that could occur with exposure to cyanotoxins, including typical symptoms. Other important information should be included about routes of exposure, so the public will understand how they or their animals are exposed to the toxin, such as the swallowing of a surface scum, contact with the skin, or inhalation of aerosols during swimming, bathing or showering in contaminated waters. This should be followed by suggested ways in which people can avoid or limit their exposure. Finally the public needs to be educated about the causes of HABs and informed about steps that concerned citizens or their representatives can take to prevent blooms or minimize their impacts.

Charge 1: Causes

Identify and prioritize research needed to better describe factors contributing to CHAB bloom initiation, maintenance, and termination in fresh, estuarine and marine waters, recognizing the interconnectivity of systems.

From research and management perspectives, identifying environmental factors which cause and sustain CHABs is key to developing an understanding of how to predict, prevent, and control these unwanted occurrences. While we know that nutrient and hydrologic conditions strongly influence harmful planktonic and benthic CHAB dynamics in aquatic ecosystems, and observations have shown that increased urbanization, agricultural and industrial development have led to increased nitrogen (N) and phosphorus (P) discharge, there are many other factors that remain unidentified, unquantified or unexplored. For example, additional factors such as N:P ratios, organic matter availability, light attenuation, temperatures, freshwater discharge, flushing rates (residence time) and water column stability likely play interactive roles in determining CHAB composition (i.e., N_2 fixing vs. non-N_2 fixing taxa) and biomass. Human activities may influence these factors either directly, by controlling hydrologic, nutrient, sediment and toxic discharges, or indirectly, by influencing climate.

Nutrients

Among the nutrient elements required for aquatic plant growth, N and P are often most stimulatory, because requirements are high relative to availability. It follows that N and P enrichment are often most effective in stimulating and supporting blooms in receiving waters (Fogg 1969, Reynolds and Walsby 1975). These elements have, and continue to be, the focus of efforts aimed at controlling blooms (Likens 1972, Schindler 1975, Shapiro 1990), although there is increasing interest in the role of trace metals in some systems. The most notable of these trace metals is iron (Fe) in its soluble form Fe^{++}. Iron is required for the synthesis and activity of photosynthetic, N_2 fixing and N assimilatory enzymes. Unlike N and P, Fe inputs are not strongly linked to human activities, such as agriculture, urbanization and most industrial activities. Rather, Fe availability is more often controlled by natural weathering or rocks, aeolian processes (dust transported by wind), and within-system oxygen (e.g., hypoxia) and biogeochemical (redox) cycling.

Excessive P (as orthophosphate) loading has been shown to promote potentially-toxic nitrogen (N_2) fixing genera (i.e., *Anabaena*, *Aphanizomenon*, *Cylindrospermopsis*, *Nodularia*), while excessive P and N (as dissolved inorganic N; nitrate and ammonium) loading can stimulate toxic blooms of non-N_2 fixing genera (*Microcystis*, *Lyngbya*, *Planktothrix*). From a supply standpoint, both the absolute amounts and relative proportions of these nutrients play important roles in determining the composition, magnitude, and duration of CHABs. There is also evidence that the production of toxic substances by CHABs is at least in part determined by the amounts and ratios of nutrients and trace metals supplied to affected water bodies (Sivonen, 1996; Skulberg *et al.,* 1994; Giani *et al.,* 2005).

Nutrient supply rates strongly interact with other environmental factors, including light, turbulence and flushing rates, temperature, pH (and inorganic C availability), salinity, and grazing pressure to determine; 1) *if* a specific water body is susceptible to CHAB formation, 2) the extent (magnitude, duration) to which CHABs may dominate planktonic and or benthic habitats, and, 3) whether an affected water body is amenable to management steps aimed at minimizing or eliminating CHABs.

Further research is needed to investigate the diversity of CHABs, including N_2 fixing and non-N_2 fixing groups, different cyanobacterial species, and toxic and non-toxic strains.

Near-term Research Priorities

1. Conduct retrospective analyses of long-term changes in eutrophication and CHABs especially in areas where eutrophication has been reversed by management actions (e.g., Lake Washington in the US, Lake Erken in Sweden, and other European water bodies). The purpose is to provide an independent approach to understanding the role of nutrients with regard to blooms and how to reverse the impacts.
2. Determine the response of a variety of N_2 fixing and non-N_2 fixing CHAB organisms to nutrients under controlled conditions in the laboratory and in the field with water enclosures (micro- and mesocosm experiments).
   - Examine and evaluate the selective impacts of various forms of nitrogenous (nitrate, ammonium, organic N) and phosphorus (orthophosphate, organic P), and nutrient ratios on CHAB growth, bloom dynamics and toxin production.
   - Determine the role(s) of iron and trace metals, alone or in combination with macronutrients, on CHAB growth, bloom dynamics and toxin production.
   - Determine the role of other environmental conditions, such as light intensity and quality, temperature, and water column stability on nutrient utilization and toxin production.
3. Conduct ecosystem-scale field studies, combined with use of monitoring data to determine how nutrient supplies and ratios interact with other anthropogenic stressors, the rest of the biota, hydrology, light, local weather patterns and climatic changes, vertical mixing, residence time, and benthic/pelagic coupling to control CHAB dominance and bloom occurrence and toxicity.

Long-term Research Priority

1. Develop models that can be used to predict CHAB bloom events and evaluate the effectiveness of preventive measures, such as setting Total Maximum Daily Loads based on current nutrient and turbidity conditions.

