Agricultural Runoff, Cyanobacterial Blooms in Lake Erie and Public Health:

A Knowledge Synthesis

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March 17, 2015

Summary

- Freshwater lakes around the world are an important water source for many people.
- The Great Lakes are increasingly becoming nutrient-rich due primarily to agricultural runoff despite previous efforts to reduce nutrient loading from other sources.
- Cyanobacterial (also known as blue-green algae) blooms flourish in eutrophic lakes like Lake Erie and produce harmful toxins that pose a risk to human health.
- Current testing and diagnostic methods, water treatment systems, and regulations intended to limit nutrient runoff can be inadequate in reducing cyanobacterial blooms and are often unaffordable by small municipalities.
- The majority of farmers seem willing to adopt additional best management practices and should thus be educated and supported in their efforts to reduce nutrient runoff.

Introduction

Over the past century, freshwater lakes around the world have become increasingly nutrient-rich, or eutrophic. Wastewater disposal, agricultural runoff and air pollution resulting from human activities have been major contributors to the eutrophication of the world's water sources. Climate change has recently become an important factor as well. The Great Lakes have not been exempt from this phenomenon, which provide over 24 million individuals with fresh water for drinking, recreation and industry, which supports both tourism and economic ends [1]. Lake Erie in particular has experienced several harmful algal blooms attributable to nutrient-enrichment from its source watersheds and rivers. Eutrophication of freshwater and subsequent cyanobacterial (also known as blue-green algae) blooms increases the likelihood of dangerous toxin release, which leaves humans at an increased risk for severe waterborne diseases. This review synthesizes current research pertaining to agricultural runoff to freshwater bodies, specifically Lake Erie, and its effects on human health via its promotion of dangerous cyanobacterial blooms.

Methods

A literature search for English peer-reviewed articles published between 2005 and 2014 was conducted using four databases: PubMed Central, ProQuest, Web of Science and PRIMO (University of Guelph). Combinations of the following search terms were used: Lake Erie AND (agricultural runoff OR agriculture) AND (algae bloom OR cyanobacteria) AND water safety. Articles were initially screened for relevance based on their title and abstract. Upon further review, nine articles were selected for this research synthesis. A brief summary of each article is presented in Table 1 (see Appendix).

Results and Discussion

Agricultural Runoff

Heavy application of agricultural fertilizer, along with the use of phosphorus-containing industrial and household products, was practiced well into the 1970s. Wastewater, a by-product of these human activities, contributed to decades of accumulation of high phosphorus (P) amounts in soils and river sediment [2]. During the 1980s, limitations on the use of P in household detergents greatly reduced the amount of P runoff into lakes from wastewater [2]. Despite efforts to reduce nutrient export, nonpoint agricultural sources of nutrients, especially P, continue to be a major contributor to the eutrophication of Lake Erie via rivers [2-5]. Phosphorus originating from nonpoint agricultural sources can be described as a legacy nutrient that exhibits a lag time between its deposition in sediments and its release, which will continue to have effects well into the future [2, 6].

Han *et al.* (2012) reported an exceptionally high discharge of P from American watersheds into Lake Erie during 2007, a reversal of previous downward trends in the early 2000s. This was consistent with an increased use of P fertilizer in excess of crop needs across most of the watersheds assessed [2, 5]. Ritter *et al.* (2011) estimated that P loading from human activities is responsible for up to 80% of the P present in water systems. Phosphorus levels in Canadian waters range from 0.01-0.1 mg/L; however, these levels can increase five-fold in agricultural areas, which is further indicative of over-fertilization [5]. Modern agricultural practices have not been entirely conducive in reducing nutrient runoff. No-till farming practices may prevent deep fertilizer incorporation into the soil profile, thus allowing more P runoff [2, 3]. A need for increased production per acre and large-scale monoculture may be driving forces behind the practice of broadcast fertilizer application without the use of cover crops to reclaim nutrients [2, 3]. The effects of climate change are also becoming more apparent in terms of more frequent spring storms contributing higher rainfalls and subsequent runoff from agricultural lands to watersheds and lakes [3, 6-8].

