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Review

The state of U.S. freshwater harmful algal blooms assessments, policy and legislation

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ABSTRACT

The incidence of harmful algal blooms (HABs) is increasing in the United States and worldwide. HAB toxins cause a substantial but unquantified amount of human and animal morbidity and mortality from exposures in recreational, commercial, drinking-source and potable waters. HAB biomass and toxins threaten the sustainability of aquatic ecosystems. U.S. Congressional legislation mandated the establishment of a National Research Plan for Coastal Harmful Algal Blooms, but no similar plan exists for freshwater HABs (FHABs). Eutrophication and FHABs are conservatively estimated to cost the U.S. economy 2.2–4.6 billion dollars annually. A National Research Plan for Freshwater Harmful Algal Blooms is needed to develop U.S. policy and regulations or guidelines to confront FHAB risks. This report reviews the state of FHAB occurrence, risk and risk management assessments in the U.S. Research is identified that must be accomplished to characterize occurrence and risks, and develop cost effective strategies for preventing, suppressing and mitigating FHABs. U.S. Congressional legislation is needed to mandate a National Research Plan for FHABs, establish a timeline for developing policy and fund competitive research-grant programs. The research results will provide a sound scientific basis for making policy determinations and implementing risk management strategies. Successfully confronting FHAB risks will strengthen the U.S. economy, protect human and animal health and help ensure the sustainability of our Nation's freshwater bodies.

1. Introduction

Harmful algal blooms (HABs) are rapid and massive expansions of cellular populations such as cyanobacteria, diatoms and dinoflagellates in aquatic ecosystems. HABs pose serious risks for human and animal health, aquatic ecosystem sustainability and economic vitality (HARRNESS, 2005; Dodds et al., 2009; Falconer, 2008; Hudnell, 2008a; Lopez et al., 2008a; Stewart et al., 2008). Dozens of HAB species produce highly potent toxins, and huge bloom biomasses deplete dissolved oxygen after bloom die offs as the cells decay (Havens, 2008; Humpage, 2008; Lopez et al., 2008a,b). United States Congressional legislation led to the establishment of a National Research Plan for Coastal Harmful Algal Blooms to monitor and assess HABs in U.S. oceans, estuaries and the Great Lakes (HABHRCA, 1998). The plan fostered HAB research that contributed to the scientific basis for making U.S. policy determinations to protect U.S. interests from the adverse effects of coastal HABs. Comparable legislation is needed to establish a National Research Plan for Freshwater Harmful Algal Blooms (FHABs) to confront the risks FHABs present in recreational, commercial, drinking-source and potable waters. FHABs are conservatively estimated to cost the U.S. economy between 2.2 and 4.6 billion dollars annually (Dodds et al., 2009). However, no U.S. Federal policy, regulations or guidelines have been developed for FHABs.

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States, tribes and localities confronting the risks of freshwater blooms increasingly rely on guidance from the World Health Organization (WHO, 1999) in developing strategies to reduce FHAB risks.

The process for making policy determinations for FHAB risk management uses a systems approach as illustrated in Fig. 1. The FHAB pathway, ranging from causes to effects, is assessed to determine FHAB incidence and the risks FHABs pose for health and ecosystems so that appropriate intervention strategies can be developed to reduce the risks. The assessments provide the scientific basis for making policy determinations. Policy determinations are based on FHAB risks within the context of other societal concerns and priorities. Risk management practices implement selected strategies to prevent or suppress FHABs and mitigate the risks. Policy determinations concerning the issuance of regulations or guidelines for FHABs and their toxins require sufficient information on: (1) the occurrence of blooms in U.S. freshwaters to determine if incidence warrants action; (2) dose-response relationships between toxin concentrations and adverse health effects and/or cell densities and ecological impacts to determine if the risks warrant action and; and (3) methods to prevent, control and mitigate FHABs to determine if cost effective means of reducing or eliminating the risks are available (Donohue et al., 2008). The U.S. Environmental Protection Agency (EPA) currently considers the available information in each of these areas to be insufficient for making policy determinations (Fristachi et al., 2008; Donohue et al., 2008; Perovich et al., 2008).

The scope of this report is to describe the state of U.S. HAB legislation and programmatic outcomes, and U.S.