Climate Change

Considerable evidence indicates that the Earth and the oceans have warmed significantly over the past four decades, suggesting long-term climate change. Increasing temperatures and changing rainfall patterns have been documented. Cyanobacteria have a long evolutionary history, with their first occurrence dating back to at least 2.7 billion years ago. They evolved under anoxic conditions and are well adapted to environmental stressors including UV exposure, high solar radiation, high temperatures, and fluctuations in nutrient availability. These environmental conditions favor the dominance of cyanobacteria in many aquatic habitats, from freshwater to marine ecosystems. The responses of cyanobacteria to changing environmental patterns associated with global climate change are important subjects for future research. Results of this research will have ecological and biogeochemical significance as well as management implications.

Near-term Research needs

1. Retrospective analyses of existing literature, long-term observational programs and datasets of environmental patterns coupled with cyanobacterial abundance to examine the relationships between global change parameters and regional expansion of CHABs along temperature, precipitation, and nutrient gradients.
2. Studies of physiological conditions for cyanobacterial bloom dynamics and toxin production in different species and strains in relation to a variety of abiotic factors (e.g., temperature, light, UV, CO_2, pH).
3. Experimental (mesocosm, manipulative) studies to decouple various climatic and anthropogenic factors (e.g., temperature, light, UV, CO_2, nutrients).

Long-term Research Needs

1. Couple above-mentioned approaches, techniques and indicators to ongoing and developing observational programs (IOOS, IEOS, Coastal GOOS, etc.).
2. Develop models for predicting influence of climate change on occurrence and toxicity of CHABs.

Food Webs

Food web interactions may impact cyanobacteria bloom dynamics both positively and negatively. For example, outbreaks of cyanobacteria blooms in some US lakes appear to be partly stimulated by the arrival of recently established zebra mussel populations (*Dreissena* sp.; Vanderploeg et al. 2001, Raikow et al. 2004). However, the relationship between zebra mussels and toxic cyanobacteria has been temporally and spatially inconsistent. Some reports indicate that zebra mussel invasions have yielded increased cyanobacteria bloom occurrences (Vanderploeg et al. 2001, Raikow et al. 2004) while others state that zebra mussels have decreased densities of toxic cyanobacteria in NY waters (Caraco et al. 1997, Smith 1998). Moreover, many freshwater systems without zebra mussels experience very intense blooms of toxic cyanobacteria (Chorus and Bartram 1999). Intense grazing by herbivorous or planktivorous fish could also directly or indirectly promote blooms either through a trophic cascade or by consuming competing algae. However, these questions have yet to be investigated.

Laboratory experiments and field-work from ecosystems around the globe have indicated that grazing by some zooplankton can be disrupted by toxic cyanobacteria (Lampert 1987, de Bernardi and Giussani 1990, Sellner et al. 1993, Boon et al. 1994, Christoffersen 1996, Paerl et al. 2001) or negatively influenced by the secondary metabolites produced by cyanobacteria (Pennings et al. 1997, Nagle and Paul 1998 and 1999, Capper et al. 2006). Thus, the chemical defenses of cyanobacteria may play a critical role in bloom formation and persistence by limiting the grazing activity of potential consumers. In many systems which experience dense and/or toxic blooms, both cladocerans and copepods can be impacted, experiencing reduced feeding, reduced food assimilation or even mortality (Lampert 1987, de Bernardi and Giussani 1990, Paerl et al. 2001). However, the degree to which zooplankton and other consumers graze cyanobacteria blooms can be influenced by many factors including toxin concentrations, strains of cyanobacteria species, species of herbivore, various environmental conditions (Paerl 1988, Sellner et al. 1993, Boon et al. 1994, Christoffersen 1996, Nagle et al. 1998) and, perhaps, prior exposure to toxins (Walls et al. 1997, Hairston et al. 2001, Sarnelle and Wilson 2005).

Research is needed to clarify the role of food web interactions in the occurrence of CHABs. Research should strive to understand how these interactions impact the proliferation of different CHAB species and strains (i.e. toxic and non-toxic), as well as co-occurring, non-HAB species.

Near-term Research needs

1. Describe the ability of various clades of zooplankton (protozoa, cladocerans, copepods) and other consumers to graze individual CHABs species and strains relative to non-HAB species.
2. Determine how alteration of upper trophic level predator densities (e.g. fish) ultimately impacts the development of CHABs via alteration of aquatic food webs.
3. Determine the impact of benthic filter feeders on the development of CHABs and how this impact may vary with ecosystem trophic status.
4. Assess the impact of invasive species on the occurrence (development or prevention) of CHABs.
5. Assess the interactive effects of nutrients and climate change on food web interactions relative to the occurrences of CHABs.

Charge 2: Prevention (pre-bloom) through *Watershed Management*

What are the best prevention options available right now for use by managers? Are there easily identifiable factors that will improve their efficacy? Identify and prioritize research to improve land and water management strategies for preventing or minimizing CHABS, focusing both on techniques that are currently available and emerging approaches in fresh, estuarine, and marine water environments with the intent of providing guidelines to managers.

Eutrophication has long been known to be a major causal factor producing HABs (Chorus and Muur 1999, Paerl this volume). Current measures to reduce eutrophication and CHABs address the source, transport and fate of nutrients and include: 1) land management for reduction of nutrient export (USDA SCS 1996); 2) water management to minimize nutrient transport (e.g., hydrologic manipulation and water management practices such as removal or routing of water for irrigation, timing and extent of flow released from dams, etc.); and 3) water management to minimize impact of available nutrients in ambient water. These three approaches are discussed in detail in the following sections. All can be utilized both to prevent CHABs from occurring and to reverse the effects of excess nutrients in existing eutrophic systems.

