Nutrients in Lake Erie and Lake Ontario: Synthesis of International Joint Commission Recommendations and Assessment of Domestic Action Plans

A report submitted to the International Joint Commission by the Great Lakes Science Advisory Board and the Great Lakes Water Quality Board Joint Work Group on Nutrient Synthesis

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Table of Contents

List of Figures

List of Tables

List of Acronyms

BMPs	Best Management Practices
DAPs	Domestic Action Plans
ECCC	Environment and Climate Change Canada
HABs	Harmful Algal Blooms
HU	Hydrologic Unit
LAMP	Lakewide Action and Management Plan
NOAA	US National Oceanic and Atmospheric Administration
TMDLs	Total Maximum Daily Loads
USDA	US Department of Agriculture
USEPA	US Environmental Protection Agency

Executive Summary

For over a century, the Great Lakes faced many threats including longstanding problems related to nutrients. Excessive nutrient loads to Lake Erie in the 1960s and early 1970s—and associated impacts such as harmful algal blooms (HABs)—were a motivating factor in the signing of the Great Lakes Water Quality Agreement between Canadian and US governments ("the Parties") in 1972. Subsequent policies to regulate nutrients from point sources led to substantial reductions in eutrophication problems in Lake Erie. However, algal blooms began reappearing in the late 1990s and have increased in frequency and severity since then.

The impacts of HABs in Lake Erie have been costly. HABs can produce toxins which threaten the health of humans, fish and wildlife, pets, and livestock. A 2014 bloom in the western Lake Erie basin led to a multi-day drinking water advisory for Toledo, Ohio and extensive subsequent expenditures to upgrade water treatment systems. But the human impacts of algal blooms go well beyond water treatment costs. Property values, tourism, recreational activities and aesthetic values are all adversely affected by nuisance and harmful algal blooms. The impact on the local economy of HAB occurrences in 2011 and 2014 is estimated to exceed US$135 million (CDN$182 million), and the cost of Lake Erie algal blooms could cost Canadian citizens alone as much as CDN$5.3 billion (nearly US$4 billion) over the next 30 years. In addition to problems associated with excessive nutrients in Lake Erie and certain other nearshore waters, the opposite problem of lower nutrient levels is impacting fisheries in the offshore waters of Lakes Huron, Michigan, Ontario and the eastern basin of Lake Erie.

In response to the re-emergence of HABs, the Parties developed nutrient loading targets in 2016 for the western and central basins of Lake Erie (collectively a 40 percent reduction from 2008 levels of phosphorus). To achieve those targets, the Parties, Ontario and the states draining to Lake Erie developed domestic action plans (DAPs) in 2017 and 2018. In a parallel effort, Michigan, Ohio and Ontario agreed to a 40 percent reduction target in total and dissolved reactive phosphorus loads, to be attained by 2025. In addition to these agreements, the International Joint Commission produced eight reports over the past decade, advising Canadian and US governments by offering over 100 recommendations related to nutrient problems, with the majority focused on Lake Erie, but many applicable to the other Great Lakes.

In light of the ongoing nutrient-related impacts in Lake Erie, the adoption of the DAPs by the Parties and the extensive set of past Commission recommendations, the Commission's Great Lakes Science Advisory Board's Science Priority Committee and the Great Lakes Water Quality Board organized a project to undertake a comprehensive synthesis of these developments. This report is the outcome of that project. The primary goal of this report is to assess the DAPs and their implementation to date in the context of the Commission's nutrient-related recommendations as well as findings from recent scientific literature. This assessment is intended to uncover critical gaps in knowledge and barriers inhibiting progress towards achieving nutrient loading targets, to make new recommendations that will lead to more rapid progress toward the 40 percent reduction target for Lake Erie, and to inform efforts by representatives of the Parties, states in the Lake Erie basin and Ontario to carry out scheduled updates to DAPs in 2023. A secondary goal is to explore priority issues concerning nutrient-

related impacts in Lake Ontario which, unlike Lake Erie but like Lakes Michigan and Huron, involve both increased nearshore and decreased offshore nutrients concentrations.

The focus on the western basin of Lake Erie is not meant to diminish the serious eutrophication problems that occur in other areas of the Great Lakes, such as in Lake Michigan's Green Bay, Lake Huron's Saginaw Bay, and Lake Ontario's Bay of Quinte. Instead, the focus is based on the emphasis of nutrient related Commission reports over the past decade, current priorities within Agreement's Annex 4 (Nutrients), and an intention to keep the scope of this project manageable. The work on this project was carried out through the guidance, contributions, and review of a work group, an extensive review of the literature and programs by a contractor and drafting of this report by the work group co-chairs and support staff.

Addressing nutrient impacts in the Great Lakes means addressing nutrient loads. While nutrient loadings from point sources (such as wastewater treatment plants) have been highly regulated for many years, loadings from nonpoint agricultural sources are not regulated; instead, both countries rely on voluntary nutrient reduction programs. This is a key point because nonpoint agricultural sources (largely associated with commercial fertilizer application and manure application) are now the main contributor of nutrient loadings to the western and central basins of Lake Erie. Consequently, the 40 percent reduction target to which the Parties have committed will not be met without substantial reductions from these sources.

In addition to drawing on assessment work by the project contractor, the project team assessed the extent to which the DAPs address each of 12 program areas that contribute to the overall objective of reducing the severity and frequency of Lake Erie HABs and hypoxia (or low oxygen conditions). We found that most DAPs comprehensively address many program areas such as research, monitoring, adaptive management and watershed-level planning. In addition, all DAPs rely exclusively on voluntary programs for addressing agricultural nonpoint source nutrient runoff by offering cost sharing and technical consultation for best management practice (BMP) adoption. But DAPs do vary considerably in the level of detail regarding targeting, consideration of cost-effectiveness and other aspects of BMP implementation. Tracking and reporting are covered to some extent in all DAPs but, as we indicate below, more is needed in specific areas. Manure management receives uneven attention with only a couple of DAPs including detailed discussion. Very few of the DAPs address human health issues.

We also identified key gaps and barriers inhibiting more rapid progress towards achieving nutrient loading objectives. Knowledge gaps regarding the extent of BMP implementation and nonpoint source nutrient loadings at multiple scales (e.g., including subwatershed and smaller) for the western Lake Erie basin present a barrier to effective policy action. There is a need for increased information on BMP implementation (including types, time period and locations) and water quality monitoring across jurisdictions. In addition, continued reliance on voluntary programs to encourage BMP adoption may be a major barrier to further progress because their effectiveness is likely to be subject to diminishing returns; the easiest and least-costly BMPs are likely the first to be voluntarily adopted. Further BMP adoption will be increasingly costly, and farmers are not likely to voluntarily adopt practices that jeopardize on-farm net benefits. Concerning Lake Ontario, key findings of this project focus on the need to better understand phosphorus loads, cycling and impacts in the lakes, including implications for addressing nearshore eutrophication and offshore low nutrient problems.

Based on the findings identified in this project, insights from the contractor technical report, and previous Commission recommendations, we identify a set of recommendations for Lake Erie and for Lake Ontario. Recommendations are directed at the Parties, with US Environmental Protection Agency (USEPA) and Environment and Climate Change Canada (ECCC) being the lead agencies, though in many cases the Lake Erie states (particularly the western Lake Erie basin watershed states of Michigan, Indiana, and Ohio) and the province of Ontario play key roles. Here we briefly list the recommendations. **Section 4** provides more detail on each of the recommendations.

For Lake Erie, there are four action-related and three science-related recommendations:

1. The Parties should work with state, provincial, First Nations, Métis and Tribal governments, and agricultural and nongovernmental partners and stakeholders to incorporate an accountability framework into work under Annex 4 by 2024 that includes reporting on and evaluating progress on Lake Erie nutrients.

2. The Parties should work with state, provincial, First Nations, Métis and Tribal governments, and agricultural and nongovernmental partners and stakeholders to ensure that the 2023 DAPs contain a framework for developing adoption targets for BMPs for the western and central basin watersheds of Lake Erie, and ensure resources are available to increase BMP implementation efforts over the 2023-2025 triennial period.

3. The Parties should work with state, provincial, First Nations, Métis and Tribal governments, and agricultural and nongovernmental partners and stakeholders in developing and implementing a common framework for assembling, analyzing and making publicly available more comprehensive information on generation and application of manure and commercial fertilizer, and associated phosphorus and other nutrients, at appropriate scales within the western Lake Erie basin, and consider such information in developing any new management regimes for both broad nutrient sources.

4. The Parties should, within two years, work with states, provincial, Tribal, First Nations and Métis governments, and agricultural and nongovernmental partners and stakeholders to develop and/or revisit indicators needed for tracking progress in reducing nutrient loads and improving Lake Erie conditions, including an entire suite of driver, pressure, state, impacts and management-response indicators, and improve indicator communication.

5. The Parties should reduce the barriers to voluntary adoption of effective BMPs by undertaking—and completing an initial round by 2025—studies to assess the on-farm costs, benefits and communication barriers to adoption of the BMPs most likely to result in more widespread phosphorus reductions (e.g., subsurface fertilizer placement, fertilizer rate reduction, riparian buffers and potentially cover crops). Ongoing and new research findings, including on the impacts of BMPs on water quality objectives (last recommendation for Lake Erie below), should be synthesized and communicated, including via peer-to-peer communication networks among farmers.

6. The Parties should set a goal in the 2023 DAPs to undertake a study to examine the feasibility of the group-level economic instrument outlined in Section 2.3 of this report for reducing nonpoint source nutrient loadings in the western Lake Erie basin. The Parties should direct their relevant agencies to fund and support such a study (or studies) and report on results in the 2025 Progress Report of the Parties.

7. The Parties should set a goal in the 2023 DAPs to undertake and/or fund and facilitate new research to advance understanding of the effectiveness of specific BMPs and combinations of BMPs at achieving water quality improvements. As outlined in this report, research should include:

    1. Edge-of-field studies that measure nutrient export at the field level and variation with BMP implementation and other measures;
    2. Integrated assessment models that link economic models of farmers' phosphorus-related management practices to biophysical models of the resulting changes in nutrient loadings; and
    3. Empirical studies that link nutrient concentration data (and other water quality measures) at the watershed or subwatershed level (e.g., 10 or 12 digit hydrologic unit scale in the United States) with BMP adoption data in the same regions.

For Lake Ontario, one action-related and one science-related recommendation:

1. The Parties should develop and make publicly available a process and timeline for reviewing nutrient objectives and targets for Lake Ontario, revise as appropriate based on a comprehensive review of the science, and identify potential no regrets nutrient reduction actions for nearshore areas.

2. By 2024, the Parties should identify the best approach to improving science and management of nutrients and related issues in Lake Ontario, whether through existing Annex 4 processes or through a new, multistakeholder committee.

There are extensive efforts underway by the Parties, states in the Lake Erie and Ontario basins, the province of Ontario, and other jurisdictions to address nutrient-related problems facing Lake Erie and Lake Ontario. However, given ongoing nutrient-related problems in Lakes Erie and Ontario, we believe that by drawing on the recommendations from this report, a more concerted effort by the Parties, states, provinces, the Commission, First Nations, Métis and Tribal governments, the private sector, nongovernmental organizations and the public can successfully tackle these problems and restore and protect Lake Erie and Lake Ontario.

1.0 Introduction

The Laurentian Great Lakes have suffered from human-caused stresses since the 1800s. Significant among these, beginning in the mid-20th Century, are excessive nutrient loadings from agricultural, industrial and other activities that have led to eutrophication (or increased biological productivity driven by increased nutrients) in many areas of the Great Lakes, including most of Lake Erie and nearshore areas in the other lakes such as Green Bay (Lake Michigan), Saginaw Bay (Lake Huron), and much of the Lake Ontario nearshore zones (Beeton 2002; Sterner 2021).

Such eutrophication is often manifested through harmful algal blooms (HABs), including cyanobacteria that can produce toxins, which in turn can threaten the health of humans, wildlife, pets and livestock. In 2014, a HABs bloom in the western Lake Erie basin contaminated the city of Toledo, Ohio's water supply, leading to a drinking water advisory and, ultimately, millions of dollars of expenditures to upgrade water treatment plants in the region and hundreds of thousands of dollars in ongoing monitoring, treatment, and disposal costs (Alliance for the Great Lakes, 2022). Property values, tourism, recreational activities and aesthetic values are all adversely affected by algal blooms. Bingham et. al. (2015) estimate that HABs events in 2011 and 2014 in the western basin of Lake Erie together imposed one-time costs on the local economy exceeding US$135 million (CDN$182 million). Smith et. al. (2019) estimate that Lake Erie algal blooms could cost Canadian citizens alone as much as CDN$5.3 billion (nearly US$4 billion) over the next 30 years.

Eutrophication can also lead to hypoxia (low-oxygen conditions) and the development of nuisance algae (discussed in **Section 1.1**). In addition to eutrophication of many areas of the Great Lakes in recent decades, other areas of the lakes (particularly offshore) have experienced oligotrophication, or a transition to lower nutrients levels (and lower productivity) (Hecky et al. 2004). This phenomenon has been attributed to increased retention and cycling of nutrients in the nearshore areas and/or in sediments offshore, likely involving invasive zebra and quagga mussels (Sterner 2021). This offshore oligotrophication in turn has negative implications for the food web and fisheries and has been an issue particularly in offshore waters of Lakes Michigan, Huron and Ontario, as well as the eastern basin of Lake Erie (International Joint Commission Great Lakes Science Advisory Board 2020a). The combination of excessive nutrients in some parts of the lakes and nutrient deficits in others further complicates science-driven solutions to addressing nutrient-related problems in the Great Lakes and underscores the importance of having adequate research and monitoring programs in place to best inform management decisions.

A major step towards addressing nutrient-related problems in the Great Lakes was the signing by the Canadian and US governments (the Parties) of the Great Lakes Water Quality Agreement in 1972, with a major driving force being a 1964 reference under the 1909 Boundary Waters Treaty to address problems associated with eutrophication of the lower lakes (Botts and Muldoon, 2005). Eutrophication of certain Great Lakes waters—in particular Lake Erie—was a major emphasis initially under the Agreement, with subsequent amendments (in 1978, 1987, and most recently 2012) expanding its scope to include more explicitly toxic chemicals, an *ecosystem approach* to addressing Great Lakes water quality, and, more recently, additional stresses (Botts and Muldoon, 2005; Canada and the United States, 2012, 1987, 1978, 1972).

The current Agreement includes multiple higher-level general objectives, including that the waters of the Great Lakes "be free from nutrients that directly or indirectly enter the water as a result of human activity, in amounts that promote growth of algae and cyanobacteria that interfere with aquatic ecosystem health, or human use of the ecosystem" (Canada and the United States., 2012). The Agreement also contains ten annexes, with Annex 4 addressing nutrients, including calling on the Parties to establish objectives and loading targets, and implement programs to meet the objectives. The Parties' work under the Agreement is led by the US Environmental Protection Agency (USEPA) and Environment and Climate Change Canada (ECCC).

Annex 4 of the 2012 Agreement includes Lake Ecosystem Objectives addressing several aspects of nutrient-related conditions in the lakes (see box to the right). The 2012 Agreement also includes interim substance objectives for phosphorus (or open water total phosphorus concentrations, such as 15 micrograms per liter (ug/L or parts per billion), for western Lake Erie, as well as interim phosphorus loading targets for all five lakes (Canada and the United States, 2012).