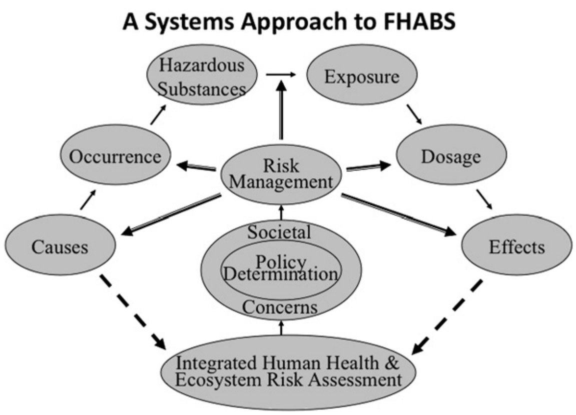

Fig. 1. The ovals around the sides and top illustrate the components in the FHAB pathway from causes to effects. The components and their interconnections (thin arrows) are the subjects of research that describes the environmental conditions that stimulate blooms, the incidence of blooms, the production of hazardous substances, exposure to those substances and the dosages that cause adverse effects. All factors in the FHAB pathway are considered during risk assessment (dashed arrows) to characterize the risks and potential intervention strategies to reduce risks. Policy determinations are made within the context of other societal risks and priorities to develop cost effective risk management strategies. Risk management strategies are implemented (thick arrows) to reduce risks. The risks are most strongly reduced by ecological interventions that target FHAB causes to prevent blooms, that are effective and that have no adverse environmental impacts. The occurrence of blooms necessitates implementation of other strategies to terminate the blooms or mitigate the risks. This figure is reprinted from Hudnell et al. (2008a) with permission.

assessments of FHAB occurrence, risk, and risk management. Research needed to make FHAB policy determinations is identified. Key components of legislation needed to create a National Research Plan for FHABs are described. Research that characterizes occurrence, risks and intervention strategies, and legislation that mandates a National Research Plan for FHABS and the creation of Federal policy are needed to protect human and animal health, ecosystems and economies from the risks of U.S. FHABs.

2. State of HAB legislation and programmatic outcomes

HABs gained the attention of the U.S. Congress during the 1990s when high densities of the newly discovered dinoflagellate, *Pfiesteria*, were associated with numerous, large fish kills (Burkholder et al., 1992; Glasgow et al., 1995) and adverse human health effects in East Coast estuaries (Grattan et al., 1998; Hudnell, 1998; Shoemaker, 2001; Haselow et al., 2001; Hudnell, 2005). These events prompted the U.S. Congress to enact the *Harmful Algal Bloom and Hypoxia Research and Control Act* (HABHRCA, 1998). The Act directed, and authorized funding for, the National Oceanographic and Atmospheric Administration (NOAA) to lead the development of a National Research Plan for Coastal HABs to confront the health, ecological and economic risks posed by the blooms and their toxins. The plan was developed (HARRNESS, 2005) and implemented by establishing extramural, competitive research-grant programs for *Monitoring and Event Response for Harmful Algal Blooms* (MERHAB; NOAA, 2006) and *Ecology and Oceanography of Harmful Algal Blooms* (ECOHAB; NOAA, 2007), as well as intramural programs for bloom and toxin identification and quantification, monitoring, response and prediction (Jewett et al., 2007; NOAA, 2008a). Implementation of the plan produced scientific advances for HABs within NOAA's purview, oceans, estuaries and the Great Lakes, such as prediction of the 2008 red tide in the Gulf of Maine that severely impacted the commercial shellfish industry (NOAA, 2008b). The reauthorization of HABHRCA (2004) expanded the Act to include blooms in all U.S. freshwaters. The expanded Act mandated an assessment of FHABs (Lopez et al., 2008a), for which an interagency monograph described the state of the science and research needs (Hudnell, 2008b). The reauthorization also mandated a National Research Plan for reducing HAB occurrence and impacts; *The HAB Research, Develop, Demonstrate and Technology Transfer Plan* to prevent, control and mitigate blooms in all U.S. waters (Dortch et al., 2008). NOAA recently implemented the plan for coastal HABs by establishing a third competitive research-grant program entitled *Prevention, Control, and Mitigation of HABs* (PCM HAB; NOAA, 2009). However, the effort to address freshwater blooms was hampered because the Congressional committees that sponsored HABHRCA lacked jurisdiction over the EPA. HABHRCA could not authorize funding for the EPA or direct the Agency to establish a National Research Plan for FHABs. EPA is the appropriate Agency to establish such a plan; all U.S. freshwaters are within the purview of the EPA, as defined in the Clean Water Act (2002) and the Safe Drinking Water Act (2002).

The Agency acknowledges its mandate for safe and clean water in Goal 2 of the 2006–2011 EPA Strategic Plan (EPA, 2008), "Ensure drinking water is safe. Restore and maintain oceans, watersheds, and their aquatic ecosystems to protect human health, support economic and recreational activities, and provide healthy habitat for fish, plants, and wildlife". Although the EPA recognizes the need for a National Research Plan for FHABs (Lopez et al., 2008b), the Agency has not begun development of a plan primarily due to the lack of a clear Congressional directive and funding.