In general, research in the area of prevention through watershed management must include research components across two major temporal scales of relatively equal importance; first, research into effective means for reducing and reversing eutrophication of aquatic systems over the long-term, and second, research into methods to reduce the impacts of existing eutrophication and decrease the likelihood of CHABs in the interim. Research at multiple spatial scales is needed to guide design and placement of strategies to reduce and prevent eutrophication, and to inform efforts to mitigate and reverse effects of excess nutrients in existing eutrophic systems. There is also a need to develop generalizable (across system) intrinsic indicators of land use and land use change that can be applied as predictive tools for CHAB potential (e.g., influence on stream flow and hydrodynamics).

Here, we outline and prioritize research needs in the area of CHAB prevention. In addition to the charge as described above, we also asked, what important data must be gathered to assure that prevention plans are as sound and successful as possible? Following are the priorities for research to improve watershed management strategies aimed at preventing or minimizing CHABs. The priorities focus both on currently available techniques and emerging approaches in fresh, estuarine, and marine water environments with the intent of providing guidelines to managers.

External vs. Internal Nutrient Control

Nutrient supplies often control the growth of CHABs in aquatic systems and managing nutrients is a common approach to preventing CHAB proliferation. Because nutrients are available through both internal and external sources, strategies must account for both sources and consider which type is more appropriate for management. Consideration of internal supplies is also crucial because many aquatic systems will not respond to reduction of external nutrients because of enormous internal stores. Triggers for internal loading are often distinct from those for external loading. External loading is often triggered by precipitation or river loading, whereas internal loading can be triggered by diverse mechanisms including changes in sediment redox potential and wind events.

Near-term Research Needs

1. Improve the understanding of the importance of internal and external supplies of nutrients in the full range of aquatic systems.

Long-term Research Needs

1. Of particular need are cost-benefit models that accurately predict the relative benefits and feasibility of internal and external nutrient supply management.

Land Management

The development of regionally appropriate land management practices for reduction in nutrient applications and exports draws upon two bodies of prior research. First, the US EPA has developed a classification scheme for dividing the US into regions on the basis of their geologic, physiographic, hydrologic, and water quality characteristics (Omernik 1987, Griffith et al. 1994). This framework can be used to guide the development of regional research plans and strategies for reducing the occurrence of CHABs. Second, the USDA (USDA SCS 1996) along with agronomists and agricultural specialists (Keeney 1990) have been working for decades to develop sustainable agricultural practices that will reduce the environmental impact of agriculture, and in particular, decrease erosion and sediment and nutrient export from cropland. The USGS programs for monitoring streamflow and water quality in multiple basins across the US are absolutely critical to understanding the interaction of management practices and water quantity and quality in producing CHABs. These USGS programs (such as the National Water-Quality Assessment Program) must be supported and continued if we are to have the long-term hydrologic data needed to understand existing conditions and trends, and to inform predictive models.

Arrays of methods already exist for decreasing nutrient exports through land management practices on agricultural lands (USDA NRCS 1997, SCS 1996). Mitsch et al. (2001) outlined the nature and extent of management practices needed to substantially reduce N export from the Mississippi River Basin, whereas authors of other studies (Vache et al. 2002, Santelmann et al. 2004, Boody et al. 2005) designed and evaluated watershed-specific alternative future landscapes to estimate the impact of the practices in the various alternative designs on flow, N (as nitrate), and erosion or sediment export. Most of the existing studies focus on N as the nutrient of interest. However, P export (often strongly influenced by sediment) and

N:P ratios have been found to be extremely important in determining the occurrence of CHABs. Research is needed to better understand the effects of various land management practices on P and sediment as well as N.

In order to guide policy and quantify the benefits of programs to reduce eutrophication, research is needed to decide what practices should be employed, where they should be implemented, and to what extent they should be used. Multi-scale, systems-level research is needed to understand and quantify watershed (areas on the order of 10,000 to 100,000 ha.) and basin (areas on the order of 100,000 to 1,000,000 ha) response to land use and management measures, as well as uncertainty and variability inherent in the system response. Because the appropriate methods to reduce nutrient exports will vary among regions, research is needed to design effective approaches and to implement methods appropriate to the region in which they are to be used (Santelmann et al. 2001). Finally, all future research should involve regional experts and stakeholders who can: 1) identify regional goals, benchmarks and timetables for achieving those goals; 2) develop regional strategies to achieve those goals; and 3) ultimately decide how to best implement strategies that include specific practices that either reduce nutrient applications, enhance nutrient uptake/ removal, or prevent movement of excess nutrients to aquatic systems.

Near-term Research Needs

1. Describe the effects of various land management practices on P, N, and sediment, export from land to waterbodies.
2. Assess the effectiveness of constructed wetlands as a management strategy for CHABs, to determine their ability to remove nutrients, and to determine the effects that resulting N:P rations will have on downstream aquatic systems.
3. Perform basin-scale research to help optimize site-selection for restored or constructed wetlands in watersheds.
4. Similarly, in lotic systems, describe the potential effectiveness of practices such as riparian plantings along streams and rivers to shade and cool streams.

Water Management

Water management activities to effectively reduce the occurrence of CHABs must focus on methods for mitigating effects of nutrients already present in such systems (e.g., dynamics of sediment-bound P), and efforts to manage the hydrodynamics of these systems to dilute nutrients at key points in the season during which low flows increase the probability of CHABs.