The 2012 Agreement also calls on the Parties to review and revise interim phosphorus concentration objectives, and determine loading allocations for each Great Lake, phosphorus concentration objectives for nearshore waters, and load reduction targets for priority watersheds[1] that have a "significant localized impact on the Waters of the Great Lakes," to be completed by 2016 (Canada and the United States, 2012). Furthermore, the Agreement calls on the Parties to carry out program work under Annex 4 (including addressing municipal wastewater treatment plants, agricultural and other nonpoint sources of phosphorus, and other sources) to meet the Agreement's objectives "in cooperation and consultation with State and Provincial Governments, Tribal Governments, First Nations, Métis, Municipal Governments,

2012 Great Lakes Water Quality Agreement Nutrient-Related Lake Ecosystem Objectives (Annex 4)

1. Minimize the extent of hypoxic zones in the Waters of the Great Lakes associated with excessive phosphorus loading, with particular emphasis on Lake Erie
2. Maintain the levels of algal biomass below the level constituting a nuisance condition
3. Maintain algal species consistent with healthy aquatic ecosystems in the nearshore waters of the Great Lakes
4. Maintain cyanobacteria biomass at levels that do not produce concentrations of toxins that pose a threat to human or ecosystem health in the Waters of the Great Lakes
5. Maintain an oligotrophic state, relative algal biomass, and algal species consistent with healthy aquatic ecosystems, in the open waters of Lakes Superior, Michigan, Huron and Ontario
6. Maintain mesotrophic conditions in the open waters of the western and central basins of Lake Erie, and oligotrophic conditions in the eastern basin of Lake Erie

[1] See Appendix A for terminology on watersheds relevant to this report.

watershed management agencies, other local public agencies, and the Public...” (Canada and the United States, 2012).

The 2012 Agreement also calls for development of phosphorus reduction strategies and domestic action plans (DAPs) to meet substance objectives, loading targets and load allocations apportioned by country for Lake Erie within five years of entry into force (e.g., by 2018). Finally, the 2012 Agreement also references the importance of increasing scientific research on nutrients in the Great Lakes, including the distribution, movement, and effects of nutrients, technologies, and management actions, as well as monitoring and regular reporting, through a triennial Progress Report of the Parties (Canada and the United States, 2012).

In response to requirements in the 2012 Agreement, in 2016 the Parties adopted phosphorus reduction targets (using a 2008 baseline) for Lake Erie addressing both western basin HABs and central basin hypoxia, as follows:

- A 40 percent reduction in spring total phosphorus and soluble reactive phosphorus loads from the Maumee River, to maintain cyanobacteria biomass below levels resulting in toxins that otherwise pose threats to human or ecosystem health in the waters of the western basin of Lake Erie;
- A 40 percent reduction in spring total phosphorus and soluble reactive phosphorus from specific Canadian and US watersheds to maintain algal species consistent with healthy aquatic ecosystems in the nearshore waters of the western and central basins of Lake Erie; and
- A 40 percent reduction in total phosphorus entering the western and central basins of Lake Erie to minimize the extent of hypoxic zones in the waters of the central basin of Lake Erie (ECCC and USEPA, 2016).

This work was followed by the development and release in 2017-2018 of DAPs, including at the state (Indiana, Michigan, Ohio, and Pennsylvania), federal (United States) and joint federal-provincial (Canada-Ontario) levels, as discussed in more detail in **Section 2.4**.

While the Parties lead work related to most aspects of the Agreement, the International Joint Commission also has Agreement responsibilities, including analyzing and disseminating data and information from the Parties and others working in collaboration with the Parties relating to the quality of Great Lakes waters. This work includes examining data relevant to General Objectives, Lake Ecosystem Objectives, and Substance Objectives, and in relation to “the operation and effectiveness of the programs and other measures established pursuant to this Agreement” (Canada and the United States, 2012). The Commission is also responsible for assisting and advising on scientific matters involving the Great Lakes basin ecosystem, carrying out public consultation and engagement, and coordinating with other related institutions. A formal reporting responsibility of the Commission is the preparation of a Triennial Assessment of Progress Report, drawing on the Progress Report of the Parties, the State of the Great Lakes report, a summary of public input, and other information as appropriate (Canada and the United States, 2012).

Nutrients and eutrophication were the focus of a number of IJC assessments in the years following the signing of the 1972 Agreement (see text box below) and before increased attention to toxic chemicals in the 1987 Agreement (e.g., Canada and the United States, 1987; International Joint Commission, 1984, 1982). But increased manifestations of eutrophication in Lake Erie starting in the mid-1990s and continuing in the 2000s (Watson et al. 2016) led the IJC to undertake a series of studies related to the causes and impacts of nutrient loadings in the Great Lakes.

The first of these, the Lake Erie Ecosystem Priority project in 2012, which resulted in the report "A Balanced Diet for Lake Erie: Reducing Phosphorus Loadings and Harmful Algal Blooms," made recommendations addressing phosphorus load reductions, monitoring, and research for Lake Erie (International Joint Commission 2014). Seven additional studies on eutrophication and other impacts in Lake Erie and other lakes were produced in subsequent years. Collectively, nutrient-related reports of the Commission over the past decade have included over 100 recommendations to the Parties (LimnoTech 2022 and summarized in Table 1 in **Section 2.2**).

International Reference Group on Great Lakes Pollution from Land Use Activities

While the emphasis in this review and assessment is on nutrient-related activities over the past decade, it is worth noting attention to nonpoint sources of nutrients in the Great Lakes dates back at least five decades.

The original 1972 Agreement referenced a Commission study on nonpoint source pollution, which would lead to the formation of the International Reference Group on Great Lakes Pollution from Land Use Activities, known as PLUARG (Canada and the United States, 1972). The effort addressed multiple substances in the Great Lakes, including nutrients.

The final report noted that nonpoint source (or "diffuse") phosphorus loads were appreciable in the lower lakes, and that "intensive agricultural operations have been identified as the major diffuse source contributor of phosphorus" (International Joint Commission International Reference Group on Great Lakes Pollution from Land Use Activities 1978).

Furthermore, the report called for the development of management plans with site-specific approaches that include a timetable with program priorities, identification of agencies ultimately responsible for program implementation, coordination arrangements, identification of programs and sources of funding, estimates for loadings to be achieved, and provisions for public review.

The final report also included more detailed recommendations related to land use planning, fiscal arrangements, regulation, technical assistance (including on farm-scale planning), and other matters.

In the end, the effort resulted in 121 study plans, modeling and other reports (International Joint Commission International Reference Group on Great Lakes Pollution from Land Use Activities 1979).

Considering the extensive number of recommendations of the Commission over the past decade and the adoption of DAPs by the Parties in 2018 to address the ongoing eutrophication impacts in Lake Erie, the Commission's Great Lakes Science Advisory Board-Science Priority Committee in coordination with the Commission's Great Lakes Water Quality Board organized this project involving an assessment of progress to date on nutrients under the Agreement's Annex 4 (Nutrients). The two goals of the project were first to assess federal DAPs (as well as state and provincial plans) and their implementation to date, in light of recent IJC nutrient-related recommendations and other information from the literature concerning actions needed to address nutrient-related impacts in Lake Erie, and second, explore priority issues concerning nutrient-related impacts in Lake Ontario.

This work entailed a review of IJC recommendations, review of the recent literature, and an assessment of DAPs and programs in place to address nutrient-related problems in Lake Erie and Lake Ontario. The process included multiple components, including assembling and having regular meetings with a work group; working with a contractor (LimnoTech) that carried out a literature review, synthesis, and summary; review by the work group of multiple versions of the technical report, and broader review through a virtual workshop; additional assessment and review work by the report authors; and development of this work group report. Further details on the assessment and review process are provided in **Appendix A**.

Section 1.1 begins with a brief overview of nutrient-related problems in the Great Lakes as a whole. **Sections 2** and **3** provide our syntheses of findings for Lake Erie and Lake Ontario, respectively. Within each of these sections, we provide a summary of lake-specific nutrient problems, a summary of Commission recommendations, a review of recent literature, and an assessment of DAPs to address these problems and conclude with our assessment of the remaining barriers that are impeding further progress towards achieving the nutrient reduction goals of the Agreement. **Section 4** contains recommendations to the Parties for addressing these barriers. **Section 5** provides a summary of key findings, knowledge gaps, and recommendations, followed by References and Appendices.

1.1 Brief overview of nutrient-related problems in the Great Lakes

Nutrient-related pressures in the Great Lakes have been recognized for decades (e.g., Bails et al., 2005; Beeton, 2002, 1965). Prior to European settlement there were generally oligotrophic conditions in Lakes Superior, Michigan and Huron, generally more eutrophic conditions in Lake Erie, and intermediate conditions in Lake Ontario (Beeton, 2002, 1965). However, beginning in the early 20th Century the lower four Great Lakes experienced increased chemical loading (e.g., calcium, sulfate and chloride), and Lake Erie in particular experienced increased phosphorus loadings and "cultural" (e.g., human-driven) eutrophication (Beeton and Edmondson, 1972). By the 1970s, lake conditions had shifted to include oligotrophic (Lake Superior and offshore Lake Huron), mesotrophic (inshore Lake Huron, offshore Lake Michigan and Lake Ontario, and eastern basin of Lake Erie), eutrophic (inshore Lake Ontario and Lake Michigan, and Lake Erie central basin) and highly eutrophic (western Lake Erie basin, Saginaw Bay, Green Bay, and Bay of Quinte) (Evans 2005).

With phosphorus abatement programs through the initial Agreement (Canada and the United States, 1972) and under federal laws such as the US Clean Water Act (in particular addressing certain uses of phosphorus such as in detergents, and increased controls on point sources such as wastewater treatment plants), phosphorus loadings to the Great Lakes began to decrease, leading to decreased eutrophication and associated impacts in Lake Erie (Beeton 2002; Evans 2005; Sterner 2021).

However, over the past two decades progress has stopped or even been reversed, with elevated phosphorus loadings—in particular to the lower lakes—persisting, at a time of other major changes to the lakes (including the ongoing spread of invasive dreissenid mussels). In general, phosphorus yields (e.g., mass of phosphorus per area of land in a given watershed) are higher in the more developed, and agricultural southern portions of the watershed, and resulting water concentrations are also higher in the lower lakes, as shown below in **Figure 1**.

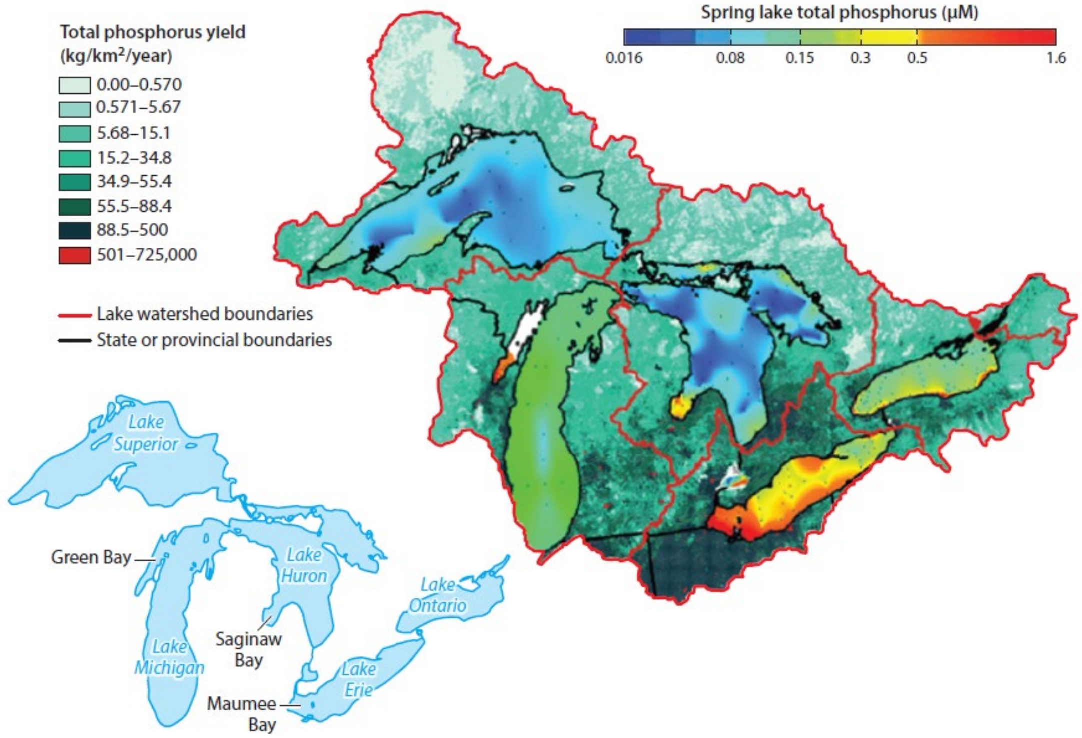


Figure 1. Total phosphorus yield and spring water total phosphorus concentrations in the Great Lakes basin (from Sterner 2021). Note that the main map overlays modeled watershed phosphorus yield estimates from the Spatially Referenced Regression On Watershed attributes model (Robertson et al. 2019) with springtime lake phosphorus concentrations for 2016 (Lake Superior) and 2017 (other lakes) (ECCC and USEPA, 2019) (Sterner, R., personal communication).

For Lake Erie, the continuing elevated phosphorus loadings are contributing to ongoing seasonal HABs (especially in the western basin) and central basin hypoxia conditions (e.g., International Joint Commission 2014; Mohamed et al. 2019; Scavia et al. 2014; Watson et al. 2016). Unlike prior blooms in Lake Erie in the 1970s that were dominated by *Anabaena* (syn. *Dolichospermum*) and *Aphanizomenon*, in recent decades, HABs in the western Lake Erie basin tended to be dominated by *Microcystis* species (Watson et al. 2016), with the potential to produce over 100 different toxic compounds (Carmichael and Boyer, 2016). HABs can pose threats to fish species, including through impacts on diet (e.g., on zooplankton populations), although effects can be complex (e.g., Briland et al. 2020). Recent research on wildlife has shown the potential for *Microcystis* toxins to negatively affect American bullfrog tadpoles (through liver and intestinal toxicity) (Su et al. 2020) as well as contribute to physiological stress and decreased immune function in certain songbirds and reptile species (Refsnider et al. 2021).

Hypoxia has been an issue in the central basin of Lake Erie for decades, commonly attributed largely to excessive phosphorus loadings, although the physical characteristics of the lake (in particular the relatively thin hypolimnion, or bottom layer when the lake is stratified in warmer months) and other factors (such as other nutrient loadings from Lake Huron) may contribute to the phenomenon (Reavie et al. 2016; Tellier et al. 2022). Low-oxygen conditions can lead to negative impacts on fish habitat quality, although the potential for population-level impacts is not clear (Almeida et al. 2022; Stone et al. 2020; Watson et al. 2016). Eutrophication is also associated with growth of nuisance algae such as *Cladophora*, which can lead to beach fouling (affecting recreation activities and potentially human health (Chun et al. 2017)) as well as potential impacts to fish and wildlife (Princé et al. 2018).

HABs (such as cyanobacterial blooms) may also cause human health impacts, in particular chronic impacts following drinking water or recreational exposure to HAB toxins (Carmichael and Boyer, 2016). As noted above, elevated toxin levels in the drinking water system in the Toledo, Ohio area in August 2014 led to a three-day drinking water advisory affecting nearly 500,000 people (Carmichael and Boyer, 2016). There have been few assessments of economic impacts from Great Lakes HABs, though a study for the Commission estimated impacts of the 2014 Toledo water crisis at US$65 million (CDN$87 million) (Bingham et al. 2015), and a more recent Canadian study estimated economic impacts of Lake Erie HABs in general (including via decreased tourism) at CDN$272 million (US$203 million) annually (Smith et al. 2019).

Programs to address nutrient loads in Lake Erie have been underway for decades. Given significant progress of regulatory programs addressing point sources such as wastewater treatment plants starting in the 1970s , the relative importance of nonpoint sources (in particular agricultural activities) of phosphorus has been increasing in recent decades (Baker et al. 2019; Maccoux et al. 2016). This recognition has led to significant management, research and monitoring activities focused on both implementing agricultural programs and specific practices and better understanding various factors affecting phosphorus export from agricultural watersheds (e.g., Kalcic et al. 2016; International Joint Commission 2018; Smith et al. 2018).