3. State of U.S. FHAB & cyanotoxin occurrence assessment

Cyanobacteria (a.k.a. blue-green algae) are the predominant toxigenic phylum that bloom in freshwater, although phytoplankton such as the euryhalinic chrysophyte *Prymnesium parvum* (a.k.a. golden algae) also produce FHABs and toxins. Some cyanobacterial genera produce cyanotoxins, several of which are among the most potent toxins known (Humpage, 2008). Botulinum and dioxin (TCDD) are among the few toxic substances known to be more potent than cyanotoxins (Klaassen, 1986). Table 1 shows the lethal dose of five cyanotoxins and five better-known compounds for 50% of the rodents within 24 h of a single, intraperitoneal injection (LD_{50}). Each of the cyanotoxins can be synthesized by several genera of cyanobacteria, and single organisms often produce two or more types of cyanotoxins (Pegram et al., 2008; Humpage, 2008).

The EPA listed microcystins, cylindrospermopsin and anatoxin-a as highest priority cyanotoxins, and saxitoxin and anatoxin-a(s) as medium to high priority (Table 1), for inclusion in the first Unregulated Contaminant Monitoring Rule (UCMR; EPA, 2001). Regulatory statutes require the Agency to order water utilities to monitor selected UCMR contaminants every 5 years. No cyanobacteria or cyanotoxins have been monitored or selected for monitoring through the current UCMR 2 time period of 2008–2010 (EPA, 2007). The Agency did award four research-grants in 2008 for development and evaluation of innovative approaches to quantitatively assess cyanobacteria and their toxins in water (EPA, 2008a). The goal is to develop rapid, reliable, field-ready and inexpensive tests for cyanobacteria, cyanotoxins and genes needed for cyanotoxin synthesis.

There is widespread agreement among FHAB scientists and water managers that the incidence of FHABs is increasingly in the U.S. (Carmichael, 2008; Fristachi et al., 2008). Data from Florida (Burns, 2008), Nebraska (Walker et al., 2008) and New York and the Great Lakes (Boyer, 2008) indicated that FHABs are prevalent during warm seasons. These reports also demonstrated that the antibody based, enzyme-linked immunosorbent assays (ELISA) provided a rapid, reliable and relatively inexpensive means of quantifying classes of cyanotoxin congeners. An earlier study that used ELISA to measure microcystin concentrations during spring and summer months in 241 Midwestern U.S. water bodies observed increasing concentrations with latitude (Graham et al., 2004). Another assessment conducted during one summer week in 485 Southeastern U.S. catfish ponds indicated that cyanobacteria were present in 98% of the ponds, and that microcystins were present in 47% (Zimba and Grimm, 2003). However, there are no comprehensive databases on FHAB occurrence in the U.S., and few states systematically monitor cyanobacteria or cyanotoxins in surface waters. A comprehensive, quantitative assessment of predominant genera and species, toxin production and toxin mixture compositions in the U.S. must await implementation of the UCMR for cyanobacteria and their toxins.

4. State of U.S. FHAB risk assessment

FHAB toxins cause a substantial but unquantified amount of human and animal morbidity and mortality in the U.S (Lopez et al., 2008b). To help fill this data gap, the EPA selected cyanobacteria, other freshwater algae and their toxins for inclusion on the Contaminant Candidate List 1 (CCL1; EPA, 1998) of microbes and chemical contaminants of concern in drinking water. Policy determinations concerning CCL contaminants, and revised lists, are to be made within each 5-year period. Microcystin-LR, cylindrospermopsin and anatoxin-a are listed as chemical contaminants in the current CCL3 (EPA, 2008b). However, no policy determinations have been made under CCL1, 2 or 3.

Table 1
Compounds and rodent 24 h intraperitoneal LD_{50s} (μg/kg).

Cyanotoxins	LD_{50}	EPA priority	Comparison	LD_{50}
Saxitoxins[a]	10	Medium/high	Ricin[f]	22
Anatoxin-a(s)[b]	20	Medium/high	Cobra venom[g]	185
Microcystin-LR[c]	50	Highest	Sarin[h]	218
Anatoxin-a[d]	200	Highest	Curare[i]	500
Cylindrospermopsin[e]	300/180	Highest	Strychnine[j]	2500/980