An entire mosaic of aquatic habitats is affected by water management, global climate change, and relative sea level rise. Freshwater supplies downstream will be affected by changes in consumptive uses, releases from reservoirs, and changes in precipitation. Increases in relative sea level rise will push salt water farther upstream. Successful research in this area will require a broad national campaign, conducted within each major eco-region, with priority given to regions in which the occurrence of CHABs is increasing, to examine the interactive effects of freshwater flow modification on nutrient supplies, hydrologic properties, and temperature. For example, increasing freshwater discharge has been shown to reduce the prevalence of CHABs in some water bodies by decreasing residence time and destratifying the water column. Among the methods for increasing freshwater discharge is removing impediments to flow, including dams and reservoirs. The impacts of removal of these structures on nutrient transport downstream, perhaps through enhanced discharge or changes in nutrient inputs, should be modeled prior to implementation and assessed post-implementation. This research will assist in the development of models to forecast the net implications for CHABs that may result from the removal of in-stream obstructions. System responses and practices considered appropriate for the region will vary from region to region, but general principles should be developed.

Additionally, trophic interactions and processes within aquatic systems can be managed to prevent movement of nutrients from compartments in which they are less likely to induce harmful algal blooms (e.g., sediments or deep in the hypolimnion) to compartments in which they are more likely to promote algal blooms (water column or metalimnion). Alternatively, ecosystem trophic structures may have been altered by human activities so that top-down controls on CHABs are no longer effective. In the near-term, although we may not be able to rapidly reverse the eutrophication of aquatic systems which has proceeded over the past half-century, we may be able to manipulate the system to favor the growth of aquatic macrophytes and algal species that are more amenable to removal or remediation, or less harmful while progress is made in efforts to reduce eutrophication. According to Chorus and Muur (1999), measures addressing light availability or targeting aquatic community trophic structure (e.g., biomanipulation) tend to be most successful in less eutrophic situations, but such measures may also accelerate restoration in highly eutrophic water bodies.

Near-term Research Needs

1. Develop tools to predict changes in aquatic habitat that will result from a variety of global climate change and water management scenarios, and to predict the net effects of such changes on the occurrence of CHABs.
2. Models that describe CHAB dynamics in relation to causative factors and ecosystem trophic structure are needed to evaluate prevention and mitigation measures.
3. Determine the community dynamics of CHABs at the wetland-water body interface, the potential interactions among CHABs and wetland vascular plants, and trophic interactions that might be manipulated to reduce the probability of CHAB occurrence.
4. Describe the conditions under which the aforementioned mitigation measures can be employed effectively.

Unintended consequences

It is often easier to focus on one problem at a time, but because CHABs likely result from a variety of causes, care must be taken in regard to unintended or secondary effects when manipulating some causative factors. For example, current regulations and monitoring schemes have focused largely on control of N. Phosphorus, however, has been shown to be a key nutrient in the determination of CHAB occurrence. If regulatory strategies focus exclusively on N, reductions in N concentrations could shift N:P ratios toward the conditions that strongly favor cyanobacteria rather than other, less harmful algal taxa (Piehler et al. 2002).

Near-term Research Need

1. Evaluate existing management practices and regulatory measures for their potential impacts not only on N, but on P and sediment (and perhaps other nutrients such as iron) as well, so that they can be optimized to prevent CHABs.

Establishing thresholds: uncertainty and phase shifts

Significant attention has been focused on identifying threshold levels of physical and chemical drivers that cause major destabilizing shifts in previously stable ecosystems (Scheffer et al. 2001). This response in ecosystem function to forcing mechanisms can have enormous ecological, economic, and management implications. For example, better constraints on ecosystem thresholds provide context in which to interpret long-term monitoring data such as nutrient levels and CHAB prevalence. It also has bearing on remediation efforts because phase shifts and hysteresis may make it impossible to return a system to its original 'pristine' state.

Near-term Research Need

1. Determine the relationship between drivers (e.g., nutrients, hydrologic modification) and CHABs responses (e.g., productivity, toxicity) in the freshwater-marine continuum to improve our understanding of threshold attainments to cause sudden changes in the response variables.

Sociological Impediments

The implementation of management strategies for environmental change often requires difficult societal decisions. Thus, an understanding of public perception regarding the benefits and values associated with controlling CHABs is critical in designing successful management plans. The choices required to control CHAB prevalence may carry significant costs, and without an understanding of the full range of benefits that result from CHAB control, a true cost-benefit analysis cannot be presented to inform policy determinations. Targeting funding to watershed-based programs where residents are actively working to improve water quality and ecosystem function may help develop "model watersheds" that will assist in quantifying the economic benefits of CHAB control. Programs should be selected to provide an array of watersheds that represent variety of different land use and management practices.

Long-term Research Needs

1. Describe societal obstacles to changes that would reduce nutrient inputs to water bodies and sociopolitical strategies to help overcome these obstacles in order to implement any of the practical solutions to the problems that have produced CHABs.
2. Develop comprehensive and accurate cost-benefit analyses of CHAB control that are based on both pre- and post-implementation evaluations of CHAB control practices.

Charge 3: Control/Mitigation (post-bloom)

Can draft guidelines for controlling and mitigating CHABs be developed now for use by managers? If not, identify and prioritize research to improve processes for removing cells and toxins from fresh, estuarine, and marine water bodies and drinking water, focusing both on current and emerging techniques with the intent of providing guidelines to managers.

Cyanobacterial toxins in recreational and drinking waters have become an increasingly visible public health and environmental issue, both nationally and internationally. Newspaper headlines, recreational water closings, and reported animal deaths have contributed to this greater visibility. To control the risk from cyanobacteria and their toxins, it is important to implement a multi-barrier approach. Control strategies should take into account the most important factors influencing cyanobacterial growth and toxin production in ambient waters, especially nutrient types and levels, and water temperature. At the drinking water treatment facility, a better understanding is needed on the effectiveness of various widely used treatment processes (e.g., coagulation, sedimentation, filtration, oxidation, granular activated carbon) for controlling various types of harmful cyanobacterial cells and their toxins. While much work has already been published on this topic, especially for the microcystins, important knowledge gaps remain. These are identified in the research needs listed below.