Among the findings from research and monitoring has been recognition of the importance of addressing more bioavailable forms of phosphorus, whether dissolved reactive phosphorus[2] or the bioavailable fraction associated with particles (Baker et al. 2019). Finally, there is increasing appreciation of the importance of considering other factors that can affect in-lake impacts of

[2] For purposes here, we assume “dissolved reactive phosphorus” is synonymous with “soluble reactive phosphorus” and use the term used in the original publication cited.

excessive nutrients, including the role of *legacy* phosphorus (e.g., a portion of previous phosphorus inputs to a watershed accumulating at various locations along transport pathways), climate change and alterations in temperature and precipitation patterns, and any potential complicating role of nitrogen in HAB formation and toxicity (e.g., International Joint Commission 2018; Michalak et al. 2013; Mohamed et al. 2019; also see further discussion in **Section 2.3**). Based on findings from this project and other research/assessment work over the past decade, there is a clear need for strengthened policy management, research, stewardship initiatives and monitoring efforts, in particular addressing agricultural nutrient sources, to address the eutrophication problems in Lake Erie.

For Lake Ontario, there are different nutrient-related impairments. As with Lakes Michigan and Huron, it is believed a key mechanism affecting phosphorus is the nearshore phosphorus shunt. Through this process, much of the phosphorus entering the lakes is maintained in nearshore areas, in particular benthic (or bottom) zones, likely through the actions of invasive zebra and quagga mussels and other organisms (Hecky et al. 2004). This phenomenon leads to eutrophication of some nearshore areas and oligotrophication of offshore waters through reduced offshore transport. General outcomes of this process in Lake Ontario have included increased abundances of nuisance algae (in particular *Cladophora*) in nearshore waters, and declining overall productivity—including of fisheries—in offshore waters (International Joint Commission Great Lakes Science Advisory Board 2020a). This situation poses a challenge to managers. Efforts to further reduce nutrient inputs to Lake Ontario to meet nuisance algae reduction objectives risk exacerbating problems with offshore fisheries productivity (discussed further in **Section 3.1**). This challenge involving distinct nearshore and offshore problems will need to be considered in Agreement Annex 4 efforts to establish targets and any new nutrient programs for Lake Ontario (International Joint Commission Great Lakes Science Advisory Board 2020a).

2.0 Synthesis of Findings for Lake Erie

We begin with an overview of the state of nutrients and their impacts in Lake Erie. This is followed in **Section 2.2** by a summary and synthesis of the more than 100 recommendations that have been made in IJC reports over the past decade regarding nutrient-related issues in Lake Erie. A brief review of recent and relevant scientific literature follows in **Section 2.3**, and **Section 2.4** contains a summary of the domestic action plans of the two federal governments and the state and provincial governments as well as an overview of existing government programs in place concerning policy, monitoring and research. In **Section 2.5**, we assess the extent to which Commission recommendations have been integrated or are reflected in the domestic action plans. Finally, **Section 2.6** outlines our assessment of the remaining barriers that are impeding progress towards achieving the nutrient-related objectives of the Agreement.

2.1 Overview of the state of nutrients and impacts in Lake Erie

Comprehensive reporting on the state of the Great Lakes now occurs through the triennial State of the Great Lakes reports, with the most recent report released in summer 2022. Reports include assessments of status (*good*, *fair* or *poor*) as well as trends (*improving*, *unchanging* or *deteriorating*) for nine overarching indicators, which in turn are built on 40 sub-indicators (ECCC and USEPA, 2022a). Trends for most indicators are assessed over approximately a 10-year period (e.g., 2010-2020). One of the overarching indicators is nutrients and algae, comprised of three sub-indicators.

For Lake Erie, the Parties' 2022 summary report indicates the lake was alone among all five Great Lakes with all three nutrients and algae sub-indicators given a *poor* rating, and sub-indicator trends as *unchanging* (nutrients in lakes and *Cladophora*) and i*mproving* (harmful algal blooms: nearshore and embayments) (ECCC and USEPA, 2022a). For the nutrients in lakes sub-indicator, the Parties' technical report notes elevated nutrient concentrations have tended to be persistent in Lake Erie for decades, with significant variability often seen in a given year, but with median concentrations in the western basin consistently above the GLWQA interim total phosphorus objective of 15 µg/L (ECCC and USEPA, 2022b). For the *Cladophora* sub-indicator, the alga remains an issue in particular along the northern shore of the eastern basin of Lake Erie as well as some offshore shoals. *Cladophora* biomass varies year-to-year but has tended to be present at nuisance levels at most sites sampled. Challenges in assessing trends include the lack of a long-term monitoring framework and program, and significant interannual variability, though more systematic monitoring has been underway for *Cladophora* in Lake Erie since 2018 (ECCC and USEPA, 2022b).

The western Lake Erie basin experiences HABs regularly each year, in particular along the southern shore of the western basin, and occasionally extending into the central basin. While HABs areas can be quite variable year-to-year, satellite data cited in the State of the Great Lakes 2022 report indicates the percentage of nearshore areas (less than 16 meters in depth) in the western basin experiencing HABs declined from 2012 to 2020 (ECCC and USEPA, 2022b). At the same time, it should be noted this measure may not fully indicate the significance of a given bloom event or period. For example, the 2014 bloom that led to a three-day drinking water advisory affecting nearly 500,000 people in the Toledo, Ohio area was in a year that ranked lower than most others in bloom occurrence during the assessed period. Other factors, including wind conditions and water circulation in relation to drinking water intakes are also important determinants of the human impacts of a bloom.

Another indicator of Lake Erie HABs is the HAB severity index developed by the National Oceanic and Atmospheric Administration (NOAA). The severity index accounts for both bloom spatial extent and biomass over the peak 30 days of a given bloom and is determined based on satellite imagery (Stumpf et al. 2022). The index for the past two decades is shown in Figure 2 below, which indicates final calculated indices through 2022. Importantly, the data show generally higher severity indices since 2010 (compared to the previous decade), implying little if any progress in reducing HAB severity has been made in Lake Erie since 2008. Indeed the total of spring loading data for four major western Lake Erie basin tributaries (Maumee, Portage, River Raisin, and Thames rivers) vary year-to-year, but do not show any systematic declines for either total or dissolved reactive phosphorus for 2008-2020.[1]

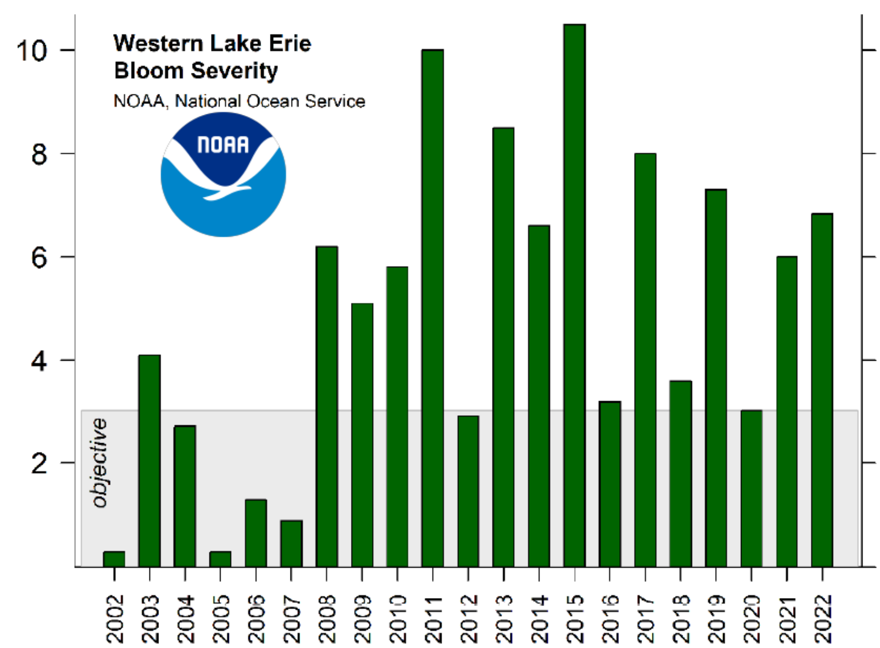


Figure 2. Western basin of Lake Erie HAB severity index 2002-2022 (Stumpf et al. 2022).

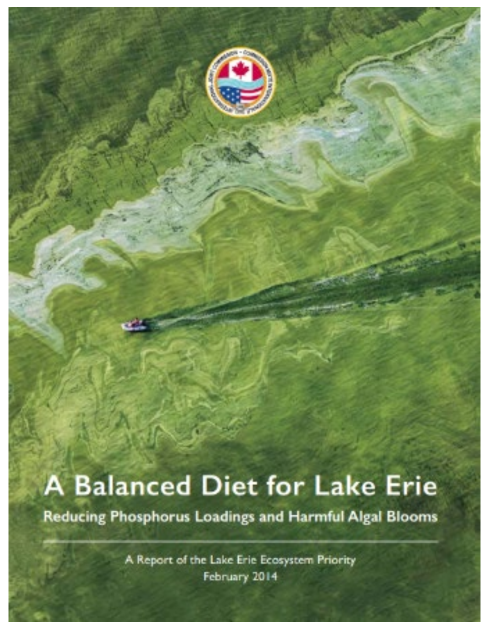
In addition to addressing HABs and nuisance algae, under Agreement Annex 4 one of the Lake Ecosystem Objectives is to minimize the extent of hypoxic zones. In the case of reducing hypoxia in the central basin of Lake Erie, a 40 percent loading reduction target for phosphorus entering the western and central basins of Lake Erie was recommended to and adopted by the Parties in 2016 (Great Lakes Water Quality Agreement Nutrients Annex Subcommittee 2019).

[1] Data accessed through ErieStat, blueaccounting.org/issue/eriestat/

However, although hypoxia is referenced on several occasions in the State of the Great Lakes 2022 technical report, it is in the context of other indicators (e.g., phytoplankton and dreissenid mussels), and there is no separate hypoxia sub-indicator under the overarching nutrients and algae indicator (ECCC and USEPA, 2022b). At the same time, USEPA carries out annual monitoring at 10 sites in the central basin through the Lake Erie Dissolved Oxygen Monitoring Program. The most recent report of the program did not formally assess hypoxia trends over the period of record but noted spatial and temporal (within season) variation in low oxygen conditions and noted the annual oxygen depletion rate for 2016 was similar to the long term 1970-2016 average (USEPA 2021a).

2.2 Summary and synthesis of Commission recommendations for Lake Erie

Commission reports over the past decade addressing nutrients in the Great Lakes—emphasizing Great Lakes advisory board work group projects—are summarized in **Table 1** (on the next page). These include reports on results of the Lake Erie Ecosystem Priority project noted previously, the economics of HAB reductions, health impacts of cyanotoxins, watershed management, fertilizer application, nutrient modeling, manure management and declining offshore productivity (citations in footnotes of Table 1). Most of the reports have addressed eutrophication issues (largely Lake Erie), while the most recent of the reports addressed the opposite issue of declining offshore productivity in Lakes Michigan, Huron, Ontario and the eastern basin of Lake Erie (International Joint Commission Science Advisory Board 2020a).



International Joint Commission 2014 Lake Erie Ecosystem Priority report.

Table 1. Commission reports: report emphasis, key recommendations, and extent to which recommendations have been addressed in Domestic Action Plans to date.

Commission Report Title/ Subject (Year)[2]	Recommendations[3]		Key Recommendations[4]	Addressed in DAPs[5]
	Total #	Action #		
A Balanced Diet for Lake Erie (2014)[6]	41	20	• Adopt target phosphorus loads (spring, annual; and total, dissolved reactive phosphorus) for Lake Erie • Develop domestic action plans. • List U.S. waters of western basin as impaired under Clean Water Act, implement total maximum daily loads. • Consider suite of actions to address nutrient runoff.	Much
Economics of HAB Reduction (2015)[7]	12	0	• Develop and implement models and survey tools to link HAB occurrence to economic impacts on property values, tourism, recreational demand, drinking water treatment and use, agriculture, and industry.	Little
Health and Cyanotoxins (2017)[8]	6	0	• Improve drinking water monitoring, treatment for cyanotoxin removal. • Increase standardization of treatment approaches, improve testing. • Enhance monitoring and reporting for beaches. • Develop numerical health limits for a suite of cyanotoxins.	Some
Watershed Management (2016, 2017)[9]	8	6	• Develop nutrient management plans for Lake Erie watershed. • Improve governance, incentivize implementation. • Standardize metrics for reporting progress, improve communications.	Some
Fertilizer Application (2018, 2019)[10]	14	4	• Improve quantitative understanding and tracking of phosphorus application and cycling, tile drainage, best management practice adoption and effectiveness, changes in eutrophication phenomena, and climate change.	Some
Nutrient Modeling Approaches (2019)[11]	33	5	• Maintain and improve ensemble modeling approaches, couple lake and watershed models, enhance monitoring and ground-truthing, improve model accuracy and predictive skill, coordination and governance, and implement adaptive management.	Much
Manure Management (2020)[12]	12	12	• Increase tracking, regulation of animal feeding operations, manure application. • Promote development of collaborative management efforts.	Little
Declining Offshore Productivity (2020)[13]	6	2	• Improve connections between fisheries management and nutrient-related monitoring, modeling, and forecasting, including through multiple agencies/commissions.	Little

[2] Adapted from LimnoTech 2022, Table 1 and Appendix A.
[3] Based on LimnoTech 2022, Appendix A. The work group subsequently grouped recommendations into action, science or institutional science categories, for purposes of identifying general emphasis.
[4] Focus of recommendations in Commission reports in contractor assessment of extent of reference in domestic action plans, from LimnoTech 2022.
[5] From LimnoTech 2022.
[6] International Joint Commission 2014.
[7] Bingham et al. 2015.
[8] International Joint Commission Health Professionals Advisory Board 2017.
[9] International Joint Commission Great Lakes Water Quality Board 2017, 2016.
[10] International Joint Commission 2018; LimnoTech 2019.
[11] International Joint Commission Great Lakes Science Advisory Board 2019.
[12] International Joint Commission Great Lakes Water Quality Board 2020, 2019.
[13] International Joint Commission Great Lakes Science Advisory Board 2020.

As noted in **Table 1**, the reports have included over 100 discrete recommendations. There are two important issues concerning Commission recommendations and potential adoption by the Parties in the DAPs. First, half of the Commission reports were released either after initial DAPs were prepared or as they were being developed, and hence opportunities for addressing recommendations in those cases would arise in subsequent DAP reports (or ancillary documents). Second, in our general assessment, by grouping recommendations in either *action*, *science* or *institutional science* categories (**Appendix A**), the breakdown for a given report varies significantly. The Lake Erie Ecosystem Priority report (also the earliest of the set) and other reports led by the Commission's Great Lakes Water Quality Board have a larger fraction of action recommendations, while, not surprisingly, reports of the Commission's Great Lakes Science Advisory Board have a larger fraction of science or institutional science recommendations.

Key recommendations from the reports utilized in the contractor assessment of the extent of reference or adoption in DAPs are identified in the fourth column of the table (and in some cases with grouping of multiple recommendations together). The recommendations cut across a wide range of issues related to nutrients in the Great Lakes, but with an emphasis on managing and better understanding (including impacts of) excessive nutrient loads, in particular to Lake Erie, and a secondary emphasis on issues involving offshore oligotrophication.

