Reducing Harmful Algal Blooms in Michigan and the Great Lakes

Krystina Hird[1], Elyse Baden[2]
[1]Michigan State University, Department of Biochemistry and Molecular Biology, East Lansing, MI, USA
[2]Michigan State University, James Madison College, East Lansing, MI, USA
https://doi.org/10.38126/JSPG230104
Corresponding author: hirdkrys@msu.edu
Keywords: harmful algal blooms (HABs); Great Lakes; Michigan; phosphorus; alternative fertilizers; waterways; agriculture

Executive Summary: Cyanobacterial harmful algal blooms (HABs) threaten the health of the Great Lakes and, by extension, the plants, animals, and humans who live in the region. Excess phosphorus from synthetic fertilizers that leach into water systems are the primary cause of HABs. To attempt to address the issue, the Michigan state government has focused on causal factors and tracked HABs' locations. However, more effective solutions are available to prevent excess nutrients from entering at-risk surface water. We propose a state policy to limit the amount of phosphorus in cropland soils to 30 parts per million (ppm). This policy would greatly reduce nutrient runoff at the source, thereby mitigating the growth of HABs in Michigan waterways.

I. The Great Lakes algal bloom crisis

The Great Lakes are the world's largest freshwater system and provide food, water, transportation, and economic opportunities to millions of people (EPA 2023). Currently, cyanobacterial harmful algal blooms (HABs) endanger the health of the Great Lakes. HABs are explosive algal growths that produce toxic and harmful effects on other organisms, including plants, animals, and humans living in the region (US NOAA 2022). Freshwater HABs are predominantly cyanobacteria (also known as blue-green algae), which cause large green mats of growth that float on waterways (Pal et al. 2020; Watson et al. 2015). These growths tend to be seasonal as summers bring warmer water temperatures and sunlight which accelerate algal growth.

In Michigan, excess amounts of nutrients from synthetic fertilizers cause HABs to form in water systems (GLISA 2023). While many nutrients contribute to algal bloom growth, phosphorus is the main driver of HABs (Schmale et al. 2019). Michigan farmers often use synthetic fertilizers because of their continued effectiveness and consistency, leading to wide use across the agricultural sector. However, synthetic fertilizers have high concentrations of nutrients, only some of which plants can use. These unused nutrients then leach into the groundwater or into runoff that reaches inland waterways and the Great Lakes, causing HAB pollution.

These blooms damage the environment in several ways. They cover the water's surface, block sunlight from plants, and steal oxygen and nutrients that are essential for aquatic life (CDC 2023; Sha et al. 2021). HABs also produce cyanotoxins, which are natural poisons that can cause illness in humans and animals (Gobler 2020; US EPA 2022). These toxins can affect those who drink from, swim in, or otherwise interact with the Great Lakes. In 2014, the reoccurring HAB in Lake Erie resulted in 500,000 Toledo residents' drinking water being suspended for three days (Brooks et al. 2016; US National Office for Harmful Algal Blooms 2019). As of 2019, 43 US states had reported illnesses in humans and animals due to toxins from freshwater blooms (USGS 2019).

In 2021, the CDC reported that Michigan's seventy-seven confirmed HAB occurrences resulted in five cases of human illness and five cases of animal illness. The same year, the CDC confirmed HABs caused an additional eight human illnesses and thirteen animal illnesses in neighboring Great Lakes states. Animals who contracted HAB-related illnesses experienced a 92% mortality rate during this period (CDC 2021). Researchers at Michigan State University's Institute of Water Research also found links between HAB hotspots and areas with significantly higher rates of asthma likelihood, particularly in the Michigan cities of Grand Rapids, Kalamazoo, Muskegon, Saginaw, and Detroit (O'Neil and Triezenberg 2022).

The Michigan Department of Environment, Great Lakes, and Energy (EGLE) and the Michigan Department of Health and Human Services (MDHHS) have collaborated to review reports of potential HABs. In 2021, EGLE received reports of seventy-nine harmful algal blooms in 43 counties across the state (EGLE, MDARD, and MDNR 2021). In 2022, that number increased to roughly 130 complaints about eighty water bodies with verified HABs (EGLE Water Resources Division 2022; MDHHS 2022) (Figure 1).