Bloom Control and Toxin Fate

In addition to understanding the causes and prevention of CHABs, it is also important to have mechanisms in place to control them once they occur. Numerous techniques already exist for managing blooms. However, techniques have often not been explicitly evaluated and optimized for use in the control of CHABs, particularly when toxins are present. The following research needs are designed to fill existing gaps and identify appropriate CHAB control options in ambient water.

Near-term Research Needs

1. Artificial destratification–The use of artificial destratification for cyanobacterial control has had mixed success. A potential exists to improve this process by modifying the configuration. Are there

different configurations of water mixers that would increase basin scale circulation and disrupt stratification in the surface layer (e.g., an additional bubble line at a shallower depth than the first bubble plume line). This would directly target mixing in the surface zone where the cyanobacteria grow and facilitate transport of cells deeper into the water column where they may become light-limited.

2. Increasing flushing rates by enhancing freshwater discharge -- Reducing water residence time by increasing flushing has bee shown to decrease the dominance by relatively slow-growing cyanobacteria (c.f. Paerl et al., 2001). If upstream freshwater supplies are available, this could be a "low tech" approach to minimizing the opportunities for CHABs to form and dominate in otherwise susceptible (i.e., nutrient-enriched) downstream waters.
3. Ultrasound–Determine the effectiveness of commercially available ultrasound units to control CHABs. Assess the mode of action of ultrasound on cells and the best methods for applying ultrasound in large reservoirs.
4. Electrocoagulation–Unlike most commonly used coagulation processes, electrocoagulation adds few metals into the water system. Determine the effectiveness of commercially available units to control CHABs.
5. Evaluate new and existing coagulants for recreational sources (metal and non-metal based). Evaluate the ultimate fate of the coagulated and/or sedimented cyanobacterial cells and their toxins, and assess impacts of the coagulants.
6. Evaluate new and innovative algicidal or algistatic compounds that show promise for the control of CHABs. It is also necessary to identify unintended impacts.

Drinking Water Treatment

Drinking water utilities ensure potable water by using a source-to-tap multi-barrier approach to water treatment. The multi-barrier approach recognizes the importance of individual procedures, unit processes, and tools, and their inter-relationships, to control drinking water contamination. A short review of the efficacies various treatment processes and the multi-barrier approach to remove and inactivate cyanotoxins is presented in Westrick (this volume).

Near-term Research Needs

1. Determine if the enhanced coagulation technology (currently required under recent revisions to the U.S. EPA's Surface Water Treatment Rule) for removal of dissolved organic carbon, is also effective in removing harmful cyanobacterial cells. Also determine how enhanced coagulation could be improved to better remove cyanobacterial cells and their toxins.
2. Determine the efficacy of widely used water filtration processes in controlling cyanotoxins, including the biodegradation of cyanotoxins on sand filters.
3. Develop methods for real-time monitoring of source waters and drinking water intakes for the presence of harmful cyanobacterial cells and their dissolved toxins or their easily measured surrogates.
4. Determine the CT values (disinfectant concentration x time) needed to inactivate important freshwater cyanotoxins (including emerging cyanotoxins) for all widely used water disinfectants.
5. Determine the extent to which the control of cyanotoxins by disinfection will increase the levels of those toxic disinfectant byproducts regulated under U.S. EPA's drinking water regulations.

Long-term Research Needs

1. Assess the applicability of new technologies for degrading cyanotoxins, such as advanced oxidation with titanium oxides catalysts.
2. Determine the toxicity of major byproducts resulting from the interaction between widely used water disinfectants and various cyanotoxins.
3. Develop and evaluate the utility of smart sensors for assessing system performance and coupling sensors to models for prediction.

Charge 5: Economic Analysis

What ecological factors should be included in models used to predict the relative costs and benefits of processes used to prevent or reduce the occurrence of CHABS in water bodies and cyanotoxins in drinking water?

Today's environmental resource managers are faced with increasingly difficult decisions that require a balance between the responsible use of public funds and the maximization of environmental benefits. In making such decisions, managers traditionally consider many objectives, including environmental quality, and threats to ecosystem integrity. However, benefits to the natural environment alone are not enough to encourage the changes in public behavior that may be needed to manage a threatened resource. A demonstration of the societal benefits associated with a given management strategy is also required, and this is usually done through economic analysis. Thus, environmental managers need comprehensive decision-making tools to help them evaluate the tradeoffs between different management scenarios – tools that take into account economic impacts and benefits in addition to environmental ones.

What follows is a discussion of *ecological factors* that the group felt must be considered in order to accurately predict the relative costs and benefits of various management strategies for CHABs. This is meant to provide input on the types of information that should be incorporated in economic models. It is not a strategy for doing so, but rather a starting point from which to engage experts in both disciplines (ecology and economics) in a productive dialogue, to begin addressing the difficulties in incorporating ecological complexity and multi-dimensional effects into economic valuations.

Designing Assessments

While there is widespread agreement that eutrophication is responsible for the initiation of CHABs (Chorus and Muur 1999, Paerl this volume), there is less agreement as to the most appropriate, mitigation and prevention activities. Once eutrophication has occurred, the system may respond slowly to efforts to reduce additional nutrient input. In the near-term, harmful algal blooms are still likely to occur. In contrast, the mitigation and prevention measures required to reduce nutrient input to aquatic systems may have other immediate and substantial economic impacts.