In addition to work group reports summarized in Table 1, multiple Commission biennial and triennial reports have addressed nutrients, with multiple recommendations to the Parties. Examples of recommendations include the following:

- In anticipation of the revised Agreement in 2012, the Commission recommended the Parties issue a reference for the Commission to undertake a binational scientific investigation into causes of resurgent eutrophication symptoms in the Great Lakes, including to tests hypotheses linking land management changes to ecosystem changes, and also implementation of no regrets actions (e.g., actions that would be justified under all plausible scenarios) to retain nutrients and sediments on the land (International Joint Commission 2011).
- In the first report following signing of the 2012 revision to the Agreement, the Commission recommended further actions by the Parties addressing agricultural nutrient sources, including supporting farmers in applying fertilizer and manure only when needed (based on available nutrient levels in the soil), development of additional technologies to address manure application issues (e.g., digestors), and develop, maintain, and share an inventory of effective land management actions. Furthermore, the Commission recommended the states of Ohio, Michigan and Wisconsin work with the USEPA in developing phosphorus total maximum daily loads (TMDLs) for the western Lake Erie basin, Saginaw Bay and Green Bay, respectively (International Joint Commission 2013).
- In its first Triennial Assessment of Progress Report, the Commission recommended that DAPs include timelines, identification of responsible entities, deliverables, outcomes and performance metrics in order to ensure accountability, and also recommended the Parties act on recommendations in the Lake Erie Ecosystem Priority report (International Joint Commission 2014) concerning developing enforceable standards on the application of

fertilizer and animal waste, among other recommendations (International Joint Commission 2017).

Based on the original scope of work for this project, assessment of the Parties' progress addressing nutrients had a particular focus on recommendations in the Commission's advisory board work group reports indicated in Table 1, although we have kept in mind issues addressed in the Commission assessment reports. Work group report recommendations and extent of incorporation in DAPs are discussed in more detail in **Section 2.4**.

2.3 Literature review

Significant research continues to be carried out on nutrients and Lake Erie, including research regarding loadings from the watershed (including due to commercial fertilizer and manure) and factors on the land influencing them, legacy phosphorus, nitrogen and nutrient ratios, invasive species, climate change, modeling, and approaches to policy design to address nutrient loadings, particularly from nonpoint sources. Much of the discussion involves information or processes in watersheds, which can be of interest at varying scales (as briefly reviewed in **Appendix B**). As we note in this report, it is particularly helpful to have information available at finer scales, and where we reference *subwatershed* in this report, it is analogous to a 12-digit hydrologic unit (HU) level in the US Watershed Boundary Dataset (Jones et al. 2022), consistent with the approach used in the Ohio Domestic Action Plan (Ohio Lake Erie Commission 2020).

This section briefly highlights key literature in the past decade on these issues, drawing in particular on the technical report for this project (LimnoTech 2022), while also summarizing additional recent studies of note, with more emphasis on the policy and economics literature.

2.3.1 Relative contributions of commercial fertilizer and manure

In support of a recent Commission project, LimnoTech synthesized agricultural census data for both countries, and determined that for the most recent data then available (2011-2012 census years), manure generated phosphorus was approximately 21 percent of total phosphorus applied in the United States portion of the western Lake Erie basin, 33 percent for the Canadian portion, and 25 percent overall (International Joint Commission 2018; LimnoTech, 2019, 2017). Concerning commercial fertilizer application, the assessment showed generally declining application rates (pounds of phosphorus per acre) in the Michigan portion of the western Lake Erie basin, with no clear trends for the Indiana and Ohio portions, through 2012 (International Joint Commission 2018; LimnoTech 2017). In contrast, data for Ontario showed generally upward trends in commercial fertilizer application rates through 2011 (LimnoTech 2019).

A more recent modeling study assessing contributions of loads to Lake Erie and focused on the Maumee River watershed found manure phosphorus contributed smaller fractions of loads to Lake Erie compared to commercial fertilizer, for both total phosphorus (8 versus 45 percent) and dissolved reactive phosphorus (12 versus 58 percent) over the March-July period, with legacy soil phosphorus accounting for 40 percent of total phosphorus loads (Kast et al. 2021).

The most comprehensive data relevant to questions on phosphorus additions to the land from commercial fertilizer and manure in the western Lake Erie basin are from the two federal agricultural censuses, carried out every five years. Data on livestock operations and animal numbers for the United States portion of the western Lake Erie basin watershed for the three most recent censuses are provided in **Table 2** below.

Table 2. Livestock operations and numbers in the United States' western Lake Erie basin, 2007-2017.

Livestock[14]	Year					
	2007		2012		2017	
	# Operations	Inventory	# Operations	Inventory	# Operations	Inventory
Cattle	4,649	293,729	4,470	327,895	4,226	348,067
Hogs	1,244	845,309	1,014	927,083	1,039	1,312,171
Chickens	1,376	8,354,381	1,864	10,743,331	1,886	13,284,366

As shown in **Table 2**, there was a clear increase in livestock numbers in the United States portion of the western Lake Erie basin for the 2007-2017 period, amounting to over 55 percent increases for both hogs and chickens. Other data from the census showed the acres treated with manure over the period increased by 36 percent, while the acres treated by commercial fertilizer (which encompassed lime and soil conditioners) decreased by 5 percent over the same period, although the manure-treated acres in 2017 still represented less than 10 percent of acres treated with commercial fertilizer (US Department of Agriculture n.d.).

One recent approach to independently assess numbers and trends in livestock operations in the watershed entailed use of satellite data, and based on findings from the effort, the authors argued for a potentially larger role of livestock manure in contributing to Lake Erie phosphorus loads (Environmental Working Group 2019).

Regarding commercial fertilizer use, in addition to federal agricultural census data on the US side, the US Department of Agriculture (USDA) also carries out periodic surveys that include estimates of nitrogen, phosphorus, and potash fertilizer use. In accessing survey data for the two major crops in the western Lake Erie basin (corn and soybeans) and for the three western Lake Erie basin states, total statewide phosphate application amounts for corn were either down slightly or with no systematic change comparing the 2010s to the 1990s, while for soybeans, phosphate application amounts were generally higher in the past decade, in particular for Indiana and Ohio (USDA, n.d.). A recent study of the Ohio Department of Agriculture showed commercial phosphorus fertilizer sales in the Maumee River watershed declining on average from 2007-2020, although county-wide data for the western Lake Erie basin counties did not

[14] From the US Department of Agriculture, n.d., Queries in QuickStats, for the western Lake Erie Basin watershed. Note there are also other livestock (e.g., turkeys) in the western Lake Erie basin.

show declines from 2007-2017 (see Ohio Environmental Protection Agency 2022, including Appendix 3, Table A3.6).

These recent efforts highlight two important and related issues that limit understanding of the relative importance of the two broad nutrient sources in the western Lake Erie basin. First, as discussed in **Section 3**, the individual regulatory frameworks for animal feeding operations are typically based on size thresholds, with smaller operations tending to have minimal if any regulatory requirements, for example (see International Joint Commission Great Lakes Water Quality Board 2019). On the other hand, larger facilities (e.g., over 1,000 head of cattle) are classified as large, concentrated animal feeding operations with more stringent requirements. As with any sized facility in the United States, they would need a National Pollutant Discharge Elimination System permit under the US Clean Water Act if they have the potential to discharge to a surface water body.

However, it can be challenging to assess the fraction of operations and livestock in a given jurisdiction covered by any regulations, whether under the US Clean Water Act or state rules. In one assessment based on the 2012 US Agricultural Census and state permit information for the Ohio portion of the Maumee River watershed, Kast et al. (2019) estimated the percentages of cattle, hog and poultry populations housed in concentrated animal feeding operations at 25, 22, and 94 percent of the total populations in the watershed. A more recent assessment by Environmental Working Group again using satellite data and other information estimated 63 percent of manure phosphorus in the United States portion of the western Lake Erie basin came from facilities without permits (making up 90 percent of total facilities in the basin) (Environmental Working Group 2022). Hence, a large fraction of the livestock in the western Lake Erie basin are at smaller facilities that have less regulatory requirements and do not report manure production and application to regulatory agencies.

A second related issue involves the comprehensiveness of information available on both manure generation and disposition as well as commercial fertilizer application. On the former, given privacy laws relating to the censuses, information for individual operations is withheld in certain situations (e.g., cases of a small number of operations in a given county where individual operation data could be more easily inferred). For example, for the 2017 Agricultural Census, data were withheld at the county level for laying chickens in eight of the seventeen counties in northwest Ohio (USDA n.d.). Furthermore, in many cases manure generated at a given operation is processed through a distribution and utilization system (Kast et al. 2019), whereby a farmer uses a manure broker or another party for distribution or application. Although additional requirements apply to both, the process can complicate tracking the movement of manure after generation. In the case of commercial fertilizer, fertilizer sales are often used as a proxy for application, given more limited information available on the latter.

In spite of data limitations, available census data do indicate that even though lesser, the relative importance of manure phosphorus relative to commercial fertilizer phosphorus has been increasing in the United States portion of the western Lake Erie basin in the past several census periods. Furthermore, given the common practice of land application of manure at locations relatively close to livestock operations (Environmental Working Group 2022; Kast et al. 2019; Long et al. 2018), there is increased risk of excessive phosphorus application (with the potential for increased runoff), even if on a relatively small fraction of total agricultural lands in the watershed.

One additional important issue in the context of major nutrient inputs to watersheds is that manure is considered a waste product, a potential source of energy, and can potentially serve as a nutrient source instead of commercial fertilizer that would be otherwise used on crops (MacDonald et al. 2009).

2.3.2 Field characteristics, conservation practices and phosphorus export

Research over the past decade has confirmed the importance of multiple factors in the field affecting nutrient export, including factors related to the crop types, tillage practices, drainage systems and conservation practices or best management practices (BMPs) generally (LimnoTech 2022). The western Lake Erie basin is dominated by agricultural land use, and to support drainage of water off the fields, most of the cropland has drainage tiles installed (Kalcic et al., 2016; USDA 2016), with still significant but generally lower use in the Ontario portion of the basin (Macrae et al. 2021). Recent research has shown that tile drains can transport large fractions (even the majority) of phosphorus leaving fields (Kalcic et al. 2018; King et al. 2018). Research using the Soil and Water Assessment Tool watershed model indicates that certain best management practices (e.g., subsurface fertilizer placement and fertilizer rate reduction) are particularly important in reducing phosphorus export (e.g., Martin et al. 2021). Other practices such as use of cover crops offer the potential to reduce phosphorus export, though questions remain about certain scenarios (e.g., related to freeze-thaw cycles) (Cober et al. 2019). Edge-of-field studies are particularly helpful in identifying potential impacts of various agricultural practices, including nutrient management (e.g., King et al. 2018).

Concerning farmer implementation of conservation practices, recent research is shedding light on factors that can increase such practice adoption. In studies in the western Lake Erie basin, farmers wanted evidence that conservation practices they might implement would be feasible and would be effective at reducing phosphorus loading to waterways (LimnoTech 2022; Wilson et al. 2018; Wilson et al. 2019).

2.3.3 Legacy phosphorus

The issue of legacy phosphorus, or, as noted previously, a portion of previous phosphorus inputs to a watershed accumulating at various locations along transport pathways, has been an active area of research for over a decade (Bruulsema et al. 2019; International Joint Commission 2018; LimnoTech 2022; Muenich et al. 2016; Sharpley et al. 2013). Recent studies have highlighted the complexity inherent in the issue of legacy phosphorus in the western Lake Erie basin. Guo et al. (2021) suggested 2019 loads were lower than would have been predicted for a wet year, due in part to less fertilizer applied on fallow fields (and hence a relatively low legacy phosphorus signal).

In a study of 15 sites in the western Lake Erie basin that included consideration of above-average spring precipitation in 2019 compared to 2017 (a similar year hydrologically), results were more ambiguous, with lower flow-weighted mean phosphorus and dissolved reactive phosphorus concentrations in the Maumee River, but both lower and higher values (including for suspended sediment particles) spread among 15 sites in the western Lake Erie basin. The implication of these findings is that upstream legacy phosphorus can be an important source in some watersheds with above-average fallow periods (Williamson et al. 2021). Similarly, a recent study involving use of an empirical model on edge-of-field data for eight fields in northwest Ohio found that legacy phosphorus was the dominant source of dissolved reactive phosphorus for tile drains, although the authors noted there was significant variability in new phosphorus losses, and a need to consider additional management regimes, including manure management (Osterholz et al. 2023).

A study of the Grand River watershed in Ontario using a process-based model found the watershed has been a net sink for phosphorus considering fertilizer application back to 1900, with the potential for legacy phosphorus losses continuing for decades (Van Meter et al. 2021). These and other studies on legacy phosphorus in the western Lake Erie basin further highlight the importance of considering the potential for “drawdown” of such phosphorus as part of more sustainable agricultural operations (LimnoTech 2022; Zimnicki et al. 2020).

2.3.4 Nitrogen and nutrient ratios

Most of the focus on nutrient reduction programs in Lake Erie (and the Great Lakes more broadly) has focused on phosphorus, given it is commonly the limiting nutrient in freshwater ecosystems (Wetzel 2001), and all five Great Lakes are considered to be phosphorus limited currently (ECCC and USEPA, 2022b). However, it has been known for some time that consideration of other nutrients, in particular nitrogen (and nitrogen/phosphorus ratios), can play a role in eutrophication processes, including the development of HABs and toxins (e.g., Chaffin et al. 2014; Sterner 2021). Recent research has indicated the importance of considering nitrogen availability in development of certain HABs (in particular non-nitrogen fixing organisms) and production of toxins (e.g., Chaffin et al. 2018; Hellweger et al. 2022; Newell et al. 2019; LimnoTech 2022).

Even though more research is need, the potential for nitrogen in some cases to play a role in HABs formation and toxicity argues for the value in considering both phosphorus and nitrogen in nutrient management programs, in particular actions that can reduce both nutrients simultaneously. Note that the emphasis in this report is on nutrients and Lakes Erie and Ontario, and other environmental risks potentially deriving from agricultural practices in the western Lake Erie basin (e.g., associated with pesticides, pathogens, and antibiotics) are beyond the scope of this report.

2.3.5 Invasive species

One group of invasive species of particular relevance to nutrients in the Great Lakes are dreissenids (zebra and quagga mussels), which over the past few decades have become (in particular quagga mussels) the dominant organism group living in sediments in most offshore waters of all the Great Lakes except Lake Superior (Burlakova et al. 2018). As noted previously, these mussels have likely contributed to the “nearshore shunt” phenomenon, with mussel filtering activity leading to phosphorus being retained in nearshore areas (Hecky et al. 2004). Some evidence suggests mussels can facilitate cyanobacteria blooms through selectively feeding on green algae (Vanderploeg et al. 2001), though other work suggests the phenomenon is not a significant driver of blooms, particularly in the western Lake Erie basin (LimnoTech 2022; Verhamme et al. 2016). Other research has shown invasive mussels can have indirect impacts on hypoxia in the central basin of Lake Erie, through reducing plankton productivity in Lake Huron, allowing for increased silica transport to the central basin, and hence promoting spring diatom blooms and oxygen depletion associated with their decomposition (Reavie et al. 2016).

2.3.6 Climate change

The implications of climate change for nutrient-related impacts in Lake Erie (and the other Great Lakes) has received extensive attention over the past decade, with potential impacts both in watersheds and in the lake itself. Recent research has noted an increase in spring rainfall, runoff, and nutrient loading in the western Lake Erie basin in recent decades (Williams and King, 2020). As noted in Scavia et al. (2021), modeling studies over the past decade have found the potential for both increases and decreases in phosphorus loads in future decades with climate change, with differences potentially due to factors such as time scales considered in the regional analyses, models used (and whether bias correction of outputs was done), and the linking approaches. In this same work coupling climate, Soil and Water Assessment Tool, and Lake Erie HAB models, projections showed decreases in mid-century loads and HAB extent, consistent with some other recent studies. While models show for example that precipitation intensity and overall precipitation may increase, decreased snowfall and increased evapotranspiration may present countervailing effects on hydrology (Scavia et al. 2021).