[a] Alkaloid, voltage-gated sodium channel antagonist, Kuiper-Goodman et al. (1999).
[b] Alkaloid (similar to organophosphate pesticide), acetylcholinesterase inhibitor, Carmichael et al. (1990).
[c] Cyclic peptide, protein phosphatase inhibitor, cytoskeleton damage, other, Kuiper-Goodman et al. (1999).
[d] Alkaloid, nicotinic acetylcholine receptor agonist, Carmichael (1997).
[e] Alkaloid, protein synthesis inhibitor, other, 300/180 = 24 h/5 days, Hawkins et al. (1997).
[f] Glycoprotein, from castor bean (*Ricinus communis*), protein synthesis inhibitor, other, SOPCFC (2008).
[g] Polypeptide, from Egyptian *Naja haje haje* cobras, nicotinic acetylcholine receptor antagonist, Fry (2009).
[h] Organophosphate, synthetic, acetylcholinesterase inhibitor, US Army ERDEC (1994); ORNL (1996).
[i] Alkaloids (e.g., *d*-tubocurarine), poison arrow toxin plants (e.g., *Strychnos toxifera*), nicotinic acetylcholine receptor antagonist, Wenningmann and Dilger (2001).
[j] Alkaloid, from *Strychnos* plants, glycine receptor antagonist, 2500/980 = rat/mouse, IPCS (2009).

The Agency developed draft toxicological reviews for the highest priority cyanotoxins (EPA, 2006). The toxicological reviews assessed the scientific literature to determine whether or not the available dose-response data were sufficient to develop reference doses (RfDs) for ingested compounds, reference concentrations (RfCs) for inhaled compounds and cancer assessments. When sufficient dose-response data were available, guideline levels of daily intake considered safe during acute, short term, subchronic and chronic exposure periods were developed. The guideline levels in the draft toxicological reviews for microcystins, cylindrospermopsin and anatoxin-a are shown in Table 2. No reviewed studies were of sufficient quality to develop RfCs, acute RfDs or cancer assessments for any of the cyanotoxins. Subchronic RfDs were developed for each cyanotoxin class. The subchronic guideline values ranged from 3.0 to 0.006 μg/kg per day for anatoxin-a and microcystin-LR, respectively. The chronic RfD for microcystin-LR was 0.003 μg/kg per day.

The EPA has not characterized the risks that FHABs pose to aquatic ecosystems (Havens, 2008; Ibelings et al., 2008; Ibelings and Havens, 2008) through formal risk assessment procedures. An interagency workgroup recommended an integrated approach to assessing FHAB risks to health and ecosystems because blooms simultaneously impact a wide variety of assessment endpoints, and those risks are likely interconnected (Donohue et al., 2008; Orme-Zavaleta and Munns, 2008).

5. State of U.S. FHAB risk management assessment

There is no U.S. Federal program for assessing the efficacy and sustainability of approaches to HAB risk management. Dortch et al. (2008) discussed approaches to HAB risk management. Those discussed here are most relevant to FHAB risk management. The management of FHAB risks entails mitigating the adverse effects of the cells and their toxins, and preventing, suppressing and terminating blooms. Mitigation approaches include using alternative drinking-source waters, removing cyanotoxins and taste and odor compounds during potable water processing (Westrick, 2008), monitoring water bodies and posting notices to the public of closure or the need for caution, and on educating the public about FHAB risks. State programs such as that implemented in Nebraska greatly reduce the chance that the public will be exposed to cyanotoxins unknowingly during recreational activities (Walker et al., 2008). The efficacy of the Nebraska program was demonstrated in 2004 at Pawnee Lake when total microcystin levels exceeded the “health alert” level of 15 μg/l (ppb). Authorities posted warning signs on a Friday afternoon at one beach, but not at the other primary beach or at boat ramps. Pawnee Lake was heavily used on the weekend. The state received more than 50 telephone calls the following week reporting non-specific, flu-like illness onset shortly after recreating on the lake. Nebraska collected 748 samples from 111 different lakes in 2004, resulting in “health alerts” at 26 lakes and “health advisories” ($>2<15$ ppb) at 69 lakes. A few of the warnings were in place for more than 3 months. The state received reports that year of five dog deaths, several livestock and wildlife deaths and additional human illnesses associated with FHABs in other lakes. Several other states systematically monitor and post freshwater bodies, and provide educational materials in print, at public meetings and on the Internet (California, 2007; Florida, 2008; Oregon, 2009).

Approaches to FHAB prevention, suppression and termination are generally classified as ecological or chemical (Straskraba, 1996). This review focuses on current and

Table 2
Cyanotoxin toxicological reviews.