Managers must balance these immediate economic impacts (both positive and negative) with the future benefits of nutrient reduction, such as fewer algal blooms. No solution to the problem of CHABs will be effective without reductions in nutrient input, particularly P loading. In order to be ultimately effective in preventing CHABs, management activities must address both the long-term and critically important goal of nutrient reduction and removal from the system, and the implementation of effective near-term practices that mitigate existing eutrophication.

Assessment of the economic benefits and costs of management practices designed to reduce algal blooms should include all of the benefits and costs resulting from their implementation. Also, since reducing nutrients inputs into water bodies will impact other ecosystem services, any other ecological benefits that result from these practices should be included in the economic assessment, as well. For instance, a management practice might generally improve water quality which can lead to increased recreational opportunities, improved wildlife habitat and health, and reductions in drinking water treatment costs. Since costs of such management measures may occur in the near-term, while benefits might occur in the long-term, all benefits and costs should be discounted to the present so they can be compared equally. Although the near-term costs may be greater than the near-term environmental benefits, the inclusion of other indirect benefits may make the *total* benefits larger than the *total* costs in the long run. Additionally, benefits and costs that accrue to those beyond the immediate management area should be included as appropriate for the scale of the analysis. For instance, in a national or regional analysis, all benefits and costs occurring in the nation or region should be included if they result from management actions. It will also be critical to link any of the physical and biological model outputs to economic endpoints that will change as a result of the management measures. Thus, in order to design a good assessment, it is necessary to ensure that the correct biological endpoints are being monitored and matched with the appropriate economic endpoints. In order to achieve this, the connection between changes in the biological and physical components of the system and changes in the economic components must be well-understood.

In designing an assessment, managers may want to compare the benefits and costs of a number of practices that could be implemented and to choose the one that provides the highest net benefits (benefits-costs) or the highest benefit/cost ratio. Alternatively, if a given level of nutrient reduction is desired, the assessment could be designed to achieve the given level at the least cost. In this case, standard linear programming models could be used to determine the best solution.

Requirements of Models across Multiple Scales

Local Watershed Scale

At the small watershed scale (5-10,000 ha), the economic impacts and environmental benefits of practices and programs designed to decrease nutrient export could be modeled based on the usual factors included in farm enterprise budgets and models that calculate crop yields and water quality response to various practices (such as Erosion/Productivity Impact Calculator - EPIC or Soil and Water Assessment Tool - SWAT). At this scale, compensation to producers from USDA environmental improvement programs could offset some of the costs paid for by producers. Examples of economic and environmental modeling efforts at this scale are published in Coiner et al. (2000), Santelmann et al. (2004) and Boody et al. (2005). None of the studies employed at this scale to date have been able to explore sufficient numbers of alternatives to discern whether the response of the system is linear or whether there may be thresholds of response. For example, a nutrient reduction in surface water may be very gradual until a threshold level is reached at which the response rate increases significantly. Further efforts to explore the linearity or non-linearity of watershed response to measures implemented at this scale could be quite valuable in helping to inform policy concerning the minimal extent of changes that must be made in order to achieve significant, measurable results across multiple environmental objectives.

County and Basin Scale

At the spatial extent of counties and small river basins, the economic impacts of additional components should be considered. Some negative economic impacts of existing practices are already occurring, such as impacts of environmental degradation on regional infrastructure (costs of water treatment, costs of road and bridge replacement over eroding stream channels, episodic environmental disasters from failure of manure containment facilities, and a decline in property values surrounding large confinement feeding operations). Thus, an accurate modeling of economic impacts at this scale must consider the benefit of reducing the negative consequences of existing practices. Another component to consider at regional (and national) scales would be the potential for banking of credits for carbon sequestration, wetland mitigation and habitat restoration can improve surface or groundwater quality. These elements could all be factored into models developed for larger regions. Capturing the value of such ecosystem services over longer time frames (25-50 years) would be necessary to demonstrate the economic value of changes in land use and management over time (e.g., so that the different impacts of 100 year flood events or drought under different management regimes could be quantified). Again, exploration of response thresholds (in terms of both spatial and temporal extent) over which significant measurable change can be expected, would be important.

Among the costs that might be expected to emerge at this scale are losses in revenue to rural communities and counties for land enrolled in set-asides, such as decreased commodity production, the sales of agricultural supplies, and any decline in need for services or losses of jobs that might occur in response to changes in practices.

Regional Scale

Models developed to evaluate alternatives at the regional scale should include some key factors or "pressure points" whose alteration may change the behavior of the modeled system and thereby have implications for the selection of nutrient-control techniques. For example, it would be extremely valuable develop models for evaluating the influence of changes in energy costs on the relative costs of control processes, or to explore the costs and benefits of alternative control processes as the system response changes with key climatic shifts in precipitation or temperature patterns.

National Scale

At the national scale, models should incorporate the effects of implementing specific programs or guidelines which, when accumulated at a national scale, could influence the balance of trade by increasing commodity supply for export. Additionally, models at this scale must consider the effects of potential changes in commodity supply and demand on prices, unintended consequences of specific agricultural programs (e.g., "slippage" in response to set-aside programs), as well as the environmental benefits that accrue at a national scale outside the region in which the land use practices are implemented (decreased need for some forms of water treatment, improved flood control along major rivers, carbon or pollutant trading credits etc.).