2.3.7 Modeling

Modeling is briefly described here, although models are also used in work addressing most of the process issues described in this section. The LimnoTech assessment noted significant work in watershed modeling over the past decade in the western Lake Erie basin (LimnoTech 2022). One commonly used watershed model for assessing nutrient export from watersheds is the Soil and Water Assessment Tool noted previously. The model has multiple applications, including in "what if" scenarios, for example assessing the implications of adoption of specific BMPs on phosphorus export from a watershed. Several such modeling efforts have shown that implementation of several BMPs across significant portions of the western Lake Erie basin watershed (and/or targeted to areas with high export potential) would be needed to meet load reduction targets (e.g., Scavia et al. 2016; Scavia et al. 2017).

While the Soil and Water Assessment Tool model has been used extensively in the western Lake Erie basin and elsewhere, it is important to recognize the limitations and identify opportunities for ongoing improvement in model performance. Some challenges with modeling were identified in the Great Lakes SAB RCC modeling report (Arhonditsis et al., 2019a, 2019b; International Joint Commission Great Lakes Science Advisory Board 2019). Furthermore, in a recent review of 28 Soil and Water Assessment Tool modeling studies in the western Lake Erie basin, the authors found mostly "unsatisfactory" model performance for phosphorus loads, in particular for dissolved reactive phosphorus, potentially due to problems in the model formulation as well as setup of parameters (e.g., use of unrealistic values for a particular area). The authors argue further work is needed, including better understanding watershed conditions, hydrologic processes, and having more real-world observations on which to draw in model use (Yuan and Koropeckyj-Cox, 2022.)

One other watershed model that has been used extensively to assess nutrient loads in the Great Lakes Basin is the Spatially Referenced Regression On Watershed attributes model, developed by the US Geological Survey (Robertson et al. 2019). While the Soil and Water Assessment Tool is more process-based, the Spatially Referenced Regression On Watershed attributes model uses a mass-balance/statistical approach. The model has been used to determine total phosphorus and nitrogen loads and yields from all Great Lakes watersheds in the Basin (Robertson et al. 2019) and has been part of a model intercomparison study for the Maumee River watershed (Scavia et al. 2016). One limitation of the model is that it does not incorporate dissolved reactive phosphorus, while among other advantages it has been used in binational watersheds, drawing on recent Canada-US data and hydrographic harmonization work of the Commission's International Watersheds Initiative (International Joint Commission 2020). In addition, other watershed models have been used in the western Lake Erie basin, particularly in the Ontario portion of the basin (e.g., LimnoTech 2017).

There has also been extensive work on lake modeling of nutrients and impacts over the past decade. Verhamme et al. (2016) described the Western Lake Erie Ecosystem Model, a three-dimensional, fine-scale process-based model that can ultimately link phosphorus loads to cyanobacteria biomass. Other models of HAB formation have been developed (e.g., Obenour et al. 2014; Stumpf et al. 2016), as reviewed in Scavia et al. (2021). Multiple efforts have been carried out to model central basin hypoxia (e.g., Rowe et al. 2019; Scavia et al. 2014), including drawing on work of NOAA and the University of Michigan Cooperative Institute for Great Lakes Research, and other mechanistic lake models have also been developed for both the central and eastern basins of Lake Erie (LimnoTech 2022). Other modeling efforts have been carried out, as noted in the recent Progress Report of the Parties (ECCC and USEPA, 2022c).

2.3.8 Pollution control instruments

An extensive literature on the relative merits of alternative policy instruments for regulating pollution releases has also developed in recent years. We provide here a brief overview of that part of the literature that is focused on nonpoint sources of pollution such as agricultural nutrient exports. Note we generally reference pollution *control* here, though approaches that are also more prevention-focused (e.g., a nutrient management measure such as reducing the rate of application of fertilizer or manure) would also be covered in this discussion.

The economics literature on pollution control argues that economic instruments are preferable to command-and-control regulations or voluntary measures on cost-efficiency grounds; putting a price on pollution encourages those polluters with low pollution control costs to reduce the most and those with high pollution control costs to reduce the least. Consequently, an overall pollution reduction objective can be achieved at the lowest possible overall cost. Emissions fees, such as carbon prices, or trading programs such as the US Acid Rain Program are examples of economic instruments for pollution control. However, traditional economic instruments such as these are not well suited to dealing with nonpoint source nutrient pollution, such as from agricultural production, because farm-specific nutrient losses are not easily observable and verifiable with a sufficient degree of accuracy to form the basis for an economic penalty or benefit to be applied (Xepapadeus 2011).

Nevertheless, the Fox River (Wisconsin) phosphorus trading program is an example of an attempt to circumvent the problems presented by nonpoint source pollution. In this program, a point source can, in principle, purchase phosphorus reduction credits from a nonpoint source, such as a farmer, who undertakes actions designed to reduce phosphorus runoff such as planting cover crops, conservation tillage, or creating buffer strips (Great Lakes Commission 2016). The phosphorus reduction at the nonpoint source permits the point source to avoid reducing its own phosphorus loadings (by the amount of the credit purchased). The point of the offset trading program is to allow phosphorus reductions to occur where they are most cost effective, but the underlying assumption is that offset trading does not increase phosphorus loadings. This is a significant assumption because of the uncertainty associated with measuring and verifying the effect of an individual farmer's actions on phosphorus loadings, a problem that is exacerbated by the field-scale variability that can occur in phosphorus reduction for a particular BMP.

There are two alternative economic instruments have been proposed in the literature that rely less on the need for a central authority to observe and verify phosphorus reductions at the farm level. The first is an input-based pricing scheme, such as a tax on fertilizer. The second is a group-level economic instrument.

Input-based schemes such as a tax on commercial fertilizer are second-best approaches to controlling nutrient losses. By raising the cost, a tax encourages the conservation of commercial fertilizer and so leads to some reductions in nutrient exports. The administrative advantage of this instrument is that fertilizer purchases are more easily observable than phosphorus reductions and, hence, easier to tax. The disadvantage, however, is that it does little to create incentives for adopting a cost-effective mix of other BMPs that can reduce nutrient losses. Moreover, a tax on commercial fertilizer could have the unintended effect of encouraging greater substitution of manure fertilizer for commercial fertilizer thereby undoing, to some extent, the effect of the tax on phosphorus application.

On the other hand, a group-level, or ambient tax/subsidy, approach to applying economic instruments has the potential to be cost effective (Kotchen and Segerson, 2020, 2018; Segerson, 1988; Xepapadeas 2011). With this approach, a well-defined group (e.g., farmers within a subwatershed) is subject to an outcome-based standard such as a collective nutrient load allocation. The group, as a whole, receives a payment when the group's combined loadings (measured at a suitable point in the subwatershed) are below the collective nutrient loading target (or lead to nutrient concentrations below a concentration standard) and pay a fee when combined loadings exceed the standard. It is up to the group to self-organize to allocate the payments or fees among its individual members as well as allocating individual responsibilities for achieving the group's goals. Participation in a group is mandatory for all nonpoint sources within the area of control. Liability for each individual depends on the abatement efforts of all members of the group, not just the individual's efforts, as well as stochastic environmental factors such as weather (Poe et. al. 2004). All members of the group, when cooperating, have an incentive to engage in the most cost-effective combination of pollution control practices possible. This approach does not dictate which practices farmers should adopt. Instead, it gives them the flexibility to adopt the most appropriate and most cost-effective practices suited to their particular field conditions. This flexibility, combined with the payment/fee incentives, helps ensure that cost-effective solutions tailored to specific farming conditions can be achieved.

Conceptually, the group-level economic incentive approach can be thought of as a TMDL program that is supplemented with incentives and enforceability. Under a TMDL, the total maximum load to a waterbody must be allocated among point and nonpoint sources. The nonpoint share is often allocated among groups of nonpoint sources rather than individuals given challenges in monitoring individual nonpoint loadings. A group may be defined as the set of farms whose phosphorus exports reach a common receptor point where group-level loadings can be calculated to determine if the group is exceeding or complying with its allocation. The TMDL provision does not give USEPA (or the states) authority to regulate nonpoint sources (Congressional Research Service 2014) or enforce compliance. But under a group-level economic incentive approach, compliance is rewarded with a payment and noncompliance is penalized with a fee. Specifically, each group is rewarded with a payment that is proportional to the amount by which its loadings are lower than its allocated share of the TMDL or are penalized by a fee that is proportional to the amount by which its loadings exceed its allocation. In any one time period, such as a year, random weather events may cause group loadings to exceed or fall short of the allocation but, on average, payments and fines will net out to be approximately zero if the group is meeting its allocation on average.

Individual members of a group may have an incentive to free-ride on the phosphorus-reducing actions of others within the group and this can hinder the likelihood of success of a group-level approach. Literature, originating with Ostrom (Ostrom 1990; Ostrom et al., 1994) outlines the conditions under which free-riding is minimized and collective coordination is most likely to be successful. As Kotchen and Segerson (2020) argue, successful coordination will depend on the group's ability to develop internal operating rules, and monitor and influence decisions by group members, either with formal mechanisms or informal mechanisms such as trust and peer pressure.

The group-level or ambient tax/subsidy approach is not new in the literature (e.g., Segerson 1988) but it remains almost completely untested in practice. The Florida Everglades Agricultural Area privilege tax may be the only practical example. Here, the tax rate on land is reduced (through a tax credit) when aggregate phosphorous loadings from the basin are reduced below a target threshold, thereby rewarding farmers for basinwide water quality improvements that go beyond the threshold (Daroub et al. 2011; Hoffmann et al. 2006). Apart from this example, the evidence of the effectiveness of group-level ambient taxes/subsidies comes from laboratory and field experiments (Deacon et al. 2008, Suter et al. 2010; Suter et al. 2014). On the whole, this evidence indicates such schemes can be quite effective. In reviewing this evidence, Kotchen and Segerson (2020) conclude: "The findings and conclusions of our review suggest that, in certain contexts and when properly designed, group-level policies can be an important tool for regulators to use in managing environmental and natural resources."

2.3.9 Policy evaluation

Unlike nutrient releases from point sources, such as wastewater treatment plants and certain animal feeding operations, nonpoint sources of nutrient loadings are not directly regulated under the Clean Water Act in the US and are not subject to mandatory regulations in Canada. Instead, the Parties rely almost exclusively on voluntary measures combined with cost-sharing programs to encourage farmers to adopt BMPs that are believed to reduce farm-level nutrient exports. The challenge in evaluating the effectiveness of these programs is that because participation is voluntary, participation rates are subject to adverse selection bias; that is, farms for which a particular BMP implementation would have been profitable anyway are the most likely to participate in the program. For example, according to Lichtenberg (2021):

> the most likely participants in cropland conversion programs are those for whom crop production is unprofitable, and the most likely participants in programs that pay for installations of erosion and runoff-reducing farming practices are those for whom it pays to use those practices to protect the future productivity of their land.

The challenge in assessing the effectiveness of these voluntary programs is to statistically control for the adverse selection bias so as to distinguish the share of implementations that is due to the programs from what would have occurred anyway. The literature therefore focuses on the concept of additionality: a measure of the amount of BMP implementation due to programs alone, net of the implementation that would have occurred anyway, in the absence of the programs.

Studies (Claassen et al. 2018, Mezzatesta et al. 2013; Lichtenberg 2021) have generally shown low degrees of additionality for conservation practices and combinations of conservation practices that lead to higher on-farm profits (such as only 47 percent additionality for conservation tillage (Claassen et al. 2018)), meaning most of these implementations would have occurred without the program subsidies, and degrees of additionality as high as 96 percent (Claassen et al. 2018) for practices that have high degrees of up-front costs or little or no on-farm benefit (e.g. filter strips, riparian buffers and field borders), meaning most of these implementations would not have occurred without the program subsidies. The importance of understanding additionality is amplified by looking at its implications for estimating a program's unit cost of reducing nutrient loadings. If additionality is only 47 percent for a specific practice, for example, the true unit cost of reducing nutrient exports by subsidizing that practice is nearly double the unit cost estimated under the assumption of perfect additionality.

Other studies have examined factors that affect farmers' decisions to opt-in to voluntary programs. While the overwhelming reason is financial motivation (Liu et al. 2020; Liu et al. 2018), studies of observed adoption practices find that adoption rates tend to be higher among larger farms (Liu et al., 2020) and where farmers have a higher degree of education (Norris and Batie, 1987). Dupont (2010) finds younger farmers in Ontario are more likely to adopt BMPs, but this effect is not observed in Liu et al (2020) for farmers in the Maumee River basin. Survey data indicate that farmers in the western Lake Erie basin are highly motivated to adjust their land management practices but that the biggest barrier to adoption is that many farmers believe proposed BMPs are not feasible or cost-effective to implement or that they will not yield the expected water quality benefits (Wilson et al. 2019). These results indicate that in addition to financial motivation, outreach with high-quality, science-based information will increase the likelihood that farmers will adopt BMPs (Wilson et al. 2018).

Few studies have investigated empirically the effect of agricultural subsidy programs on water quality at the scale investigated in Liu et al. 2022. The authors used econometric analysis of spatially linked water pollutant concentrations from monitoring stations with Environmental Quality Incentives Program payment information at the Hydrologic Unit Code 10 level throughout the United States. They found that Environmental Quality Incentives Program payments have led to a statistically significant reduction in biochemical oxygen demand and nitrogen concentrations, but are also associated with increased total suspended solids, fecal coliform and phosphorous. The authors conclude that these mixed results are consistent with studies that have documented the complex interaction of conservation practices and potential unintended consequences outlined in Capel et al. (2017). Nevertheless, these findings are cause for concern about the effectiveness of relying exclusively on voluntary programs to reduce phosphorus concentrations in the western Lake Erie basin and warrant further consideration.

Finally, research that integrates economic and biophysical models will likely prove to be the most useful in helping to evaluate policy effectiveness. These integrated assessment models make it possible to predict the impact of different policy scenarios on outcomes of interest, such as nutrient loadings at the basin level and the associated impact on the value of ecosystem services. A well-designed and executed integrated assessment model is essential to a comprehensive evaluation of the effectiveness of agri-environmental policies (Lupi et. al. 2020).

Liu et al. (2020) develop an integrated assessment model that links a behavioral model of farmers' choices (of fertilizer application rates and adoption or not of two other BMPs: subsurface placement and cover crops) to a Soil and Water Assessment Tool model that predicts total phosphorus and dissolved reactive phosphorus output in the Maumee River basin. The behavioral model predicts farmers' responses to changes in policy parameters (a tax rate on fertilizer and the per-acre subsidy rate for BMP adoption) and the Soil and Water Assessment Tool model then predicts the likely nutrient export outcome for the basin. For example, the model predicts that increasing the BMP subsidy from US$20 (CDN$27) to US$80 (CDN$108) per acre increases the adoption rate of subsurface placement from 46 percent to 63 percent of acres in the watershed and leads to an additional 8 percent reduction in total phosphorus and 13 percent reduction in dissolved reactive phosphorus in the watershed. The findings also indicated increased cost effectiveness of subsurface placement and fertilizer rate reductions as compared to cover crops (Liu et al. 2020).

Lupi et al. (2020) go a step further in model development. They describe the development of an integrated assessment model for phosphorus that links policies designed to induce changes in farmer behavior to resulting changes in the economic value of key endpoint ecosystem services of the lakes, rivers, and streams in watersheds draining to the Great Lakes from Michigan's Lower Peninsula as well as the downstream coastal zones of Lakes Michigan, Huron and Erie. The central contribution of their paper is the presentation of an integrated assessment model that characterizes the chain of effects from an economic model of farmer response to a policy scenario through to ecosystem service impacts and economic models of consumer demand for ecosystem services.