Cyanobacterial Blooms and Cyanotoxins

Agricultural over-fertilization leading to high nutrient runoff does not directly affect human health; rather, the downstream eutrophication of a water supply promotes algal growth and toxin release that is potentially dangerous to humans. Cyanobacteria are phytoplankton that have been responsible for oxygenation of water bodies for millennia, and grow best in waters that are eutrophic, warm (≥ 25°C) and exposed to light [3, 6-9]. The shallow western basin of Lake Erie is an ideal location for cyanobacterial blooms since it is surrounded by agricultural industry and its waters tend to be warm [7, 9]. Natural waters are normally deficient in nutrients and thus support only limited growth of algae [9]. High nutrient input from human activities has greatly increased the naturally slow rate of eutrophication, leading to premature aging of Lake Erie [6, 9]. Weirich & Miller (2004) explain that as eutrophic conditions worsen, cyanobacteria spread farther into freshwater bodies to previously unaffected areas.

Cyanobacterial blooms form a thick layer on the water surface, which blocks light and prevents reoxygenation, leading to turbidity, hypoxia, cell death and toxin release [6, 9]. Cyanobacteria produce many secondary metabolites during growth that are typically released during cell lysis or senescence [8]. Some of these metabolites have contributed to fish deaths and a loss of biodiversity [1, 5, 8]. Cyanobacterial compounds, such as 2-methylisoboorneol and geosmin, contribute to the production of volatile organic compounds that lead to water quality issues with odours and off-tastes [1, 5, 7, 8]. More importantly, cyanobacteria produce hepatotoxins, neurotoxins and endotoxins, which have acute and chronic physiological effects in humans at both high dose and low dose (parts per billion) prolonged-exposure, respectively [1, 5-8]. However, not all species of cyanobacteria produce toxins, and not all toxin-producing species release harmful metabolites, making them highly dependent on environmental conditions [1, 7, 8].

Cyanotoxins are colourless and tasteless, making them very difficult to detect using sensory methods [1]. Several field- and laboratory-based analytical tests can identify and quantify cyanobacterial indicators, such as chlorophyll *a* (common to all phytoplankton), phycocyanin (a cyanobacteria-specific pigment) and microcystin-LR [7]. The specificity of detection increases when these methods are used in conjunction, which can become very expensive, especially for small municipalities.

Human Exposure to Cyanotoxins

Effective doses of cyanotoxins are poorly understood [1, 7, 8]. Health Canada's guideline for consumption of algal toxins from drinking water is currently 1.5µg/L [5]. However, these guidelines do not consider the potential long-term effects of cyanotoxin exposure and they do not apply to recreational water activities [5].

Ingestion, inhalation and dermal contact with these toxins can lead to flu-like symptoms, gastrointestinal illness, ear-eye-throat-mouth irritation, blurred vision, rashes, and in extreme cases of prolonged exposure, organ damage, hemorrhage and liver cancer [1, 5-8]. Bioaccumulation of cyanotoxins in fish and shellfish is another source of exposure, although it is unclear what level of consumption is needed to exceed tolerable daily intake levels [7, 8].

Children are at an increased risk for the adverse effects of these toxins, including both immediate acute reactions and chronic conditions caused by a longer exposure time. Low body weight, early developmental stage and risky behaviours (such as swallowing water during recreation and ignoring posted warnings), contribute to a higher incidence rate of cyanotoxin illness and mortality in children than adults [8].

Cyanotoxins have short half-lives within the body, which makes diagnosis of cyanotoxin poisoning difficult without an extensive patient history [1]. Cases related to recreational exposure are often isolated events and affected individuals either do not seek medical attention or are misdiagnosed [8]. Drinking contaminated water, on the other hand, can lead to massive outbreaks that are often examined more comprehensively [8].

Prevention, Control and Prediction of Cyanobacterial Blooms

The trend toward eutrophication of the Great Lakes in the last century was recognized in 1987 with the establishment of the binational Great Lakes Water Quality Agreement [1, 2]. This agreement recognized the importance of managing nutrient export using the Total Maximum Daily Load Program and requires communities to submit remedial action plans when dangerous toxin-producing algal blooms are detected [1, 8].