	Exposure duration	Critical study	Critical effect	NOAEL[a] LOAEL[b] mg/kg-d	BMDL[c] mg/kg-d	Uncertainty factors[d]	Guideline level mg/kg-d
Microcystins LR, RR, YR and LA (based on microcystin-LR data)							
RfDs	Acute	–	–	–	–	–	–
	Short Term	Heinze, 1999	Hepatic	5×10^{-2} [b]	6×10^{-3}	10 × 10 × 10	6×10^{-6}
	Subchronic	Heinze, 1999	Hepatic	5×10^{-2} [b]	6×10^{-3}	10 × 10 × 10	6×10^{-6}
	Chronic	Ueno et al., 1999	Hepatic	3×10^{-3} [a]	–	10 × 10 × 10	3×10^{-6}
RfCs	All the above	–	–	–	–	–	–
Cancer	Any	–	–	–	–	–	–
Cylindrospermopsin							
RfDs	Acute	–	–	–	–	–	–
	Short Term	–	–	–	–	–	–
	Subchronic	Humpage and Falconer, 2003	Nephrotic	3×10^{-2} [a]	3.3×10^{-2}	10 × 10 × 10	3×10^{-5}
	Chronic	–	–	–	–	–	–
RfCs	All the above	–	–	–	–	–	–
Cancer	Any	–	–	–	–	–	–
Anatoxin-a							
RfDs	Acute	–	–	–	–	–	–
	Short Term	Fawell et al., 1999	Systemic	2.5[a]	–	10 × 10 × 10	3×10^{-3}
	Subchronic	Astrachan and Archer, 1981	Systemic	0.5[a]	–	10 × 10 × 10	5×10^{-4}
	Chronic	–	–	–	–	–	–
RfCs	All the above	–	–	–	–	–	–
Cancer	Any	–	–	–	–	–	–

[a] No observable adverse effect level.
[b] Lowest observable adverse effect level.
[c] Benchmark dose lower confidence limit.
[d] 10 for interspecies variability, 10 for intraspecies variability, 10 for various database deficiencies.

emerging ecological approaches to FHAB risk management because chemical approaches may have adverse ecological impacts and may not be environmentally sustainable. Algaecide application, the most commonly used method for FHAB prevention, suppression and termination, is potentially dangerous for humans and may have detrimental impacts in aquatic ecosystems. Copper sulfate lyses cyanobacterial cells, causing rapid release of all cyanotoxins to water (Touchette et al., 2008). Approximately 140 cases of human illness were attributed to cyanotoxins in potable water following copper sulfate application in source water at Palm Island, Australia (Hawkins et al., 1985). Cyanotoxins in recreational waters pose human health risks even without direct water contact. A recent study by the U.S. Centers for Disease Control and Prevention indicated that FHAB toxins become airborne due to wind and wave action (Backer et al., in press). Humans miles away from affected water bodies may inhale HAB toxins (Haselow et al., 2001; Fleming et al., 2007). The inhaled toxins may cause acute respiratory distress in asthmatic and other susceptible populations, and may contribute to the chronic and delayed health effects associated with exposure to algal toxins (Hudnell, 2005; Hudnell et al., 2008b; Pilotto, 2008). Copper sulfate is toxic to many aquatic plants and animals (Sanchez et al., 2005; Oliveria-Filho et al., 2004). Copper may accumulate to high levels in sediment with continued use, causing toxicity in benthic invertebrates (Roman et al., 2007). As with bacteria increasingly becoming resistant to antibiotics, evidence indicates that cyanobacteria are becoming resistant to copper sulfate toxicity (García-Villada et al., 2004). States and localities increasingly restrict the use of copper sulfate because aquatic ecosystems may be impaired with repeated applications (California, 1995; NOSB TAP, 2001; Naples, 2009; New Jersey, 2009; New York, 2009). Research to date has not demonstrated that algaecides or algaestats are an environmentally responsible and sustainable option for FHAB control.

Chemical flocculants, used to precipitate phosphorus and cells from the water column and to prevent the release of phosphorus from sediment, may be ineffective over the long term and detrimental to aquatic ecosystems. The effectiveness of alum (aluminum sulfate) treatment may be highly variable. Although one study concluded that the median duration of effectiveness was about 6 years in polymictic lakes (Welch and Cooke, 1999), another study reported effectiveness duration to be about 4 months (Medley, 2005). Complete ineffectiveness and no improvement in water quality after 3 consecutive years of alum application were reported in another study (Osgood, 2006). Alum applications have caused large fish kills through rapid acidification of lake water (Gillie, 2008). Excessive alum dosing, inappropriate alum and buffer ratios and/or misapplications caused a large fish kill in Cape Cod's Hablin Pond during 1995, and complete fish eradication in Wapato Lake, WA, during 2008 (Gillie, 2008). Excessive aluminum concentrations in water may cause plasma loss and osmoregulatory failure in gill-breathing fish and invertebrates (Rosseland et al., 1990). A recent review of alum applications concluded that "it is not possible to confirm *a priori* the circumstances under which a whole lake trial would be successful", and called for additional research on alum's acute and chronic toxicity in fish, invertebrates and benthic biota (Ozkundakei and Hamilton, 2007).