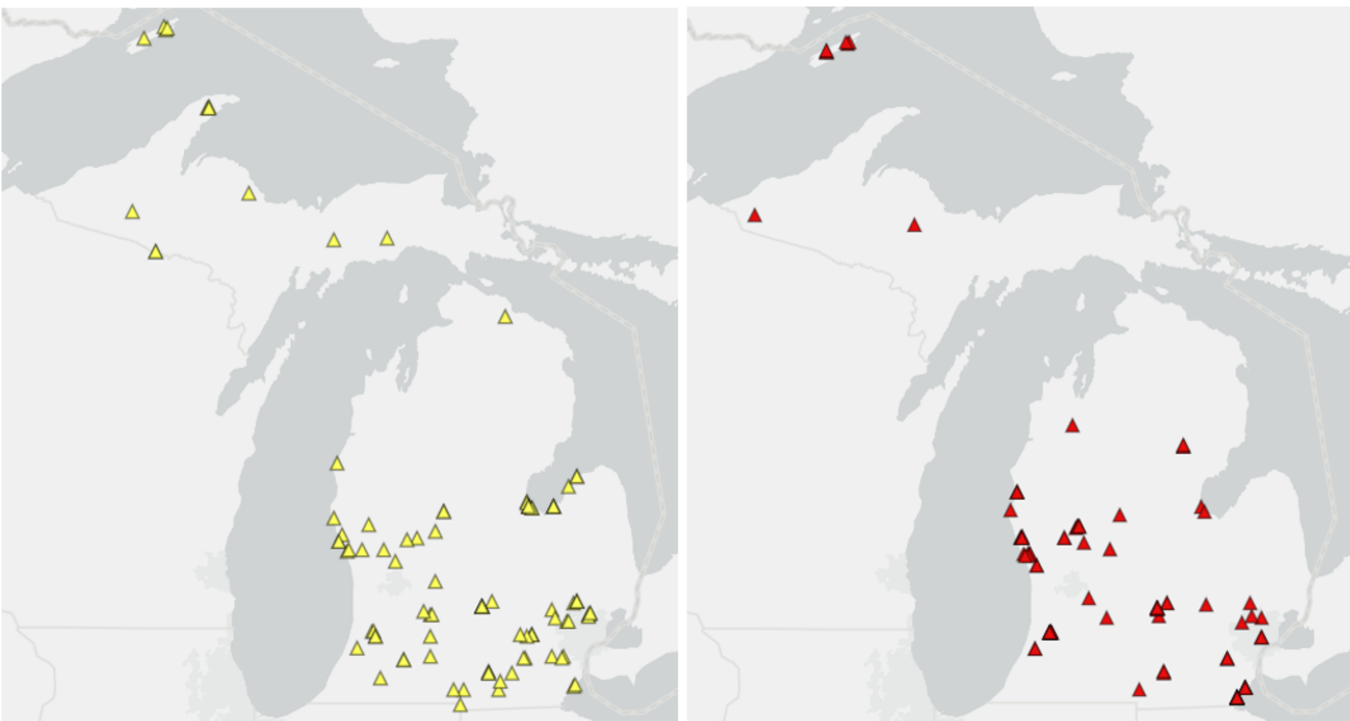

Figure 1: Michigan HAB locations in 2022. Yellow indicates the sites where cyanobacteria were detected but did not produce detectable toxins. Red indicates the sites where cyanobacteria were detected along with toxins. Figure adapted from the Michigan Harmful Algal Bloom Reports Map 2022**.**

II. Current response in Michigan

In an attempt to address the issue, MDHHS and EGLE have researched the causal factors of HABs and tracked blooms' locations via the Michigan Harmful Algal Bloom Reports map, developed in August 2022 (EGLE Water Resources Division 2022; MDHHS 2022). The departments rely on citizen reporting to know where to test for HABs before potentially updating the map. Responses, which typically include closing beaches and sending out warning advisories, are left to the local government that maintains that waterway (MDEGLE 2022). Unfortunately, blooms can appear, disappear and move unexpectedly (EGLE Water Resources Division 2022; MDEGLE 2022) and are often difficult to identify. Those reasons include: the type of algae or cyanobacteria can affect how a bloom looks, the density of the growth may cause potentially toxic blooms to go unreported or for non-harmful blooms to be reported unnecessarily, and the metrics that are used to assess the dangers of a bloom are not standardized or always applicable (Ho and Michalak 2015). This creates challenges when researchers are trying to study the cause of a bloom and determine the best treatment for it.