2.4 Summary and synthesis of DAPs, including programs in place

A major objective of this project is to review and assess domestic action plans, both in developing the technical report and the additional assessment contained in this report. As noted above, in addition to assessing the quality of DAPs, this project also aims to assess their implementation. The latter component is more challenging for two reasons: first, the relatively short time frame since DAPs have been in place, and second, challenges in tracking reporting on DAP implementation (beyond recent report in the Progress Report of the Parties (ECCC and USEPA, 2022c), partly given the wide range of potential projects and programs involved and various reporting mechanisms that might be in place. In this section, we provide a summary and qualitative assessment of Lake Erie DAPs, as well as a high-level summary of federal, state, and provincial programs addressing nutrients as part of efforts under Lake Erie DAPs.

LimnoTech provided an overall assessment of Lake Erie DAP breadth considering eight program areas, such as wastewater/septic system upgrades, urban nonpoint source reduction, and fertilizer management (see Table 2 in LimnoTech, 2022). They noted generally good attention in DAPs to the program areas, including plans from Michigan, Ohio and Canada-Ontario addressing all areas, while Pennsylvania's plan only addressed three (LimnoTech 2022).

The work group co-leads carried out an additional qualitative assessment, based on 12 program areas, some of which overlap with those used by LimnoTech (2022) (see further discussion on approach in **Appendix A**). Results of this assessment for the 12 program areas are provided in **Table 3**, with more comprehensive program components indicated with darker gray shading. As indicated in the table, there is a range of attention to individual program areas within the DAPs, as briefly reviewed here.

Table 3. Summary assessment of Lake Erie Domestic Action Plans by program area.

Program Area[15]	Lake Erie Domestic Action Plan					
	United States[28]	Indiana[29]	Michigan[30]	Ohio[31]	Pennsylvania[32]	Canada/Ontario[33]
Point Sources/ Regulatory[16]	Discussion on National Pollutant Discharge Elimination System and other regulatory programs, addressing wastewater treatment plants, combined sewer overflows and stormwater. However, limited discussion on basinwide tracking of progress in further reductions and any potential federal directive on further reductions that may be needed, including in context of climate change.	Limited details on permit limits for regulated point sources.	Details on limits for multiple wastewater treatment plants, but limited/no information on sewer outfalls or stormwater.	Details on various point sources (with National Pollutant Discharge Elimination System permits) in the Maumee River watershed, including load trends for wastewater treatment plants, and information on combined sewer overflows and stormwater discharge points.	Detailed description of various point sources in watershed, including wastewater treatment plants, combined sewer overflows, stormwater discharge points.	Details on approaches to municipal wastewater treatment plants (noting most plants in Lake Erie basin are already meeting 0.5 mg/L effluent limit), combined sewer overflows (and discussion of sewer separation, low-impact development) and industrial dischargers.
Agricultural Nonpoint Source/Best Management Practices[17]	Overall strategy section emphasizes importance of addressing agricultural sources, have details on key BMPs (e.g., fertilizer application approaches). Individual state sections address agricultural sources, with varying degrees of detail. More details on programmatic tracking would be helpful, such as extent of BMP adoption (types, general locations, etc.) with time.	Minimal discussion on specific BMPs, approaches to increase BMP adoption rates.	Implementation of BMPs occurs through Michigan Agriculture Environmental Assurance Program, and prioritization discussed. 4R Nutrient Stewardship program noted; reporting of BMP implementation for recent period.	Addressing agricultural sources major emphasis of DAP, including through nutrient, erosion and water management. Includes details on various BMPs via a toolkit, reference to 4R Nutrient Stewardship, and multiple state agricultural programs, including on nutrient management planning, variable rate phosphorus application, and subsurface phosphorus placement.	Discussion on programs addressing agricultural runoff, but extent of agricultural land in watershed not clear. Minimal discussion on conservation programs, prioritization or individual BMPs.	Notes importance of multi-BMP approaches on many farms (including promotion through the federal-provincial Canadian Agricultural Partnership), use of planning tools, such as through Environmental Farm Plans, efforts focused on greenhouses), addressing drainage, and multiple partner-led (including nongovernmental organization-led) efforts.
Agricultural Manure Management[18]	Minimal discussion on animal feeding operations, some program overviews in state sections. No discussion on further federal/binational efforts that could be pursued, such as consideration of guidance for strengthening programs (in particular for medium-sized animal feeding operations), or promotion of some type of regional framework to share best practices (e.g., following on current Commission work).	Comprehensive discussion on elaboration on requirements for manure management at regulated confined animal feeding operations.	Some details on provisions applying to regulated facilities, but notes no prohibition on winter spreading of manure (though other restrictions are in place in some cases).	Includes details on rules and programs affecting animal feeding operations (depending on size), reference in Nutrient Management Plan section, and elaboration on practice of manure incorporation.	Minimal discussion on animal feeding operations, including any reference to extent of unregulated animal feeding operations in watershed, nor provisions on manure application, etc.	Notes several aspects of manure management, including revisions to Feeds Regulations, and Nutrient Management Act requirements on nutrient management strategy for certain livestock farms in permit application process. Could benefit from more details on program implementation, potential improvements.

Program Area[15]	Lake Erie Domestic Action Plan					
	United States[28]	Indiana[29]	Michigan[30]	Ohio[31]	Pennsylvania[32]	Canada/Ontario[33]
Watershed Plans, Regulations[19]	Some discussion of watershed planning and nutrients, including via Agriculture Conservation Planning Framework pilot, and earlier National Integrated Water Quality program. Discussion of watershed plans in several state sections. Minimal discussion on TMDL program, and in particular potential for enhanced federal role (e.g., through a regional TMDL, with extensive USEPA involvement).	Discussion on watershed plans; limited discussion on TMDLs, including TMDLs developed, or scheduled to be developed.	Most of state's portion of the Lake Erie watershed has a watershed plan in place or in development. The Michigan portion of Lake Erie declared impaired in 2016. TMDLs not discussed in DAP, but are discussed in adaptive management plan (**Appendix C**), though indicating no plan to develop a formal TMDL.	Watershed planning is referenced multiple times, including in context of identifying areas for practice placement; Hydrologic Unit Code 12 planning efforts in southern portion of Maumee River watershed. TMDLs are referenced, in particular concerning TMDLs developed for smaller watersheds within the Lake Erie watershed. No details on plans to develop a Lake Erie TMDL within the DAP itself. Draft Maumee River TMDL released in 2022.	References Pennsylvania Lake Erie Watershed Integrated Water Resource Management Plan, but not clear on implementation status. Several references to impaired waters, but no reference to TMDL development.	Watershed planning underway in multiple watersheds (including as referenced in the Provincial Policy Statement of 2014), with potential new plans to be developed "as required," though it is not clear how requirements would come about. It is not apparent if there is a watershed approach to addressing all loads to meet water quality standards (as exists on US side through TMDL program).
Research Programs[20]	Extensive discussion of research, including concerning reduction targets, state efforts and agricultural nutrients. Multiple efforts of federal agencies (e.g., USDA, NOAA, US Army Corps of Engineers and US Geological Survey), including projects on modeling (e.g., in support of Lake Erie HABs forecasting system). Would be helpful to have a better sense of key research questions to address to optimize program efforts to meet nutrient targets.	Limited discussion on research programs, in particular plans for more local-scale, edge of field studies. Limited discussion on new modeling to be carried out.	Research discussed in several contexts, including agricultural tool development, BMP effectiveness, and public outreach and education, including Michigan Cleaner Lake Erie through Action and Research Partnership. Further elaborated in 2021 Adaptive Management Plan.	Significant research funded through the Ohio Department of Higher Education, including through the Harmful Algal Bloom Research Initiative. Supported projects have addressed a range of topics, including watershed modeling and phosphorus export, factors influencing HAB development, and social science research on practice adoption.	No discussion with any program details or plans for further research in support of DAP implementation.	Notes efforts on models and tools, including Soil and Water Assessment Tool and Indicator of Risk of Water Contamination by Phosphorus tool. Multiple research projects and initiatives noted, including addressing BMP effectiveness, approaches to increase uptake, potential for phosphorus recovery and reuse, and potential of green infrastructure/low impact development.
Monitoring Programs[21]	Extensive monitoring programs in place throughout the western Lake Erie Basin, implemented by multiple federal and state agencies, and academic institutions, addressing nutrient concentrations in tributaries, Lake Erie, field runoff, and in-lake HABs. More details on nutrient forms (e.g., total vs. bioavailable phosphorus) and on plans to operationalize the regional water quality monitoring network would be helpful.	Relatively comprehensive discussion on monitoring, including locations, parameters and frequency.	Relatively extensive discussion on monitoring but monitoring plan under development at time of DAP release; hence details on monitoring locations, time frame, etc. not available.	Extensive program in place, including restructured tributary monitoring program for nutrients working with federal and other partners. State required by law to produce nutrient mass balance report every two years, and other monitoring underway, including of wetlands and drinking water. Existing load monitoring stations summarized in an appendix to the DAP.	Discussion on monitoring, but mainly in context of point source discharge monitoring reports, and monitoring more generally. Limited discussion on entities currently carrying out nutrient monitoring.	Discusses multiple monitoring programs for nutrients and related parameters, in the watershed (including via the Provincial Water Quality Monitoring Network), tributaries, and offshore waters (including for algal pigments in the western basin, and *Cladophora* biomass in eastern basin).

Program Area[15]	Lake Erie Domestic Action Plan					
	United States[28]	Indiana[29]	Michigan[30]	Ohio[31]	Pennsylvania[32]	Canada/Ontario[33]
Human Health[22]	Discussion of human health mainly in context of general goals of addressing nutrients and reducing HABs, and summary of efforts under Safe Drinking Water Act, including monitoring of HAB toxins through Unregulated Contaminant Monitoring Rule and issuance of health advisories. Plan would benefit by more details on research and monitoring that could advance understanding of health risks in region.	Minimal discussion on human health, drinking water and HAB toxins, or source water protection.	Minimal discussion on human health, drinking water and HAB toxins, or source water protection.	Limited reference to drinking water/cyanobacterial toxins, including on context of monitoring priority if toxins detected in treated drinking water or have high HAB susceptibility.	Minimal discussion on human health, drinking water and HAB toxins, or source water protection.	Discussion of human health mainly in context of general goals of addressing nutrients and reducing HABs. Mention of supporting research on potential human exposure to HAB toxins via fish consumption, but plan would benefit by more details on research and monitoring that could advance understanding of health risks.
Adaptive Management Framework[23]	Adaptive management section, notes framework development underway under Annex 4. Notes importance of monitoring, reporting and public engagement. Although the plan references the Commission in the context of assessment, there is value in considering more formal engagement with the Commission and other entities in development, revision, and implementation of an adaptive management framework.	DAP discusses adaptive management, including hypotheses tested, prioritization, and topics for future consideration. More discussion on BMP implementation and adaptive management would be beneficial	Adaptive Management Plan released 2021, including emphasis on "active" versus "passive" mode, more targeted BMP implementation.	State does not have formal adaptive management framework or plan, though references adaptive management in context of program implementation, research, and monitoring.	Very brief reference to adaptive management planning, and indicates the next DAP would be released in 2022.	References an adaptive management strategy that will be pursued, including drawing on monitoring and research (including modeling), evaluation of management actions (through performance measures), and a five-year reporting and review cycle.
Interim Targets/ Deadlines[24]	Document references timeframes for major implementation, research and monitoring programs, but no explicit interim milestones for load reductions. State sections for Michigan and Ohio reference interim targets and dates identified in the 2015 Michigan, Ohio and Ontario Collaborative Agreement.	Decent discussion (including Action/Milestone table), though additional deadlines post-2020 would be helpful.	Original DAP and 2021 Adaptive Management Plan highlight interim reduction targets, including for 2020 and 2025.	DAP references interim reduction targets by 2025.	No interim targets or milestones included.	As per Ontario, Michigan and Ohio Collaborative Agreement, plan references a 2025 reduction target; also references an "aspirational interim goal" of a 20 percent phosphorus reduction to western basin by 2020.

Program Area[15]	Lake Erie Domestic Action Plan					
	United States[28]	Indiana[29]	Michigan[30]	Ohio[31]	Pennsylvania[32]	Canada/Ontario[33]
Tracking and Reporting[25]	Extensive discussion on issues involved in tracking progress, including adequate monitoring, potential lags in response to actions, and an early assessment of progress and further work likely needed. Includes identification of three groups of indicators (on the ground, in tributaries, and in-lake), though it is not clear to what extent programs were (or are) in place to monitor and report.	Discussion on tracking, but limited on details, and means of reporting (beyond sharing data through ErieStat).	DAP report noted in-lake tracking would be reported via Annex 4. Adaptive Management Plan report includes table tracking tasks and activities; more specific tracking (e.g., BMP implementation) would be advantageous.	Plans underway to track BMP adoption through H2Ohio, an online platform (Beehive), and efforts of Ohio Department of Agriculture. State is reporting on nutrient reduction progress, and intends to report on status of watershed planning implementation. Reporting through various mechanisms, including biennial Integrated Report, contributions to Progress Report of the Parties, others.	Plans for state tracking of some data (e.g., point source discharges) and working with others to report other activity (e.g., ErieStat), but it is not clear to what extent regular state-specific reporting is occurring.	References tracking and reporting on progress every five years, starting in 2023, including through development of metrics on performance measures. References that various agencies have own reporting approaches, but that Canada and Ontario will work binationally (including through Annex 4) on reporting platforms, including ErieStat.
Roles Delineated[26]	Initial discussion of partners could be more comprehensive, emphasize varying roles of nonagency partners, including academia, industry (and associations) and nongovernmental organizations. Actions and milestones address partners/responsible parties. Could have clearer discussion on coordinating/lead roles of appropriate agencies on regulatory, voluntary programs, research and monitoring.	Key agencies, private sector, nongovernmental organization community, partnerships identified. Minimal discussion of academic partners and roles.	DAP notes agency roles generally defined previously in implementation plan, and Adaptive Management Plan further clarifies roles of state agencies in particular; more discussion on partnerships with academic groups, nongovernmental organizations and private sector would be helpful.	Multiple state and federal agencies (including USEPA, US Fish and Wildlife Service, NOAA, US Geological Survey) noted, as well as involvement of academia (research, monitoring); private and nongovernmental organization efforts described in an appendix to the DAP.	Discussion on partners (including USEPA, US Geological Survey, NOAA, and Erie County), but limited discussion on other partners, in particular concerning agricultural activities.	Notes coordinating role of federal and provincial governments with other entities. Summary of work with partners (including conservation authorities, industry, nongovernmental organizations), including actions directly led by partners. Education and outreach is highlighted, including innovative programs (e.g., peer-to-peer advisory committee for poultry/livestock industry on winter application).
Funding Expenditure Available[27]	Relatively extensive discussion of expenditures through multiple programs, in particular federal programs (some of which is passed through to states) addressing program implementation, research, and monitoring. Fewer details on expenses associated with program assessment and tracking.	Various funding programs identified, but no specific amounts or plans for pursuing additional funding provided.	Programs identified, more details on some programs (if not dollar figures) are provided in Adaptive Management Plan tracking tables.	DAP includes identification of overall funds in support of Lake Erie water quality improvements, as well as some more specific programs, including through H2Ohio, through Soil and Water Conservation Districts, and wastewater infrastructure improvements. The DAP also includes costs curves for BMP implementation.	Various funding programs identified, but minimal information on amounts, nor plans for pursuing additional funding.	Multiple programs identified, but very limited information on budgets or plans for pursuing additional funding provided.

15 Addresses twelve program areas (see individual notes in the table), where program areas draw on LimnoTech (2022), domestic action plans and Commission reports. Qualitative assessment for each program area and DAP indicated by shading, with no shading indicating minimal discussion/treatment, light gray shading indicating some discussion/treatment, and light blue shading indicating more comprehensive discussion/treatment. Emphasis is on original domestic action plans, with some reference to other plans (e.g., more recent DAP or adaptive management report).