Ecological approaches target the causes of FHABs to decrease incidence and duration without causing adverse environmental impacts. Cyanobacteria and other phytoplankton bloom most frequently when four stimulatory factors are present – excessive nutrients (primarily nitrogen and phosphorus), warmth (>20 °C), sunlight for photosynthesis and quiescent or stagnant water (Paerl et al., 2007; Paerl, 2008). The factors of warmth and sunlight are impractical intervention targets in most cases, although colorants can be added to water bodies to reduce the amount of light available for phytoplanktonic photosynthesis. However, colorants indiscriminately inhibit beneficial and harmful algae, thereby adversely impacting aquatic ecosystems (Spencer, 1984). The factors of nutrients and quiescent or stagnant water are amenable targets for ecological approaches to FHAB risk management.

Nutrient input reduction is essential for sustaining aquatic ecosystems from freshwater to marine (Perovich et al., 2008; Lopez et al., 2008a,b). Nutrients enter freshwater from both point and non-point sources. Point sources are defined as "any discernible confined and discrete conveyance including but not limited to a pipe, ditch, channel, or conduit from which pollutants are or may be discharged" (FFESCAC, 2009). Point sources, including wastewater treatment plants, urban storm-water collection systems, industrial conveyances, aquacultures and concentrated animal-feeding operations, are required by the Clean Water Act to obtain state or Federal National Pollution Discharge Elimination System (NPDES) permits. Permit applications specify the type of wastewater to be treated and the water treatment technology to be used. Permit holders are required to maintain monitoring and record keeping programs, use EPA approved analytical laboratories and meet all permit requirements.

Non-point sources include lawns, roads, highways, fields, pastures and forests. Nutrients in runoff from non-point sources enter reservoirs, ponds, lakes, ditches, streams and rivers during rains and floods (Paerl, 2008; Paerl and Huisman, 2008). NPDES regulations do not apply to most non-point sources; non-point sources are unregulated unless states enact specific requirements (FFESCAC, 2009). The ecological approach of watershed management uses best management practices to limit nutrient inputs from non-point sources into surface waters (Piehler, 2008). However, nutrient runoff is increasing due to population growth, expanding agricultural production and more frequent, severe storms (Paerl, 2008; Paerl and Huisman, 2008). FHAB control through nutrient input reduction alone is a long term process. Even if nutrient inputs could be sharply reduced in the near term, nutrient concentrations in sediments would remain elevated due to prior inputs. Nutrients in sediment are released to the water column during hypoxic episodes and when storms or other events resuspend sediments. Nutrient resuspension may trigger new FHABs (Perovich et al., 2008; Paerl et al., 2007; Paul, 2008; Piehler, 2008). There are few examples of sustained FHAB prevention through nutrient input reduction alone. Approaches to nutrient control within water bodies such as hypolimnetic withdrawal, dredging and carp eradication may be appropriate and effective in some water bodies, but research has not characterize the efficacy and potential adverse impacts of these approaches (Paerl, 2008; Perovich et al., 2008).

Ecological approaches use hydrologic manipulations to target the stimulatory factor of quiescent or stagnant water for FHAB prevention, suppression and termination. Freshwater flow rates are decreasing as drought frequency and duration increase due to global climate change, and withdrawals are increasing due to rising usage demand (Paul, 2008; Paerl and Huisman, 2008). Although excess water capacity is not usually available, increasing flow rates and decreasing water residence time can eliminate FHABs even in nutrient-rich freshwaters (Paerl, 2008). Diffused air and mechanical mixing systems are used to artificially circulate water and suppress FHABs in ponds and smaller water bodies (Symons et al., 1970; Huisman et al., 2004). The scientific basis for HAB control through circulation is descried in the literature on cyanobacterial habitat disturbance and buoyancy control (Symons et al., 1970; Reynolds et al., 1983; Visser et al., 1996; Donaghay and Osborn, 1997; Wallace et al., 2000; Elliott et al., 2001; Jungo et al., 2001; Michele and Michele, 2002; Huisman et al., 2004). Artificial circulation promotes species diversity (Elliott et al., 2001; Hudnell et al., in press) and suppresses FHABs when deployed continuously during warm seasons. Intermittent deployment enables FHABs to develop rapidly during the time that aerators are turned off (Johnk et al., 2008). Deployments that destratify the water column, transporting nutrients from the nutrient-rich hypolimnion to the epilimnion and photic zone where FHABs occur, have the potential to stimulate blooms (Singleton and Little, 2006). Other disadvantages include a small area of influence for each air diffuser, the continual need for electric-grid power and applicability limited to smaller water bodies due to cost. Artificial waterfalls or fountains also may provide good FHAB control in smaller water bodies, but continually require electric-grid power (Clevely and Wooster, 2007).