To increase HAB preparedness, state and federal programs dedicated funding to researching the causes of the blooms. Some of the research plans include the Lake Erie Domestic Action Plan (MDEGLE 2018), Michigan's Adaptive Management Plan (EGLE, MDARD, and MDNR 2021), and the federal Harmful Algal Bloom and Hypoxia Research and Control Act (Harmful Algal Bloom and Hypoxia Research and Control Amendments Act 2017). This and other research indicate that agricultural runoff is a major source of the nutrient spikes in waterways that encourage cyanobacterial growth (Jankowiak et al. 2019). Additionally, pollution and invasive species weaken ecosystems which provide increased opportunities for algal growth, and warmer water temperatures from climate change allow for longer blooming seasons (Smith, King, and Williams 2015; Gobler 2020; Wells et al. 2020; Heil and Muni-Morgan 2021).

Unfortunately, Michigan currently only follows the water quality guidelines of the Clean Water Act (CWA) without stricter state guidelines. The CWA puts limits on nutrients in waterways, called Total Maximum Daily Loads (TMDLs), rather than putting limits on soil nutrients, which does not address agricultural runoff as the primary source of pollution (Clean Water Act 1972; US EPA 2015). Since nutrient runoff originates from the soil, we believe that regulating the amount of fertilizer at the source (i.e. the soil level) can prevent HABs more effectively than regulations at the water level alone.

In this memorandum, we discuss two options: 1) establishing limits on phosphorus in cropland soil and 2) investing in alternative fertilizers. In addition, we discuss the consequences of only relying on current policies.

III. Policy options

i. Option 1: Limit levels of phosphorus in cropland soil

As the Great Lakes state, Michigan holds a unique responsibility to manage and maintain clean water in these bodies. Excess soil nutrients frequently end up in these lakes, which lead to excessive HAB growth that produces harmful cyanotoxins (LimnoTech 2017).

Phosphorus is not only a key nutrient for algal growth in general (Tiwari et al. 2019), it is also a requirement for HAB growth in Michigan (Fuller and Taricska 2012). Therefore, this policy option focuses on limiting phosphorus levels in cropland.

Currently, the Natural Resources Conservation Service recommends that farmers use phosphorus-containing fertilizers to excess. National guidelines allow phosphorus levels in the soil to reach 150 ppm before instructing farmers to stop applying fertilizer or manure (USDA-NRCS 2023a). This level is far more than is necessary to grow most crops in Michigan. Major Michigan cash crops, like soybeans, corn, and dry edible beans, only need 15 ppm of phosphorus in the soil to maintain productive levels (Warncke, Dahl, and Jacobs 2009). Some soils become nutrient-saturated at levels as low as 5 ppm, far lower than 150 ppm (Pöthig et al. 2010), and any water-soluble phosphorus applied past that saturation point is easily washed away (Dari et al. 2018). Excess fertilizer is an incredible waste. In 2017, Michigan farmers spread over ninety-two million pounds of fertilizer, and vast quantities of those nutrients ended up leaching into waterways and forming HABs (Falcone 2021).

We propose an agency-led policy that would put a 30 ppm cap on soil test phosphorus (STP) levels in cropland soil. Soil phosphorus comes in many forms, some unusable by plants, and STP is generally recognized as the crop-available form of phosphorus. This cap would require farmers to test STP levels in their soil before applying any fertilizer or manure. If the STP concentration is above 30 ppm, contributing more nutrients would be prohibited. If the STP concentration is below 30 ppm, then applying fertilizer would be encouraged to ensure plants obtain enough nutrients.

Advantages

This policy would naturally decrease phosphorus concentrations in soils over time since legacy phosphorus levels (the phosphorus in soil that has built up over time through continuously applying fertilizers) would be lessened through crop removal of the nutrient (Doydora et al. 2020). According to a recent hydrologic model, the current store of legacy phosphorus in the soil is great enough to be a major impediment to clean waterways in Michigan for years to come (Muenich, Kalcic, and Scavia 2016). Therefore, applying less fertilizer would decrease the risk of phosphorus runoff. These phosphorus testing kits are also easily obtained from universities or commercial sellers who provide guidelines on how and where to take samples from crop soil for testing. Decreased fertilizer usage would also allow farmers to save money and time every growing season. In 2020, Michigan contained 9.8 million acres of farmland, and by following this new guideline, farmers can save up to an estimated fifty dollars per acre by reducing fertilizer application (USDA-NRCS, accessed 2023b). To aid in offsetting the cost of regular soil testing, the recent Inflation Reduction Act has dedicated $19.5 billion to conservation funding for more green agriculture initiatives (Inflation Reduction Act 2022). Funds from the act could be allocated to help this proposed policy.