Since phosphorus is the main limiting nutrient for cyanobacterial growth, biological controls such as aquatic macrophytes, seaweeds, and phytoplanktivorous fish, are used to reduce

P concentration in freshwater to reduce bloom size [9]. Chemical control of blooms by applying copper sulfate is less frequent due to the health risks associated with copper accumulation in sediments and drinking water [7]. Improving P precipitate filtration during sewage treatment and legislation to reduce the P content in laundry detergents have reduced phosphorus export to lakes [2, 9]. However, this has not been shown to be effective at significantly reducing algal biomass, suggesting that agricultural P sources continue to be significant [1].

The Government of Ontario encourages frequent visual monitoring of drinking and recreational water bodies that have a history of algal blooms, especially during the summer season [1]. Larger municipalities bordering Lake Erie test microcystin-LR, the most well-studied cyanotoxin, to ensure its levels are below 1.5 μg/L [1, 7, 8]. However, this can become expensive for smaller municipalities and increasingly stringent regulation discourages many from testing their water for algal toxins.

Water treatment systems are not always effective at removing cyanotoxins from drinking water. The effectiveness of the system depends on the processes it employs, the concentration of cyanotoxins present and the environmental conditions of the water source [8]. Weirich & Miller (2014) explain that activated carbon filtration is the most effective method for the removal of most cyanotoxins. However, this method is costly and unlikely to be used by smaller municipalities that already rely on chlorination, which is least effective against cyanotoxins.

Farmers play an important role in reducing nutrient runoff and subsequent cyanobacterial bloom formation by adopting best management practices (BMPs). Erosion control practices continue to be effective in reducing nutrient-laden soil and sediment release into Lake Erie [5]. Other BMPs include precision fertilizer application, use of cover crops, utilization of biofilters to improve subsurface drainage and growth of buffer strips [3, 8]. An analysis of three common

BMPs by Bosch *et al.* (2013) revealed that more aggressive implementation of a combination of BMPs would most effectively reduce nutrient loading to Lake Erie. Promisingly, a cross-sectional study of farmers in several Lake Erie watersheds by Wilson *et al.* (2014) determined that the majority of farmers had a positive attitude toward taking at least one additional action to reduce nutrient loss on their farm. This effect was even more positive when the farmer had already adopted at least one BMP and had a heightened sense of environmental stewardship.

Public information remains the primary means of reducing potential human intoxication by cyanotoxins. Low concentrations of cyanotoxins do not elicit a major response; local municipalities merely raise public awareness about the presence of toxins in the source water [7]. As the cyanotoxin concentration increases, the provincial and local governments impose restrictions or prohibitions on recreational activities and issue boil water advisories [7]. Affected municipalities are then required to monitor water toxin levels until they diminish to safe levels. Unfortunately, this presents a very reactionary approach to cyanobacterial blooms.

Future Needs and Recommendations

Firstly, a more predictive system for cyanobacterial blooms needs to be established. The Great Lakes region lacks joint formal surveillance between Canada and the United States that would assess the scope of drinking and recreational water exposure to cyanotoxins and subsequent illness. The Centre for Disease Control and Prevention in the United States currently operates a Harmful Algal Bloom-related Illness Surveillance System in Great Lakes regions known to experience frequent blooms [8]. An expansion of this into a binational system would assist in targeting high-risk regions more effectively.

Secondly, further research into improved and affordable cyanotoxin detection methods and water treatment systems is necessary [6, 8]. Rapid and specific diagnostic tests for cyanotoxins should also be developed and made available to the Great Lakes region, especially municipalities at high-risk for cyanobacterial blooms.

Finally, further empirical research should be performed to assess the effectiveness of the available BMPs at an individual watershed level [3, 4]. Promotion and support of incremental improvements in agricultural behaviours and more aggressive BMP use should target the willing majority of farmers on Lake Erie watersheds.

Limitations

The present literature review was limited by the search terms used. The scope of the search could be expanded by adding terms related to specific cyanotoxins, best management practices and predictive models. As a result, this review provided an overview of the issues related to the eutrophication of Lake Erie but perhaps was lacking in detail for specific prevention and predictive measures.

Conclusion

A broad approach to surveillance and regulation is necessary to assess overall cyanotoxin-related illnesses and to raise awareness about the issue. Data-driven, watershed-specific control measures are also needed to prevent further eutrophication of Lake Erie and subsequent cyanobacterial blooms. The majority of farmers have positive attitudes towards best management practices and should thus be supported in adopting additional practices to reduce further nutrient runoff to Lake Erie and ultimately prevent dangerous cyanobacterial blooms.