A recently developed technology, Solar Powered Circulation (SPC), overcame some of the limitations of aerators by circulating only epilimnetic water without the need for electric-grid power. SPC strongly suppressed FHABs in three drinking-source water reservoirs by restoring conditions that enabled beneficial algae to out compete cyanobacteria (Hudnell et al., in press). The mean SPC spacing was approximately 15 ha/unit, and mean water intake depth ranged from 2.4 to 6.7 m. Each unit circulated water continuously at a rate of 5.5 ha-m/day. Limnological data collected by the drinking water utility operators before and during SPC demonstrated cyanobacterial suppression and increasing densities of green algae, diatoms and zooplankton during SPC (Hudnell et al., in press). These results were consistent with the literature on FHAB control through habitat disturbance, referenced above.

There is potential for developing ecological approaches to FHAB control based on plants having algaecidal activity and microorganisms pathogenic to cyanobacteria. Barley straw and other plants contain chemical compounds that are toxic to cyanobacteria (Perovich et al., 2008). Barley straw produces phenolic compounds that can be algaecidal, although concentrations in water may be too low to suppress FHABs. The phenols may be oxidized to quinones that are more potent algaecides (Pillinger et al., 1994), or barley straw may suppress FHABs through other mechanisms such as promoting bacteria that lyse cyanobacteria cells. Umbrella plants (*Cyperus alternifolius*) and Canna (*Canna generalis*) produce phenolic and carboxylic compounds that are algaecidal. It has been suggested that these plants could be used on floating islands to suppress cyanobacteria (Nakai et al., 2008). Cyanobacteria pathogens, cyanophage (Tucker and Pollard, 2005; Honjo et al., 2006) and bacteria (Yamamoto et al., 1998; Mayali and Azam, 2004) that lyse cyanobacteria cells, potentially could be cultured (Barkley and Desjardins, 1977) and used to control FHABs. However, the efficacy and potential adverse ecological impacts of plant and microorganism approaches to FHAB control have not been sufficiently evaluated.

Ultrasonic irradiation is an emerging approach to destruction of cyanobacterial cells. Research demonstrated that sonication can reduce *Microcystis* densities when applied alone (Tang et al., 2004) or in combination with a coagulant (Zhang et al., 2009). The primary mechanism may be cavitation effects in the gas vacuoles. Further research is needed to assess the efficacy, practicality and potential adverse ecological impacts of sonication.

6. Research and legislation needed to successfully manage FHAB risks

Scientific research and Congressional legislation and are needed if U.S. human and animal health, aquatic ecosystems and the economy are to be protected from the increasing risks posed by FHABs. Legislation is needed to mandate that the EPA establish a National Research Plan for FHABs, authorize FHAB research funding for the Agency and direct the Agency to establish FHAB policy in a timely manner. Research is needed to better characterize FHAB and cyanotoxin occurrence and adverse effects on health and ecosystems, and to develop, demonstrate and optimize methods and strategies for FHAB prevention, suppression and mitigation. Comprehensive discussions of FHAB research needs are in Hudnell and Dortch (2008) and Lopez et al. (2008b). The research discussed below is that most directly relevant to making policy determinations.

6.1. Research needed

The incidence of cyanobacterial blooms, the types and quantities of cyanotoxins most commonly produced, and the composition of cyanotoxin mixtures in U.S. surface waters is unknown. A program for monitoring cells and toxins in a large sample of U.S. freshwater bodies for several years is required to characterize occurrence. Obtaining reliable and representative estimates of occurrence requires that the EPA implement the UCMR for cyanobacteria and their toxins.

Health research is needed to complete the matrix of RfC, RfD and cancer guideline levels in Table 2. Only six of the potential 27 guideline levels are proposed in the EPA draft Toxicological Reviews. No draft guideline values are proposed for inhalation exposures that could occur around recreational areas, homes or agricultural irrigation fields near affected water bodies, or in showers. Additional animal and human studies are needed to reduce the uncertainty factors of 1000 in the draft guideline value derivations, and to assess dermal exposure risks. Epidemiological studies are required to reduce the uncertainty in animal-to-human extrapolations. Perhaps the least characterized risks are those from repeated, low-level, multi-route exposures to cyanotoxins in surface and drinking waters. The most daunting task may be characterization of the risks from exposure to commonly occurring cyanotoxin mixtures. An integrated assessment of health and ecological effects would best quantify the risks because of the interdependence of human and ecosystem well being (Orme-Zavaleta and Munns, 2008).