Disadvantages

This policy would require farmers to spend time and money testing their soils regularly, which Michigan does not currently require. Soil testing (available commercially or through universities) is generally affordable and accessible (Gartley and Sims 1994), for example Michigan State University Extension sells kits for eighteen dollars and recommends no fewer than 1 sample per twenty-five acres (Curell, Charles, and MSU Extension 2022). However, the soil type, cropping history, and topography increases the number of samples that need to be taken and will therefore increase the cost of testing. Testing is not always timely, taking two weeks on average and sometimes longer for customers to receive results. Crop production, and therefore profit, may also dip as farmers are forced to become familiar with a new nutrient-spreading system. Fertilizer sellers will likely see a decrease in profits as farmers buy less fertilizer each year. This would be the first state policy to restrict applying nutrients to such a degree and will likely need to overcome unique challenges in its early stages.

ii. Option 2: Invest in alternative fertilizers

Because synthetic fertilizers contribute significantly to algal bloom growth, using alternative fertilizers that contain lower nutrient concentrations would reduce the runoff reaching the Great Lakes. Many fertilizer alternatives are on the market, but these tend to be more expensive and can have slower plant uptake than traditional synthetic fertilizers. However, recent technological advancements and ongoing research aim to make alternative fertilizers more accessible and practical. Other parts of the world have started developing their own methods for manure processing, with several European countries seeing major developments. For example, in the Netherlands, where farmers are encouraged to use manure processing, studies have found that this method allows for improved plant nutrient uptake, reduced nutrient runoff into water systems, and reduced harmful greenhouse gas emissions (European Commission 2021).

One such type of alternative fertilizer is filtered manure, an organic matter that can be used for agricultural purposes. Although traditional manure fertilizer and traditional commercial fertilizers have similar levels of phosphorus, evidence shows that filtering manure can reduce excess nutrient content, ensuring that the crops are properly fed while reducing the risk of runoff and HAB growth (International Joint Commission 2018). One such filtering process, called AMAK, can reduce pig manure's phosphorus content by 96% (Makara and Kowalski 2015).

We propose making alternative fertilizers, including filtered manure, a part of the current Michigan agriculture environmental assurance program (MAEAP).

Advantages

The creators of the AMAK process claim that their method is effective and relatively cheap, estimating that their filtered manure can be sold at a price comparable to traditional mineral fertilizers. AMAK also produces a filtrate liquid that can be used to irrigate crops and reduce water use, meaning that this process can produce fertilization and irrigation materials (Makara, Kowalski, and Saeid 2017). Michigan would also be a good location for the AMAK process, given that its strong pork industry produces over two million hogs yearly (Michigan Pork Producers Association 2023).

Further, as previously mentioned, other regions such as the Netherlands have explored and tested manure processing, making predicting how implementation could work in Michigan easier.

Disadvantages

Manure filtering processes, and especially state-sponsored manure filtering, have not yet been tested at the scale needed to support Michigan's agricultural sector, meaning little evidence exists that these systems could practically replace traditional commercial fertilizers. Moreover, the AMAK process has yet to be commercialized, and the existing filtration processes are costly to implement and maintain. This would create an economic burden for Michigan farmers without a guaranteed short-term payoff. Farmers may also be hesitant to adjust their practices from what is known to work, which could be a barrier to successfully implementing this program.