16 Addresses mainly urban sources, including wastewater treatment plants, stormwater discharges and combined sewer overflows.

17 Emphasis is on voluntary nonpoint source control programs and best management practices, examining extent of detailed discussion on such programs and practices in the DAP.

18 Encompasses regulatory programs, including permitting programs for animal feeding operations.

19 Regulations reference any regulatory program addressing pollutants at watershed scale, such as total maximum daily load provision of the US Clean Water Act requiring states to identify impaired waters and address sources contributing to impairments.

20 Research encompasses modeling.

21 Includes consideration of ambient monitoring, point source monitoring, networks and other monitoring approaches.

22 Includes consideration of extent of discussion on human health risks from HABs in Lake Erie basin, research and monitoring underway (e.g., concerning HAB toxins in source water and potential exposures) and source water protection.

23 Includes consideration of reference to framework development as well as plans for implementation.

24 As noted in main text, Ontario, Michigan and Ohio agreed to load reduction targets for phosphorus entering the western basin of Lake Erie of 40 percent by 2025, and an "aspirational interim goal" of 20 percent by 2020 (Governors for the Western Lake Erie Basin States of Michigan and Ohio and the Premier of the Province of Ontario, 2015).

25 Includes references in DAPs to current programs and plans for tracking in reporting, including for aspects such as BMP implementation.

26 Includes consideration of extent of identifying key sectors, partners and potential roles (in research, monitoring, nutrient reduction program implementation, etc.).

27 Includes consideration of extent to which plans to identify needs for ongoing funding for larger programs (regulatory, voluntary, specific research and monitoring, etc.) are discussed in DAPs and related documents.

28 US Action Plan for Lake Erie (USEPA 2018).

29 Indiana's Great Lakes Water Quality Agreement (GLWQA) Domestic Action Plan (DAP) for the Western Lake Erie Basin (WLEB) (Indiana Department of Environmental Management 2018); Indiana State Department of Agriculture DAP web page: in.gov/isda/3432.htm.

30 State of Michigan Domestic Action Plan for Lake Erie (Michigan Department of Environmental Quality 2018); Michigan's Adaptive Management Plan for Lake Erie web page: michigan.gov/LakeErieDAP.

31 Promoting Clean and Safe Drinking Water in Lake Erie: Ohio's Domestic Action Plan 2020 to Address Nutrients (Ohio Lake Erie Commission 2020).

32 Final Pennsylvania Lake Erie Phosphorus Reduction Domestic Action Plan (Pennsylvania Department of Environmental Protection 2017).

33 Canada-Ontario Lake Erie Action Plan: Partnering on Achieving Phosphorus Loading Reductions to Lake Erie from Canadian Sources (Environment and Climate Change Canada and Ontario Ministry of the Environment and Climate Change, 2018).

Concerning point sources (other than animal feeding operations), both Ohio and Pennsylvania have comprehensive descriptions in their DAPs of various point source categories and effluent limits, and in the case of Ohio, information on load trends. The Canada-Ontario DAP also has comprehensive treatment of the issue, including noting additional measures underway such as sewer system separation and low-impact development initiatives.

On agricultural/nonpoint sources, most DAPs provide details on approaches to addressing the issue, including for example the Michigan Agriculture Environmental Assurance Program, multiple efforts in Ohio (including reference to the national 4R Nutrient Stewardship program,[34] elaborated on below), and reference to multiple programs and planning tools (such as through Environmental Farm Plans) in the Canada-Ontario DAP.

On manure management, the regulatory framework is somewhat complicated. On the United States side, animal feeding operations, or facilities with animals kept and raised in confined situations may or may not be regulated. Animal feeding operations that meet certain criteria with respect to potential to discharge to a water body are termed concentrated animal feeding operations, and with three size categories based on the number of animals confined.[35] Facilities with the potential to discharge are covered under the US Clean Water Act National Pollutant Discharge Elimination System regulations. The regulatory approach to livestock farms in Ontario is covered under the Nutrient Management Act, with generally greater requirements on smaller operations than in the United States (International Joint Commission Great Lakes Water Quality Board 2020).

The DAPs themselves differ in the detail they provide on their manure management programs. For example, Indiana's DAP includes comprehensive reference to requirements on regulated confined feeding operations (which include regulations apart from the Clean Water Act National Pollutant Discharge Elimination System regulations). Ohio's DAP includes details on program requirements for affected livestock facilities, including on approaches to manure incorporation. On the other hand, the United States (federal) DAP has minimal discussion of animal feeding operations, while the Michigan DAP has more details, but there is no prohibition on winter application of manure in the state. The Canada-Ontario DAP itself has some details on the livestock farm program, but more information on programs in place and any potential changes needed to further reduce nutrient export from animal feeding operations would help indicate the capacity of the program to address the problem.

On watershed plans and regulations, none of the plans address the program area in a comprehensive way. Although most plans have discussion of watershed planning in general and/or specific plans developed, the plans lack detail on regulatory programs. On the United States side, inadequate detailed attention to TMDLs is common for most of the plans. Although Michigan has designated the state's portion of the western basin of Lake Erie as impaired under the US Clean Water Act, the DAP itself does not discuss TMDL development or implementation, although there is brief discussion in the state's Adaptive Management Plan. Ohio's DAP and subsequent work involving TMDLs is arguably the most extensive. The DAP

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[34] More information on the 4R Nutrient Stewardship program can be accessed at: nutrientstewardship.org/4rs/.
[35] More information on size categorization of animal feeding operations in the United States can be accessed at: epa.gov/npdes/animal-feeding-operations-afos.

discusses individual TMDLs in the Maumee River watershed. Furthermore, in late 2022, Ohio EPA released a draft TMDL for the Maumee River watershed, with goals to remove impairments to drinking water, recreational uses, and aquatic life associated with western Lake Erie basin HABs (Ohio Environmental Protection Agency 2022). The United States DAP has minimal discussion on TMDLs, including the potential for USEPA to coordinate TMDL development, as has been done in the Chesapeake Bay. It is not clear from the Canada-Ontario DAP if there is a potential regulatory mechanism similar to TMDLs applicable to Ontario watersheds, or if such a provision is being considered. (The TMDL program is discussed further in **Section 2.4.1.4**)

Research programs have been one area of significant progress in recent years, as noted in the technical report (LimnoTech 2022), and summarized in **Table 3** (note that modeling is considered here with research). Multiple research efforts involving various agencies are noted in the United States DAP, and states have varying levels of research programs dedicated to nutrients and Lake Erie. Ohio has arguably the most comprehensive program, including through via H2Ohio and the Ohio Department of Higher Education Harmful Algal Bloom Research Initiative. Michigan's Adaptive Management Plan includes references to individual research projects addressing BMPs, monitoring, climate change and other components. In contrast, the Indiana and Pennsylvania DAPs include few details on state-supported research supported through the DAPs. The Canada-Ontario DAP has significant details on various research programs, including in support of research on BMP effectiveness and approaches to increase BMP uptake by farmers.

Monitoring programs have been another area of significant progress through the years, with multiple programs highlighted in the United States, Indiana, and Ohio DAPs, coordinated by federal or state agencies or academia (e.g., the long-standing tributary monitoring program coordinated by Heidelberg University in Ohio). In Michigan, the DAP notes a monitoring plan is planned for development. The Canada-Ontario DAP references monitoring both in the watershed and in Lake Erie, including through the Provincial Water Quality Monitoring Network.

Concerning human health, none of the DAPs provides any details on programs to address human health risks from HABs (such as via cyanotoxin exposure in drinking water). Both the United States and Ohio DAPs mention monitoring for cyanotoxins in drinking water, but the plans in general (and in particular the federal plans) would benefit from more discussion on plans to advance research on understanding and reducing health risks to people from HAB toxins.

On adaptive management, all plans at least briefly reference the approach. Michigan is the only jurisdiction to have established a standalone adaptive management plan in support of its DAP, which includes multiple components, including approaches to targeting BMP implementation. The United States DAP includes a section on adaptive management, highlighting the importance of monitoring, reporting and public engagement. The Canada-Ontario DAP indicates plans to develop an adaptive management strategy to include five-year reporting and review.

Most DAPs include references to interim targets and milestones. The Michigan, Ohio and Canada-Ontario DAPs reference interim targets developed through the Michigan, Ohio and Ontario Collaborative Agreement signed in 2015, of a 40 percent reduction in total and dissolved reactive phosphorus loads by 2025, and 20 percent by 2020. The interim targets are mentioned in state sections of the United States DAP, but no interim targets are discussed otherwise in the United States DAP.

On tracking and reporting, most DAPs provide significant details on the approaches underway or intended to be pursued. The United States DAP discusses issues to consider in tracking and progress reporting (such as ecosystem response delays) and identifies indicators that can be developed in three categories: on the ground, in tributaries and in-lake. Michigan's adaptive management plan discusses tracking and reporting of specific tasks, and notes reporting to be carried out through Annex 4. The Ohio DAP discusses plans to track BMP implementation through H2Ohio and Ohio Department of Agriculture, with other reporting via other mechanisms. The Canada-Ontario DAP discusses planned reporting on performance measures and plans to coordinate binationally on reporting. Most DAPs note reporting being done or planned through ErieStat, hosted by the Great Lakes Commission. Although most DAPs have relatively extensive discussion on tracking and reporting, much of the discussion concerns plans going forward; see discussion below on indicators in the context of monitoring, which is relevant to this program area.

On roles and responsibilities, all DAPs discuss the issues to at least some extent. Indiana, Michigan and Ohio DAPs include some elaboration, in particular on roles of state agencies in the Michigan DAP (in more detail in the state adaptive management plan) and in the Ohio DAP (with details in an appendix). The United States DAP discusses various agencies involved but would benefit by clarification of coordination/lead roles by various agencies as well as the supporting roles of non-agency partners (including academia, nongovernmental organizations, and industry/agricultural associations). The Canada-Ontario DAP has comprehensive discussion of coordination amongst entities, including potentially innovative partnerships with non-agency organizations, such as a peer-to-peer advisory committee involving livestock farmers.

Concerning funding of programs, most DAPs have few if any details on funds available for specific programs (or funds that have been expended in the recent past). The Ohio DAP is an exception, with some details on programs and spending levels (e.g., through H2Ohio), and an appendix with cost curves for BMP implementation. Having more details on funding needs for all DAPs would be beneficial during subsequent consideration of appropriations either from state/provincial governments or the federal governments.

Most of this assessment addressing specific program areas in DAPs concerns the DAPs themselves (or related products, such as the Michigan Adaptive Management Plan). It is important to note that many programs and projects addressing nutrients are underway by the Parties, the states and Ontario (including as reported in the most recent Progress Report of the Parties (ECCC and USEPA, 2022c)). Indeed, the technical report prepared for this project identified over 300 programs, projects or goals involving nutrients in their assessment, with many having been completed in the recent past and others underway or planned (Appendix B in LimnoTech 2022), and some of which are addressed below. That being said, we believe there is value in a focus on DAPs themselves, given their importance as strategy and planning documents for the Parties, states and Ontario, and the fact they will be revised in 2023.

2.4.1 Key current federal, state, and provincial programs

Multiple programs exist at the federal, state and provincial levels addressing nutrients, within or across program areas discussed in the previous section. Several program areas were a focus of the technical report (research, monitoring, and adaptive management) (LimnoTech 2022). Drawing on the technical report and additional review, current programs in these areas are briefly reviewed here, along with summary of nonpoint source programs.

2.4.1.1 Research

Both Canada and the United States have large research programs that encompass Great Lakes nutrients issues. The US Great Lakes Restoration Initiative coordinated by USEPA addresses nutrients in particular through Focus Area 3, *Nonpoint Source Pollution Impacts on Nearshore Health*. Although there is an emphasis on on-the-ground implementation of restoration actions, the focus area includes research efforts such as in the third program area entitled *Improve effectiveness of nonpoint source control and refine management efforts* (USEPA 2019). The Maumee River watershed is one of four priority watersheds being addressed in Focus Area 3 in the current program cycle, and work overall addresses multiple issues including edge-of-field studies, monitoring and assessment activities, practice implementation and tool development (USEPA 2019).

Other federally supported research in the United States has been carried out through the USDA, programs which are particularly relevant given the significant contributions of nonpoint source nutrients (in particular agriculture) to Lake Erie. This work has included projects through the USDA Agricultural Research Service, ranging from the farm field to watershed scale (ars.usda.gov 2022). Another important USDA national program with research elements relevant to Lake Erie is the Conservation Effects Assessment Project, through which multiple projects have been undertaken over the past 15 years (e.g., USDA 2016). Significant federal research has also been occurring through NOAA, including related to harmful algal bloom forecasting (National Science and Technology Council 2017). In addition, there is significant ongoing research carried out by other entities, including the states, academic researchers, nongovernmental organizations and the private sector (selected projects reviewed in LimnoTech 2022).

In Canada, there has also been significant research over the past decade addressing Lake Erie nutrient issues, including plans outlined in the Canada-Ontario Lake Erie Action Plan (Environment and Climate Change Canada and Ontario Ministry of the Environment and Climate Change, 2018). Much of this research is carried out through research centers, such as the Canadian Centre for Inland Waters, though the province of Ontario is also heavily involved in Great Lakes research. Better understanding factors leading to loss of phosphorus from agricultural fields is one objective in the 2021 Canada-Ontario Agreement on Great Lakes Water Quality and Ecosystem Health (Environment and Climate Change Canada and Ontario Ministry of the Environment and Climate Change, 2021). A key federal program supporting such research is the Great Lakes Protection Initiative, and projects have been funded in multiple areas, including developing new approaches to reduce phosphorus from agricultural fields, evaluating effectiveness of such efforts, and communicating results and other efforts to increase use of best management practices (ECCC and USEPA, 2022c; Government of Canada 2022).

In addition to federal research efforts, there are significant efforts at the state levels. The H2Ohio program launched in 2019 addresses multiple environmental issues in Ohio, including phosphorus reduction and wetlands creation efforts in the western Lake Erie basin, including via research projects.[36] The Ohio Department of Higher Education Harmful Algal Bloom Research Initiative has supported multiple research projects addressing BMPs, nutrient transport, and in-lake processes related to HABs.[37] Michigan's Adaptive Management Plan notes research that is underway on several themes including the development of tools to identify priority fields and watersheds at a higher risk of sediment loss and to track and report water quality improvements (Michigan Department of Environment, Great Lakes, and Energy et al. 2021). There are also research efforts on Lake Erie nutrients at the more local level in both countries (e.g., conservation authorities), as well as involving academic, nongovernmental organizations and private sector researchers (LimnoTech 2022).

2.4.1.2. Monitoring and indicators

Environmental indicators, including those involving nutrients, have been used for decades in the Great Lakes. One important component of indicators often identified as a challenge is linking environmental management actions and program activities to changes in environmental conditions (Government Accountability Office 2004). One useful approach to address this challenge is a driver-pressure-state-impact-response framework. In such a framework, a driver (such as agricultural activity) leads to a pressure (such as tributary nutrient loads) which changes the system state (e.g., a more eutrophic western Lake Erie) with resulting impacts (e.g., more severe HABs), which in turn suggest management responses (e.g., improved nutrient management) (e.g., Murray et al. 2019). As indicated here, much of the monitoring (and indicator use) concerning nutrients and Lake Erie has emphasized pressure, state and impacts indicators.