Improved prevention and suppression of FHABs requires research to develop more efficient and effective nutrient input reduction strategies. Research could lead to improved strategies for reduced and slow-release fertilizer usage, containment of non-point source runoff and recapturing point source nutrients for reuse. The production of phosphorus, a frequent FHAB-limiting nutrient (Schindler et al., 2008), is predicted to peak within 30 years, and reserve depletion is predicted within 50 to 100 years (Rosemarin, 2004; UNEP, 2005; EcoSanRes, 2008). Ultimately, there will be no alternative to recapturing and reusing phosphorus, an element on which all known life forms are dependent (Correll, 1998; Driver et al., 1999). Significant reductions in nutrient input will require research to improved methodologies and regulations to require their use.

Water bodies, like human bodies, require good circulation to function properly. The continual circulation of surface waters promotes species diversity and suppresses FHABs (Elliott et al., 2001; Hudnell et al., in press), but the mechanisms providing these benefits are unknown. The mechanisms through which artificial circulation inhibits FHABs are hypothesized to be: (1) promotion and distribution of cyanobacteria pathogens, cyanophage (Tucker and Pollard, 2005; Honjo et al., 2006) and bacteria (Yamamoto et al., 1998; Mayali and Azam, 2004) that lyse cyanobacteria cells; (2) promotion of bacteria and beneficial algae that reproduce much more rapidly than cyanobacteria and transport nutrients up the food chain (Kratz and Myers, 1955; Sorokin and Krauss, 1958), thereby limiting the nutrients' availability to promote FHAB growth; and (3) interference with cyanobacteria's ability to optimize position in the water column through buoyancy control to meet nutrition and sunlight requirements (Wallace et al., 2000). The benefits of circulation can be maximized through research that identifies the mechanisms, and describes relationships between circulation parameters and the physical, chemical, biological and morphological characteristics of water bodies.

New methods of FHAB control through physical, chemical and biological applications must be effective and ecologically benign over the long term if they are to be widely used in an environmentally sustainable manner. Approaches that require repeated application of substances or physical forces that harm aquatic biota other than FHAB organisms should demonstrate that population declines and shifts in beneficial biota are not induced with prolonged usage. Toxic compounds should degrade rapidly; the accumulation of toxic substances in sediment is contrary to the intent of the Clean Water Act – to restore, maintain and protect the integrity of the nation's waters (Clean Water Act, 2002).

6.2. Legislation needed

A Freshwater Harmful Algal Bloom Research and Control Act (FHAB Act) is needed to establish a National Research Plan for FHABs, require U.S. policy determinations and authorize funding appropriations (Hudnell and Carmichael, 2009). The EPA is an appropriate lead agency because of their mandates from the Clean Water Act (2002) and the Safe Drinking Water Act (2002). Congressional committees with jurisdiction over the EPA are appropriately positioned to introduce a bill proposing the FHAB Act. The Act could be modeled after HABHRCA, but specify protection of all U.S. freshwaters. The EPA would be directed to administer the research plan in coordination with other agencies having freshwater interests to avoid duplication of efforts. Both intramural and extramural research programs could be enabled by the Act. The extramural research could be administered through the existing HAB competitive, research-grant programs of ECOHAB, MERHAB and the newly established PCM HAB. The Act could enable joint funding by EPA and NOAA for research projects in water bodies within both their purviews. The Act could specify that all extramural research funds are made available on a competitive basis; that funds are awarded to the most qualified applicants as determined through a comprehensive peer-review process. All non-Federal U.S. entities with expertise related to FHABs and water quality science and management should be eligible to submit proposals and receive the extramural research funds. Eligible entities would include public and private, for-profit and not-for-profit institutions and organizations, including academic institutions, state agencies, Indian tribes, local governments and appropriate industries (e.g., aquatic technology, fisheries, agriculture, and fertilizer). The EPA could report progress to Congress and form policy determinations to implement guidelines and/or regulations according to a timeline established by the FHAB Act.

7. Conclusion

Congressional legislation is needed to direct the EPA to establish a National Research Plan for FHABs, authorize and appropriate funds to implement FHAB research programs, establish a timeline for policy determinations and require accountability from the Agency. Successfully confronting the risks of FHABs in an environmentally sustainable manner will strengthen U.S., state and local economies while protecting human and animal health and aquatic ecosystems.

Conflict of interest

The author previously was employed by the EPA and led an interagency workgroup in identifying the state of the science and research needs for freshwater harmful algal blooms. The author currently is employed by SolarBee, Inc., a company that develops and manufactures solar powered circulation systems.

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