IV. Consequences of inaction

If the causes of algal blooms growth in the Great Lakes are not addressed, the number of HABs in the region will continue increasing. Already, HABs have become an annual occurrence for the past twenty years in Lake Erie (Ai et al. 2023; Wilson et al. 2019). With an increase in HABs, there will be less water that is safe for human consumption and recreational use. Rises in HABs will also increase the presence of cyanotoxins, to the detriment of human and animal health. Further, HABs will continue to harm aquatic plants and animals by reducing access to sunlight, nutrients, and oxygen; reducing food sources for many; and disrupting the regional food chain and economy. HABs have cost aquaculture eight billion dollars per year globally due to fish death and contamination (Brown et al. 2020; Davidson et al. 2016). Additionally, as HAB growth worsens, bloom management will become more difficult and expensive. The necessity of intentional efforts to clean up the Great Lakes could prove costly and time-consuming, especially if steps are not taken to prevent these growths.

V. Policy recommendation

We recommend Option 1, to institute a state policy to limit the amount of STP in cropland soils to 30 ppm. This policy would greatly reduce nutrient runoff at the source, thereby mitigating the growth of HABs in Michigan waterways more completely and simply than attempting to switch to alternative fertilizers as Option 2 suggests. Limiting fertilizer will provide a financial benefit to farmers and benefit the environment. The state should consider subsidizing soil test prices and providing grants to state universities to carry on their soil test analysis programs. As the Great Lakes State, Michigan has a responsibility to be a leader in water quality for those who rely on this vital water source. Should this policy succeed in Michigan, the next step will be to introduce this policy in the other states and Canadian provinces that share their borders with the Great Lakes. Organizations such as the Great Lakes Commission or the International Joint Commission would have the power to introduce these practices in the Great Lakes region.

References

Ai, Haiping, Kai Zhang, Jiachun Sun, and Huichun Zhang. 2023. "Short-Term Lake Erie Algal Bloom Prediction by Classification and Regression Models." Water Research 232 (April): 119710. https://doi.org/10.1016/j.watres.2023.119710.

Brooks, Bryan W., James M. Lazorchak, Meredith D.A. Howard, Mari-Vaughn V. Johnson, Steve L. Morton, Dawn A.K. Perkins, Euan D. Reavie, Geoffrey I. Scott, Stephanie A. Smith, and Jeffery A. Steevens. 2016. "Are Harmful Algal Blooms Becoming the Greatest Inland Water Quality Threat to Public Health and Aquatic Ecosystems?" Environmental Toxicology and Chemistry 35 no. 1: 6–13. https://doi.org/10.1002/etc.3220.

Brown, Andrew Ross, Martin Lilley, Jamie Shutler, Chris Lowe, Yuri Artioli, Ricardo Torres, Elisa Berdalet, and Charles R. Tyler. 2020. "Assessing Risks and Mitigating Impacts of Harmful Algal Blooms on Mariculture and Marine Fisheries." Reviews in Aquaculture 12, no. 3: 1663–88. https://doi.org/10.1111/raq.12403.

CDC. 2021. "2021 OHHABS Data Summary." Centers for Disease Control and Prevention. Accessed September 5, 2023. https://www.cdc.gov/habs/data/2021-ohhabs-data-summary.html.

CDC. "Cyanobacteria Frequently Asked Questions (FAQs)." Centers for Disease Control and Prevention. Accessed September 7, 2023. https://www.cdc.gov/habs/pdf/cyanobacteria_faq.pdf.

Clean Water Act. 1972. Public Law 92-500, 86 Stat. 816. United States Code, Title 33.

Curell, Christina, Christine Charles, and MSU Extension. 2022. "A Field Guide To Soil Sampling." Soil Health. October 13, 2022. https://www.canr.msu.edu/resources/a-field-guide-to-soil-sampling.

Dari, Biswanath, Vimala D. Nair, Andrew N. Sharpley, Peter Kleinman, Dorcas Franklin, and Willie G. Harris. 2018. "Consistency of the Threshold Phosphorus Saturation Ratio across a Wide Geographic Range of Acid Soils." Agrosystems, Geosciences & Environment 1, no. 1: 180028. https://doi.org/10.2134/age2018.08.0028.

Davidson, Keith, Donald M. Anderson, Marcos Mateus, Beatriz Reguera, Joe Silke, Marc Sourisseau, and Julie Maguire. 2016. "Forecasting the Risk of Harmful Algal Blooms." Harmful Algae, Applied Simulations and Integrated Modelling for the Understanding of Toxic and Harmful Algal Blooms (ASIMUTH), 53 (March): 1–7. https://doi.org/10.1016/j.hal.2015.11.005.