Temporal Scale

Progress in the near-term will be required in order to produce demonstrable results from management activities that will satisfy public desire for measurable progress, a key requirement for sustained funding for remedial programs. Metrics for measuring progress should include both reduction of nutrients within the aquatic system and decrease in the extent, duration, and toxicity of algal blooms. However, it must be acknowledged up front that significant improvements in the response of nutrient export from these systems to changes in agricultural practices may take years. McIsaac et al. (2001) modeled the influence of nitrogen applications in the Mississippi River Basin (MRB) on nutrient export into the Gulf of Mexico, and found that nutrient export at the mouth of the Mississippi reflected loading in the Basin from the previous 9 years, with strongest influence being from loading in the previous 1-5 year interval. Given these and other studies indicating time lags in system response to reductions in nutrient applications to land, it is unlikely that we will see improvements in either nutrient loading or control of algal blooms from watershed management efforts alone until 5-10 years after these measures are implemented. Yet, we also know that unless we implement such measures now, we will see continued eutrophication and degradation of these systems, which will be more and more difficult to reverse over time.

Societal Considerations

The need for informing the general public (especially those stakeholders of whom the greatest sacrifices will be demanded), concerning the needs and goals of any programs designed to decrease CHABs will be critically important. In addition, efforts must be made to ensure that the changes in land use and management that are proposed to meet environmental goals are culturally acceptable as well as perceived as fair and equitable across groups (Santelmann et al. 2001). For example, both actual and perceived fairness in regulation of various entities and activities in meeting regional water quality goals must be considered in order to achieve acceptance and participation. If urban point sources are allowed to continue to release large quantities of phosphorus and total dissolved solids into water while agricultural enterprises are stringently regulated, or vice versa, this will jeopardize the atmosphere of compliance and “we’re all in this fight together” that will be needed to make an impact on reversing current trends of eutrophication in aquatic systems.

References

Boody G, Vondrack B, Andow D, Krinke M, Westra J, Zimmerman J, Welle P (2005) Multifunctional agriculture in the United States. Bioscience 55(1): 27-37.

Boon PI, Bunn SE, Green JD, Shiel RJ (1994) Consumption of cyanobacteria by fresh-water zooplankton – implications for the success of top-down control of cyanobacterial blooms in Australia. Australian J Mar Fresh Res 45: 875-887

Capper A, Cruz-Rivera E, Paul VJ, Tibbetts IR (2006) Chemical deterrence of a marine cyanobacterium against sympatric and non-sympatric consumers. Hydrobiologia 553: 319-326

Caraco NF, Cole JJ, Raymond PA, Strayer DL, Pace ML, Findlay SEG, Fischer DT (1997) Zebra mussel invasion in a large, turbid river: Phytoplankton response to increased grazing. Ecology 78: 588-602

Chorus I, Bartram J (1999) Toxic cyanobacteria in water: a guide to their public health consequences, monitoring and management. World Health Organization. E&FN Spon, Routledge, London.

Chorus I, Muur L (1999) Remedial measures. In: Toxic Cyanobacteria in Water: A guide to their public health consequences, monitoring and management. I. Chorus and J. Bartram, eds. Published by WHO, UNESCO, and UNEP. London, UK.

Christoffersen K (1996) Effect of microcystin on growth of single species and on mixed natural populations of heterotrophic nanoflagellates. Natural Toxins 4: 215-220

Coiner C, Wu J, Polasky S (2001) Economic and Environmental Implications of Alternative Landscape Designs in the Walnut Creek Watershed of Iowa, Ecological Economics 38(1):119-139

De Bernardi R, Giussani G (1990) Are blue green algae a suitable food for zooplankton? A review. Hydrobiologia 200/201: 29-41

Fogg GE (1969) The physiology of an algal nuisance. Proc R Soc London B. 173:175-189

Giani A, Bird DF, Prairie YT, Lawrence JF (2005) Empirical study of cyanobacterial toxicity along a trophic gradient of lakes. Can J Fish Aquat Sci 62: 2100-2109

Griffith GJ, Omernik T, Wilton, Pierson S (1994) Ecoregions and subregions of Iowa: A framework for water quality assessment and management. Jour. Iowa Acad. Sci. 101(1): 5-1

Hairston Jr. MG, Holtmeier CL, Lampert W, Weider LJ, Post DM, Fisher JM, Caceres CE, Fox JA, Gaedke U (2002) Natural selection for grazer resistance to toxic cyanobacteria: Evolution of phenotypic plasticity? Evolution 55:2203-2214.

HARRNESS (2005) Harmful Algal Research and Response: A National Environmental Science Strategy 2005–2015.

Keeney D (ed.) (1990) Farming systems for Iowa: Seeking alternatives. Leopold Center for Sustainable Agriculture Ames Iowa USA.

Lampert W (1987) Laboratory studies on zooplankton-cyanobacteria interactions derived from enclosure studies. N.Z. J. Mar Freshwater Res. 21: 483-490

Likens GE (ed) (1972) Nutrients and Eutrophication. American Soc Limnol Oceanogr Special Symp

McIsaac G, David M, Gertner G, Goolsby D (2001) Nitrate flux in the Mississippi River. Nature 414: 166-167

Mitsch W, Day J, Gilliam J, Groffman P, Hey D, Randal G, Wang N (2001) Reducing nitrogen loading to the Gulf of Mexico from the Mississippi River Basin: Strategies to counter a persistent ecological problem. Bioscience 51: 373-388.