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Appendix

Table 1. Summary of articles reviewed.

Main Author(s)	Study Type	Key Points
Watson *et al.*, 2008 [1]	Assessment of cyanobacterial toxin management practices.	▪ Seasonal measurements of sediments/flushing of total phosphorus do not consider the short-term dynamics of P fractions that accompany many algal (and NAM) outbreaks. ▪ Algal toxins are colourless and taste-less, and lead to harmful effects when ingested or inhaled (gastroenteritis, vomiting, fever, flu-like symptoms, ear-eye-throat-mouth irritation, rashes, abdominal pain, blurred vision, kidney/liver damage, haemorrhage, liver cancer). ▪ Health Canada drinking water maximum acceptable concentration: 1.5micrograms MC-LR/L for the most toxic toxin and more commonly reported form. ▪ Ontario advocates visual monitoring of drinking/recreational water bodies with a history of algal blooms during high-risk (summer) season, with recommended follow-up. ▪ Larger Ontario municipalities monitor total MC in drinking water but some are discontinuing this practice due to provincial licensing requirements → ultimately, the vast majority of Ontario water supplies are not monitored for toxins.
Han *et al.*, 2012. [2]	Retrospective quantification and trend analysis (USA).	▪ Estimation of net anthropogenic phosphorus inputs (NAPI; includes P from fertilizer, atmospheric deposition, detergents and net exchange from food-feed) to 18 Lake Erie (LE) watersheds for agricultural census years 1935-2007. ▪ NAPI peaked in the 1970s then declined by 2007 to levels similar to 1935. ▪ Reductions in fertilizer application may be due to evolution in nutrient management and environmental awareness, rising cost of fertilizer, greater availability of soil testing, changes in the fate of crop products, and a decrease in manure spreading. ▪ A large pool of soil P continues to contribute to high river export of nutrients, indicative of a lag time from 1970's limitations on nutrient runoff.
Wilson *et al.*, 2014. [3]	Cross-sectional survey of farmers in the Maumee watershed that drains into the western Lake Erie basin.	▪ 303 complete respondents: 94% male, average 52-years-old, ~50% with at least high school-level education, annual gross farm sales ranged from <$50,000 to >$500,000, average 287 total owned acres, and average 588 rented acres. ▪ Most farm and farmer characteristics did not predict a farmer's attitude toward taking action, except for the minority class – consistent with the assumption that individual characteristics do not directly influence action, but rather their influence in mediated by higher order cognitions or beliefs. ▪ Main predictors: risk-perception in younger farmers (environmental stewardship) and response efficacy in older farmers (profits). ▪ Farmer attitudes toward taking at least one additional action to reduce nutrient loss on their farm were positively influenced

		by: already participating in some conservation practices, high threat appraisal and risk perception coupled with high coping appraisal.
Bosch *et al.*, 2013. [4]	ArcSWAT analysis of best management practices (BMP).	▪ A SWAT model calibrated for Huron, Raisin, Maumee, Sandusky, Grand and Cuyahoga watersheds was used to evaluate best management practice (BMP) effectiveness in reducing sediment and nutrient loads from 53% of the watersheds in the Lake Erie basin and the majority of the runoff sources to Lake Erie. ▪ BMPs implemented at the current level deemed "feasible" by the agricultural community are not likely to result in substantial reductions in sediment and nutrient yields. ▪ Non-uniform distribution of nutrients and sediments across areas require watershed-specific BMPs. ▪ There is a need for more aggressive BMP implementation using multiple strategies to reduce tributary nutrient loading to Lake Erie.
Ritter *et al.*, 2011. [5]	Report.	▪ Primary route of phosphorus loading to surface waters is runoff of sediment particles bound to phosphorus, which increases without erosion management strategies. ▪ N and P from household sewage, agriculture, forestry and atmosphere led to an increase in blooms of blue-green algae that produce harmful toxins to humans, as well as alter the taste and odour of the water. ▪ Canadian rivers/lakes/underground water bodies: P content in streams range 0.01-0.1 mg/L but up to 0.5 mg/L in agricultural runoff. ▪ Over-fertilizing reduces plants' ability to uptake N+P, leading to increased N+P in runoff and absorption into soil/sediment; P loading is responsible for up to 80% of P present in water systems ▪ Cyanobacteria proliferate quickly and have a high affinity for N+P. ▪ Canadian guidelines for consumption of algal toxins from drinking water: 1.5μg/L - this does not address toxin influence on cancer development.
Pandey *et al.*, 2014. [6]	Review.	▪ Water contamination by pathogens leads to waterborne diseases outbreaks (gastrointestinal illness and other problems), manifesting as diarrhea, nausea, vomiting, fever and abdominal pain. ▪ There is increased awareness of water treatment and water quality yet outbreaks continue to be reported. ▪ Cyanobacterial blooms occur due to excess nutrient loading of water → excessive/dense algal bloom that reduces quality and quantity of light in the water column → hypoxic water has <2-3 ppm dissolved oxygen, eutrophication decreases aquatic life. ▪ Increased risk of toxin contamination in freshwater by cyanobacteria, which produce cyanotoxins and cyanobacterial harmful algal blooms (affect liver, nervous system, skin). ▪ Combination of eutrophic water conditions with warm surface water (15-30'C) can enhance blooms; can be further enhanced by climate change leading to expansion of "dead zones"