Doydora, Sarah, Luciano Gatiboni, Khara Grieger, Dean Hesterberg, Jacob L. Jones, Eric S. McLamore, Rachel Peters, Rosangela Sozzani, Lisa Van den Broeck, and Owen W. Duckworth. 2020. "Accessing Legacy Phosphorus in Soils." Soil Systems 4 no. 4: 74. https://doi.org/10.3390/soilsystems4040074.

EGLE, MDARD, and MDNR. 2021. Michigan's Adaptive Management Plan to Reduce Phosphorus Loading into Lake Erie. Michigan Department of Environment, Great Lakes, and Energy, Michigan Department of Agriculture and Rural Development, and Michigan Department of Natural Resources. https://www.michigan.gov/egle/-/media/Project/Websites/egle/Documents/Programs/WRD/AOC/Great-Lakes-Michigan-AMP.pdf.

EGLE Water Resources Division. 2022. Cyanobacteria Bloom Monitoring in Michigan Inland Lakes During 2021 and 2022. https://www.michigan.gov/egle/-/media/Project/Websites/egle/Documents/Programs/WRD/SWAS/HAB/cyanobacterial-2021-2022-lake-results.pdf.

EPA. 2023. "Facts and Figures about the Great Lakes." Environmental Protection Agency. Accessed September 7, 2023. https://www.epa.gov/greatlakes/facts-and-figures-about-great-lakes.

European Commission. 2021. "Nitrates: Protecting waters against pollution caused by nitrates from agricultural sources." European Environment Agency. Accessed September 7, 2023. https://environment.ec.europa.eu/topics/water/nitrates_en.

Falcone, James A. 2021. "Tabular County-Level Nitrogen and Phosphorus Estimates from Fertilizer and Manure for Approximately 5-Year Periods from 1950 to 2017." U.S. Geological Survey. https://doi.org/10.5066/P9VSQN3C.

Fuller, L M, and C K Taricska. 2012. "Water-Quality Characteristics of Michigan's Inland Lakes, 2001–10." U.S. Geological Survey Scientific Investigations Report 2011–5233, 66. https://pubs.usgs.gov/sir/2011/5233/.

Gartley, K. L., and J. T. Sims. 1994. "Phosphorus Soil Testing: Environmental Uses and Implications." Communications in Soil Science and Plant Analysis 25, no. 9–10: 1565–82. https://doi.org/10.1080/00103629409369136.

GLISA. "Algal Blooms." Great Lakes Integrated Sciences + Assessments. Accessed September 7, 2023. https://glisa.umich.edu/resources-tools/climate-impacts/algal-blooms/.

Gobler, Christopher J. 2020. "Climate Change and Harmful Algal Blooms: Insights and Perspective." Harmful Algae, Climate change and harmful algal blooms, 91 (January): 101731. https://doi.org/10.1016/j.hal.2019.101731.

Harmful Algal Bloom and Hypoxia Research and Control Amendments Act. 2017. Public Law 115-55. United States Statutes at Large, 131 Stat. 1092.

Heil, Cynthia Ann, and Amanda Lorraine Muni-Morgan. 2021. "Florida's Harmful Algal Bloom (HAB) Problem: Escalating Risks to Human, Environmental and Economic Health With Climate Change." Frontiers in Ecology and Evolution 9. https://www.frontiersin.org/articles/10.3389/fevo.2021.646080.

Ho, Jeff C., and Anna M. Michalak. 2015. "Challenges in Tracking Harmful Algal Blooms: A Synthesis of Evidence from Lake Erie." Journal of Great Lakes Research 41, no. 2: 317–25. https://doi.org/10.1016/j.jglr.2015.01.001.

Inflation Reduction Act. 2022. Public Law 117-169. United States Statutes at Large, 136 Stat. 1818.

International Joint Commission. 2018. "Fertilizer Application Patterns and Trends and Their Implications for Water Quality in the Western Lake Erie Basin." https://legacyfiles.ijc.org/tinymce/uploaded/Publications/IJC_FertReport.pdf.

Jankowiak, Jennifer, Theresa Hattenrath-Lehmann, Benjamin J. Kramer, Megan Ladds, and Christopher J. Gobler. 2019. "Deciphering the Effects of Nitrogen, Phosphorus, and Temperature on Cyanobacterial Bloom Intensification, Diversity, and Toxicity in Western Lake Erie." Limnology and Oceanography 64, no. 3: 1347–70. https://doi.org/10.1002/lno.11120.