Nagle DG, Camacho FT, Paul VJ (1998) Dietary preferences of the opisthobranch mollusk *Stylocheilus longicauda* for secondary metabolites produced by the tropical cyanobacterium *Lyngbya majuscula*. Mar Biol 132: 267-273

Nagle DG, Paul VJ (1998) Chemical defense of a marine cyanobacterial bloom. J. Exp Mar Biol Ecol 225: 29-38

Nagle DG, Paul VJ (1999) Production of secondary metabolites by filamentous tropical marine cyanobacteria: ecological functions of the compounds. J. Phycol 35: 1412-1421

Omernik JM (1987) Ecoregions of the conterminous United States. Annals of the Association of American Geographers 77(1): 118-125.

Paerl HW (1988) Nuisance phytoplankton blooms in coastal, estuarine, and inland waters. Limnol Oceanogr 33:823-847

Paerl HW, Fulton RS, Moisander PH, Dyble J (2001) Harmful freshwater algal blooms with an emphasis on cyanobacteria. The Scientific World 1: 76-113

Paerl HW, Fulton III RS (2006) Ecology of harmful cyanobacteria. Pp. 95-109, In, E. Graneli and J. Turner [Eds.]. Ecology of Harmful Marine Algae. Ecological Studies, Vol. 189Springer-Verlag, Berlin .

Pennings SC, Pablo SR, Paul VJ (1997) Chemical defenses of the tropical benthic, marine cyanobacterium *Hormothamnion enteromorphoides*: diverse consumers and synergisms. Limnol Oceanogr 42: 911-917.

Piehler MF, Dyble J, Moisander PH, Pinckney JL, Paerl HW (2002) Effects of modified nutrient concentrations and ratios on the structure and function of the native phytoplankton community in the Neuse River Estuary, North Carolina USA. Aquatic Ecology 36: 371-385.

Raikow DF, Sarnelle O, Wilson AE, Hamilton SK (2004) Dominance of the noxious cyanobacterium Microcystis aeruginosa in low-nutrient lakes is associated with exotic zebra mussels. Limnol. Oceanogr. 49:482-487.

Ramsdell, J.S., D.M. Anderson and P.M. Glibert (Eds.), Ecological Society of America, Washington DC, 96 pp.
http://www.cop.noaa.gov/stressors/extremeevents/hab/current/harrness.html

Reynolds CS, Walsby AE (1975) Water blooms. Biol Rev 50:437-481

Sample Guidelines (modified from the Wisconsin Division of Public Health's fact sheet on cyanobacteria, and their toxins, and health impacts)
http://dhfs.wisconsin.gov/eh/Water/fs/Cyanobacteria.pdf

Santelmann M, White D, Freemark K, Nassauer J, Clark M, Coiner C, Cruse R, Danielson B, Eilers J, Polasky S, Vache K, Sifneos J, Rustigian H, Debinski

D, Wu J (2004) Assessing alternative futures for agricultural watersheds. Landscape Ecology 19: 357-374

Santelmann M, Freemark K, White D, Nassauer J, Clark M, Danielson B, Eilers J, Cruse R, Polasky S, Vache K, Galatowitsch S, Wu J (2001) Applying Ecological Principles to Land-Use Decision Making in Agricultural Watersheds. *In*: V.H. Dale and R. Haueber (eds.) *Applying Ecological Principles to Land Management*. Springer-Verlag, NY.

Sarnelle O, Wilson AE (2005) Local adaptation of Daphnia pulicaria to toxic cyanobacteria. Limnol Oceanogr 50: 1565-1570

Scheffer M et al. (2001) Catastrophic shifts in ecosystems. Nature 413: 591-96.

Schindler DW (1975) Whole-lake eutrophication experiments with phosphorus, nitrogen and carbon. Verh Int Verein Theor Angew Limnol 19:3221-3231

Sellner KG, Brownlee DC, Buundy MH, Brownlkee SG, Braun KR (1993) Zooplankton grazing in a Potomac River cyanobacteria bloom. Estuaries 16: 859-872

Shapiro J (1990) Current beliefs regarding dominance of blue-greens: The case for the importance of CO_2 and pH. Int Verein Theor Angew Limnol Verh 24:38-54

Sivonen K (1996) Cyanobacterial toxins and toxin production. Phyclogia 35(6):12-24

Skulberg, OM, Underdal B and Utkilen H (1994) Toxic waterblooms with cyanophytes in Norway - Current knowledge. Alogol Studies 75:279-289

Smith TE, Stevenson RJ, Caraco NF, Cole JJ (1998) Change in phytoplankton community structure during zebra mussel invasion of the Hudson River. J. Plankton Res 20: 1567-1579

U. S. Department of Agriculture Natural Resources Conservation Service (1997) Profitable pastures. USDA-NRCS, Des Moines, Iowa. 19 pp.

U. S. Department of Agriculture Soil Conservation Service (1996) Conservation Choices: Your guide to 30 conservation and environmental farming practices. USDA SCS St. Paul, MN. 34 pp.

Vache K, Eilers JM, Santelmann M (2002) Water quality modeling of alternative agricultural scenarios the U.S. Corn Belt. JAWRA 38(3):773-787.

Vanderploeg HA, Liebig WW, Carmichael WW, Agy MA, Johengen TH, Fahnenstiel GL, Nalepa TF (2001) Zebra mussel (*Dreissena polymorpha*) selective filtration promoted toxic *Microcystis* bloom in Saginaw Bay (Lake Huron) and Lake Erie. *Canadian Journal of Fisheries and Aquatic Sciences* 58(6):1208-1221

Walls M, Laurenmaatta C, Ketola M, OhraAho P, Reinikainen M, Repka S (1997) Phenotypic plasticity of Daphnia life history traits: the roles of predation, food level and toxic cyanobacteria. Freshwater Biol. 38: 353-36