		(eutrophic water bodies).
Merel *et al.*, 2013. [7]	Review.	▪ Cyanobacteria flourish under the following conditions: ≥25°C water temperature, light exposure (quantity, intensity and duration is species-specific) and trophic status of the aquatic system (ideal if eutrophic). ▪ Detection: *in situ* or laboratory analyses of chlorophyll a (Chl a); measures of phycocyanin (a cyanobacteria-specific pigment); enumeration and identification of cells by microscope; and chemical identification of toxin levels in the water (ex. with PCR). ▪ Cyanotoxins are produced during growth but most species do not release the toxins until lysis or senescence – also, not all species produce toxins and not all toxic species will produce toxins automatically. ▪ Humans become exposed via ingestion of cyanobacteria-based food ingredients or shellfish that bioaccumulated the toxins from contaminated water, dermal contact and inhalation/ingestion during recreational activities in waters containing algal bloom, and ingestion of drinking water from a contaminated resource. ▪ Toxins can lead to liver, neurological and dermatological damage. ▪ Bloom prevention and management by: controlling the growth-limiting nutrients using legislation, eradication using copper-containing algaecide or hydrogen peroxide, on-going monitoring and public information about phytoplankton counts, and regulation of cyanotoxins themselves.
Weirich & Miller, 2014. [8]	Review and case study.	▪ Cyanobacteria are ancient organisms responsible for oxygenation have evolved to produce many secondary metabolites; some can be dangerous (hepatotoxins, neurotoxins and endotoxins). ▪ Recreational water limits: determined locally along with acceptable pathogen levels; until recently, many US states unaware/uninterested in toxicity of these toxins. ▪ Microcystin-LR is most studied toxin, therefore standards are developed around this; however, there are many more compounds produced by these bacteria that we have little/no data on; some have acute effects, others have long-term chronic effects. ▪ Children are most sensitive to these toxins and have a longer time of exposure to develop chronic diseases. ▪ CDC's Harmful Algal Bloom-related Illness Surveillance System operated in regions that experience bloom events including Great Lakes region for monitoring blooms. ▪ Ability to remove toxins depends on the processes used, cyanotoxin load and environmental conditions of source water. ▪ Granulated activated carbon (GAC) filtration or powdered activated carbon (PAC) is the most effective method for removal of most toxins.
Khan & Ansari, 2005. [9]	Review.	▪ A large number of freshwater lakes are becoming highly eutrophic, most of which are surrounded with densely

		populated human settlement areas and agricultural fields that contribute high levels of phosphorus and nitrogen to local lake basins. ▪ Lake Erie is the most biologically productive of the Great Lakes because it is shallowest, warmest and excessively rich in nutrients. Lake Erie has a history of blue-green algae blooms that may become exacerbated by climate change in the near future. ▪ Eutrophication is naturally a very slow process but has been greatly accelerated by human activities. High nutrient content leads to excessive growth of phytoplanktons and their subsequent death, which creates a surface layer that increases turbidity, produces a foul smell, and produce toxins. ▪ Phosphorus is the main limiting nutrient for algal growth and is thus targeted for nutrient management using biological, mechanical and legislative controls.