LimnoTech. 2017. "Assessment of Fertilizer and Manure Application in the Western Lake Erie Basin." Completed for the International Joint Commission Science Advisory Board's Science Priority Committee. https://legacyfiles.ijc.org/publications/LimnoTech_IJC_Fertilizer.pdf.

Makara, A., and Z. Kowalski. 2015. “Pig Manure Treatment and Purification by Filtration.” Journal of Environmental Management 161 (September): 317–24. https://doi.org/10.1016/j.jenvman.2015.07.022.

Makara, Agnieszka, Zygmunt Kowalski, and Agnieszka Saeid. 2017. “Properties of the Filtrate from Treatment of Pig Manure by Filtration Method.” Open Chemistry 15, 1: 19–27. https://doi.org/10.1515/chem-2017-0003.

MDEGLE. 2018. “Domestic Action Plan for Lake Erie.” Michigan.gov. https://www.michigan.gov/egle/-/media/Project/Websites/egle/Documents/Programs/WRD/AOC/Domestic-Action-Plan-Lake-Erie.pdf.

MDEGLE. 2022. “Harmful Algal Blooms.” Michigan Department of Environment, Great Lakes, and Energy. https://www.michigan.gov/egle/about/organization/water-resources/assessment-michigan-waters/harmful-algal-blooms.

MDHHS. 2022. “HAB Tracker.” Michigan Department of Health and Human Services. Accessed September 7, 2023. https://www.michigan.gov/mdhhs/news/2022/08/08/hab-tracker.

Michigan Pork Producers Association. “Farmer Resources.” Michigan Pork Producers Association. Accessed September 7, 2023. https://www.mipork.org/farmer-resources/.

Muenich, Rebecca Logsdon, Margaret Kalcic, and Donald Scavia. 2016. “Evaluating the Impact of Legacy P and Agricultural Conservation Practices on Nutrient Loads from the Maumee River Watershed.” Environmental Science & Technology 50, no. 15: 8146–54. https://doi.org/10.1021/acs.est.6b01421.

O'Neil, Glenn, and Heather Triezenberg. 2022. “Harmful Algal Bloom Vulnerability in Michigan.” ArcGIS StoryMaps. https://storymaps.arcgis.com/stories/2ca2f8e82c8441d8905ffd8a11da806b .

Pal, Mili, Prerna J. Yesankar, Ajay Dwivedi, and Asifa Qureshi. 2020. “Biotic Control of Harmful Algal Blooms (HABs): A Brief Review.” Journal of Environmental Management 268, (August): 110687. https://doi.org/10.1016/j.jenvman.2020.110687.

Pöthig, Rosemarie, Horst Behrendt, Dieter Opitz, and Gerhard Furrer. 2010. “A Universal Method to Assess the Potential of Phosphorus Loss from Soil to Aquatic Ecosystems.” Environmental Science and Pollution Research 17, no. 2: 497–504. https://doi.org/10.1007/s11356-009-0230-5.

Schmale, David, Andrew P. Ault, Walid Saad, Durelle T. Scott, and Judy A. Westrick. 2019. “Perspectives on Harmful Algal Blooms (HABs) and the Cyberbiosecurity of Freshwater Systems.” Frontiers in Bioengineering and Biotechnology, no. 7: 28. https://doi.org/10.3389/fbioe.2019.00128.

Sha, Jun, Haiyan Xiong, Chengjun Li, Zhiying Lu, Jichao Zhang, Huan Zhong, Wei Zhang, and Bing Yan. 2021. “Harmful Algal Blooms and Their Eco-Environmental Indication.” Chemosphere 274, (July): 129912. https://doi.org/10.1016/j.chemosphere.2021.129912.

Smith, D. R., K. W. King, and M. R. Williams. 2015. “What Is Causing the Harmful Algal Blooms in Lake Erie?” Journal of Soil and Water Conservation 70, no. 2: 27A-29A. https://doi.org/10.2489/jswc.70.2.27A.

Tiwari, Pankaj Kumar, Sudip Samanta, Jocirei D. Ferreira, and Arvind Kumar Misra. 2019. “A Mathematical Model for the Effects of Nitrogen and Phosphorus on Algal Blooms.” International Journal of Bifurcation and Chaos 29, no. 10: 1950129. https://doi.org/10.1142/S0218127419501293.

USDA-NRCS. “Conservation Practice Standards Information.” U.S. Department of Agriculture, Natural Resources Conservation Service. Accessed September 7, 2023. https://www.nrcs.usda.gov/getting-assistance/conservation-practices.

USDA-NRCS. “Nutrient Management.” U.S. Department of Agriculture, Natural Resources Conservation Service. Accessed September 7, 2023. https://www.nrcs.usda.gov/getting-assistance/other-topics/nutrient-management.

U.S. NOAA. 2019. “Great Lakes: Harmful Algal Blooms.” National Oceanic and Atmospheric Administration's National Ocean Service, April 10, 2019. https://oceanservice.noaa.gov/hazards/hab/great-lakes.html.

U.S. EPA, OW. 2015. “Overview of Total Maximum Daily Loads (TMDLs).” Overviews and Factsheets. September 29, 2015. https://www.epa.gov/tmdl/overview-total-maximum-daily-loads-tmdls.

U.S. EPA, OW. 2022. “Learn about Cyanobacteria and Cyanotoxins.” Overviews and Factsheets. August 1, 2022. https://www.epa.gov/cyanohabs/learn-about-cyanobacteria-and-cyanotoxins.

U.S. National Office for Harmful Algal Blooms. 2019. “Impacts of Harmful Algal Blooms.” Woods Hole Oceanographic Institution. https://hab.whoi.edu/impacts/.

USGS. 2019. "NWQP Research on Harmful Algal Blooms (HABs) | U.S. Geological Survey." USGS: Science for a Changing World. March 3, 2019. https://www.usgs.gov/mission-areas/water-resources/science/nwqp-research-harmful-algal-blooms-habs.

Warncke, Darryl, Jon Dahl, and Lee Jacobs. 2009. "Nutrient Recommendations for Field Crops in Michigan." East Lansing, MI: Michigan State University Extension, August, 36. https://www.canr.msu.edu/fertrec/uploads/E-2904-MSU-Nutrient-recomdns-field-crops.pdf.

Watson, Sue B., Brian A. Whitton, Scott N. Higgins, Hans W. Paerl, Bryan W. Brooks, and John D. Wehr. 2015. "Chapter 20 - Harmful Algal Blooms." In Freshwater Algae of North America (Second Edition), edited by John D. Wehr, Robert G. Sheath, and J. Patrick Kociolek, 873–920. Aquatic Ecology. Boston: Academic Press. https://doi.org/10.1016/B978-0-12-385876-4.00020-7.

Wells, Mark L., Bengt Karlson, Angela Wulff, Raphael Kudela, Charles Trick, Valentina Asnaghi, Elisa Berdalet, et al. 2020. "Future HAB Science: Directions and Challenges in a Changing Climate." Harmful Algae, Climate change and harmful algal blooms 91, (January): 101632. https://doi.org/10.1016/j.hal.2019.101632.

Wilson, Robyn S., Margaret A. Beetstra, Jeffrey M. Reutter, Gail Hesse, Kristen M. DeVanna Fussell, Laura T. Johnson, Kevin W. King, Gregory A. LaBarge, Jay F. Martin, and Christopher Winslow. 2019. "Commentary: Achieving Phosphorus Reduction Targets for Lake Erie." Journal of Great Lakes Research 45, no. 1: 4–11. https://doi.org/10.1016/j.jglr.2018.11.004.

Krystina Hird is a Ph.D. candidate in the Biochemistry and Molecular Biology program at Michigan State University. Her research focuses on the global nitrogen cycle, specifically the reduction of nitrite to ammonium via the Dissimilatory Nitrate Reduction to Ammonium pathway. She interned at West Michigan Environmental Action Council and Circle of Blue. After completing her Ph.D., Krystina plans on pursuing a career in science policy.

Elyse Baden is a recent graduate of Michigan State University who focused her studies on environmental policy and ethics. She is a member of the Children and Youth Major Group to the United Nations Environment Programme and represented the United States at the United Nations Economic and Social Council Youth Forum in April of 2023. Elyse also serves as the North American lead of a global initiative to promote and expand the Sustainable Development Goals.

Disclaimer

The authors disclose that they have no conflict of interest in this form.