These indicators are addressed to varying degrees in the Lake Erie watershed through extensive monitoring programs at multiple levels, involving agencies, academia, the private sector and nongovernmental organizations (LimnoTech 2022). Key programs monitoring flow and certain water quality parameters are led by the Ontario Ministry of Environment, Conservation, and Parks and the US Geological Survey. Heidelberg University's National Center for Water Quality Research carries out what may be the longest-running tributary water quality monitoring program in the United States, with regular monitoring of flow and multiple water quality parameters for 21 tributaries in the western and central basin of Lake Erie.[38] Lake monitoring is carried out by multiple agencies and organizations. NOAA compiles information from satellite imagery and carries out water sampling for HABs, information that is utilized in the monitoring reporting and HABs forecasting work for the western Lake Erie basin.[39] Multiple federal, state

[36] More information about H2Ohio can be accessed at: h2.ohio.gov/about-h2ohio/.
[37] More information about the Ohio Department of Higher Education Harmful Algal Bloom Research Initiative can be accessed at: ohioseagrant.osu.edu/research/collaborations/habs.
[38] More information about Heidelberg University's National Center for Water Quality Research can be accessed at: ncwqr-data.org/.
[39] More information about NOAA's HABs work can be accessed at: coastalscience.noaa.gov/research/stressor-impacts-mitigation/hab-forecasts/lake-erie/.

and provincial agencies, municipalities and academic groups are also involved in lake monitoring (LimnoTech 2022).

Central basin hypoxia monitoring has been carried out by the USEPA for many years as noted previously (USEPA 2021a), and over the past decade, the City of Cleveland has monitored for hypoxia near water intakes. However, annual summaries of central basin hypoxia area or volume are not provided (LimnoTech 2022). Monitoring for nuisance algae (in particular *Cladophora*) has been done more sporadically in the eastern basin by federal, provincial and state agencies, and academic groups, and this work has included use of remote sensing in support of examining temporal trends (LimnoTech 2022).

Consistent with the emphasis of monitoring programs, most of the nutrient-related indicators currently used by the Parties in their triennial reporting entail state or impact indicators. For example, the State of the Great Lakes 2022 report notes an improvement in HABs for Lake Erie in the 2012-2020 period, based on the sub-indicator of decreasing nearshore areal extent of HABs (ECCC and USEPA, 2022b). At the same time, there does not appear to be a similar trend in a different indicator for HABs—the cyanobacterial severity index—more commonly used by NOAA in bloom forecasts and reporting (e.g., Stumpf et al. 2022), and which could be formally adopted as a sub-indicator by the Parties. In addition, there is clear value in developing an indicator of central basin hypoxia, as noted in reference to related research in the Progress Report of the Parties (ECCC and USEPA, 2022c).

In contrast with greater use of pressure, state and/or impact indicators in describing nutrients and Lake Erie, there is no similar reporting (through the State of the Great Lakes process) on key drivers (e.g., extent and nature of animal feeding operations and commercial fertilizer application) as well as tracking and reporting on BMP implementation rates, which in turn have implications for nutrient loads to Lake Erie. To be most effective, such reporting would be at a subwatershed scale or finer (as privacy laws/rules permit), including, for example, on type of BMP in place. There is particular value in reporting on a watershed or subwatershed basis (e.g., 10- or 12-digit HU scale in the United States), rather than on jurisdictions such as states or counties. Such reporting coupled with fine-scale reporting on loads could help better link actions on the land to impacts in the water.

Indicator communication is also important, which should be considered as part of discussions around indicator revision or development, including the value of involving a larger number of stakeholders in the process (e.g., Murray et al. 2021). Other issues around indicator communication have been explored in depth by the Commission (e.g., International Joint Commission Great Lakes Science Advisory Board 2016). In considering indicator reporting, there is likely value in more regular (e.g., annual) reporting of certain indicators or sub-indicators, which could be done for example through ErieStat and improved reporting through the Parties' main binational website for the Great Lakes Water Quality Agreement (binational.net), while drawing on examples from other efforts, including for example the Chesapeake Bay.[40]

[40] Website for tracking progress under the Chesapeake Bay Watershed Agreement can be accessed at: chesapeakeprogress.com/.

2.4.1.3. Adaptive management

There has been increasing interest in the use of adaptive management processes to guide management of nutrients in the Great Lakes, including in recommendations from the Commission (e.g., International Joint Commission Great Lakes Science Advisory Board 2019) and in the peer-reviewed literature (e.g., Arhonditsis et al., 2019a, 2019b; Stow et al. 2020). One key aspect of adaptive management is learning, whereby new information and understanding arising for a particular system are incorporated into actions to address the problems in the system in an iterative manner (e.g., Stow et al. 2020; Williams 2011; Williams and Brown, 2014). The Parties have been active in developing an adaptive management framework under Annex 4 (ECCC and USEPA, 2022c), and development and use of an adaptive management framework was identified as a key priority in the Canada-Ontario DAP (Environment and Climate Change Canada and Ontario Ministry of Environment, Conservation and Parks, 2018). Michigan recently released a formal adaptive management framework to guide the state's work under Annex 4 (Michigan Department of Environment, Great Lakes and Energy et al. 2021). In addition, the Commission's Great Lakes Science Advisory Board-Research Coordination Committee has an adaptive management project underway, which should lead to additional advice on implementation of an adaptive management program by the Parties under Annex 4 (International Joint Commission Great Lakes Science Advisory Board 2020b).

As part of implementing any adaptive management framework, the existence and availability of relevant data are important, and LimnoTech (2022) noted the development of information infrastructure over the past decade relevant to nutrients and Lake Erie. Examples include the ErieStat web-based system coordinated by the Great Lakes Commission, which includes reporting on phosphorus loads to Lake Erie from priority rivers in the western and central basins, and summary of the HAB severity index generated from NOAA and other data (blueaccounting.org/issue/eriestat/). A second example is the Heidelberg University National Center for Water Quality Research monitoring program which includes data on nutrient concentrations for most western and central basin tributaries on the United States side (ncwqr-data.org/).

2.4.1.4 Nonpoint source and related programs

As mentioned earlier, nonpoint sources of nutrient loadings are not directly regulated under the US Clean Water Act and are not subject to mandatory regulations in Canada. With little room left for further reduction of nutrient loadings from point sources, the objective of a 40 percent reduction of nutrient loadings will only be achieved through significant reductions from nonpoint agricultural sources. To achieve this, the Canadian and US governments, along with the state and provincial governments, rely almost exclusively on programs to encourage farmers to voluntarily adopt BMPs. For example, the USDA has used voluntary conservation programs such as the Environmental Quality Incentives Program discussed in **Section 2.3** and the Conservation Stewardship Program, to provide financial and technical assistance to farmers that qualify to support the adoption of specific agricultural practices. There are also programs such as the Conservation Reserve Program involving taking land out of production, to allow for conservation benefits (e.g., reduced phosphorus runoff). In Canada, programs, such as the Environmental Stewardship Program, also rely on voluntary participation in cost-sharing programs.

These voluntary programs typically offer subsidies to farmers to share the up-front costs, and in some cases ongoing costs, of adopting qualifying BMPs. Significant resources are allocated to these programs. For example, between 2000 and 2015, US federal government spending on these programs nationally increased from US$3.5 billion (CDN$4.75 billion) per year to more than US$5.5 billion (CDN$7.45 billion) per year, measured in 2012 US dollars (Claassen et al. 2018). Through these programs, farmers can implement a plethora of BMPs - typically referenced as conservation practice standards by USDA. While 165 standards are currently available,[41] a much smaller number of practices have been found to be particularly relevant to reducing phosphorus export in the western Lake Erie basin watershed (e.g., Martin et al. 2021 and see discussion in **Section 2.3**).

One particularly relevant BMP in the United States is the Nutrient Management conservation practice standard (590), which addresses all nutrient sources. In the case of manure, the standard stipulates application rates that can be applied based on phosphorus risk assessment results for a given field, with more stringent restrictions for higher risk fields. The standard also references the 4R approach to nutrient stewardship (right nutrient source, right rate, right time, and right place, see Bruulsema et al. 2019), which can reduce nutrient losses from fields (USDA 2019), and for which consideration of the right rate can address the general issue of new phosphorus loadings added (or not) to a watershed.

The US Clean Water Act requires that state governments maintain a list of waterbodies within their jurisdictions that do not meet applicable water quality standards. They must develop a TMDL analysis for the responsible pollutant(s), which defines the maximum pollution load that the waterbody can receive and still meet those standards. This total allowable load should then be allocated across all sources that contribute to polluting the waterbody, including both point and nonpoint sources. However, because the US Clean Water Act does not give authorities regulatory power over nonpoint sources, TMDLs do not include clear penalties for failure to meet the group limits or enforceable rules to control the behavior of all contributing polluters.

One system with some parallels to Lake Erie and where the TMDL approach for nutrients has been carried out in the Chesapeake Bay on the US Atlantic coast. Federal involvement in the Chesapeake Bay's restoration and protection has been underway for decades and was further advanced through a 2009 Executive Order calling for enhanced efforts to protect and restore the bay.[42] Since 2010, the USEPA has been overseeing a multi-jurisdiction TMDL for phosphorus, nitrogen, and sediments in the Chesapeake Bay (USEPA 2021b).

Progress through the Chesapeake Bay TMDL has been mixed. For example, according to Kleinman et al. (2019), most Bay states met phosphorus mitigation activity goals for agriculture by 2017, and reductions in phosphorus loads from nonpoint sources of 16 percent from 2009 to 2017. However, progress was more limited in Pennsylvania, for some urban sources, and for water quality in some agricultural areas (Kleinman et al. 2019). An assessment by Chesapeake Bay Foundation argues that none of the Bay states are on track to meet agricultural nutrient

[41] More information about conservation practice standards can be accessed via the USDA Natural Resources Conservation Service at: nrcs.usda.gov/resources/guides-and-instructions/conservation-practice-standards.
[42] Executive Order 13508 is accessible at: federalregister.gov/documents/2010/05/11/2010-11143/executive-order-13508-chesapeake-bay-protection-and-restoration-section-203-final-coordinated.

reduction targets by 2025.[43] Phosphorus loading data from Chesapeake Progress for nine tributaries to the Bay also show mixed results for the 2011-2020 period, with improving conditions for four tributaries, degrading conditions for four, and no trend for one tributary.[44] Research has also documented challenges in tracking changes in downstream water quality associated with management actions on the landscape, including challenges due to nutrient travel time, limited monitoring, competing factors (e.g., related to climate), and unrealistic expectations (Ator et al. 2020).

One innovative aspect of the Chesapeake Bay TMDL (which, in theory, should be helpful in addressing nonpoint sources in particular) is a four-element accountability framework, including Watershed Implementation Plans, two-year milestones, tracking and assessment of restoration progress (by the USEPA), and, as necessary, specific federal actions if Bay states do not meet their commitments (Garvin 2009; USEPA 2021b).

2.5 Integration of Commission recommendations into DAPs: an assessment

LimnoTech carried out a qualitative assessment of the extent to which recommendations in eight Commission reports have been adopted by the Parties, rating overall progress on implementation as "little," "some" or "much" (LimnoTech 2022, Table 1). Most Commission reports have a mix of policy, management or action-oriented recommendations and science recommendations (including research, monitoring and infrastructure). **Table 1** (page 12, right column) summarizes the contractor assessment of implementation of Commission recommendations in aggregate in the DAPs.

Recommendations from the Commission's earliest report (International Joint Commission 2014) have generally had significant influence, including on a subsequent Great Lakes Commission report (Great Lakes Commission Lake Erie Nutrient Targets Working Group 2015) and on nutrient target development by the Parties. Similarly, many actions on modeling carried out by the Parties and other entities are consistent with recommendations in the Commission's Great Lakes Science Advisory Board-Research Coordination Committee nutrient modeling report (International Joint Commission Great Lakes Science Advisory Board 2019). Implementation of recommendations from three other reports on fertilizer application (International Joint Commission 2018), watershed management (International Joint Commission Great Lakes Water Quality Board 2017), and HABs and human health (International Joint Commission Health Professionals Advisory Board 2017) has been more mixed, with, for example, some progress on field studies on BMP effectiveness, development and implementation of nutrient management plans, and increasing drinking water monitoring and treatment for cyanotoxins.

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[43] More information about the Chesapeake Bay Foundation assessment can be accessed at: cbf.org/how-we-save-the-bay/chesapeake-clean-water-blueprint/state-of-the-blueprint/.
[44] More phosphorus loading data from Chesapeake Progress can be accessed at: chesapeakeprogress.com/clean-water/water-quality.

For three other reports on economics of HABs (Bingham et al. 2015), manure management (International Joint Commission Great Lakes Water Quality Board 2020) and offshore productivity declines (International Joint Commission Great Lakes Science Advisory Board 2020a), there has been minimal implementation of recommendations. For the first report, the need remains for the Parties to undertake further work on economic issues associated with nutrient reduction programs and their impacts. Concerning manure management, although the Commission's Great Lakes Water Quality Board report is recent, significant work remains to be carried out by the Parties and other jurisdictions, including in light of recommendations from earlier Commission biennial reports (briefly reviewed in **Section 2.2**).

At the same time, an ongoing Commission work group (the Manure Nutrient Management Collaborative) is aiming to operationalize aspects of recommendations through potential development of an independent collaborative group to advance implementation of a framework to help improve manure management in the Great Lakes (Arvai 2022). Finally, significant work remains to be done addressing the challenges associated with offshore oligotrophication, including more coordination between agencies with different mandates (LimnoTech 2022).

2.6 Barriers inhibiting more progress on Lake Erie

Considerable progress has been made controlling nutrient loadings to the western Lake Erie basin from point sources. However, efforts to control loadings from nonpoint agricultural sources have been less successful despite billions of dollars of investment in conservation programs over the past several decades in the United States alone (Claassen et al. 2018; Ribaudo 2015) as well as significant investment in Ontario. It is clear that the targeted 40 percent reduction in nutrient loadings to the western Lake Erie basin will not be achieved without making significant progress reducing loadings from nonpoint agricultural sources. In this section, we discuss the barriers inhibiting progress towards achieving nutrient reduction targets.

As the literature review in this report makes clear, the interactions among agricultural practices, nutrient loadings and Lake Erie water quality are complex. There is no doubt that this complexity inhibits progress towards achieving a better understanding of these interactions and, in turn, taking the most effective actions to meet water quality goals. Lack of data about these interactions, therefore, is a significant obstacle towards achieving nutrient reduction targets and water quality goals. A more extensive and binationally coordinated program of monitoring, recording, and tracking of both nutrient loadings and BMP implementations by subwatershed is needed. Doing this at a sufficiently fine scale would make it possible to better link changes in BMP implementations to changes in nutrient loadings, as outlined in Recommendation 7 below, and thereby contribute to a better understanding of this complex relationship.

A second obstacle is that not enough is known about which BMPs are the most cost effective at improving Lake Erie water quality. While we note that the Ohio DAP, for example, recognizes the importance of evaluating BMPs on cost-effective grounds, this approach could benefit from refinement and more widespread adoption. Macrae et al. 2021 recently highlighted challenges in assessing cost effectiveness of BMP implementation in the western Lake Erie basin watershed.

For example, some differences in cost effectiveness were apparent even for the same general practice implemented in different jurisdictions, and, in some cases, there were regional differences within a larger watershed. The authors recommended a general approach to more effective implementation of BMPs, including through tailoring practices within “phosphorus management regions,” developing region-specific guidance both on practices and on field trials and water quality monitoring, communicating with producers and incorporating in an adaptive management framework (Macrae et al. 2021). Creating better knowledge of how specific BMP implementations affect nutrient loadings and water quality in a cost-effective manner is a critical step towards reducing the barriers to making progress on Lake Erie water quality. But that knowledge alone is not enough to ensure progress will be achieved because farmers are not likely to voluntarily adopt BMPs that jeopardize on-farm profits. Yet, many of the BMPs required to achieve water quality goals are likely to do just that. Overcoming this third obstacle requires creating sufficient financial incentives or regulatory requirements to ensure adoption of the right BMPs. It is encouraging that some progress has been made through existing voluntary programs in both countries that have raised awareness among farmers and have led to the adoption of many BMPs, including through the 4R Nutrient Stewardship program. However, it seems reasonable to argue that the cost effectiveness of voluntary programs is subject to diminishing returns. That is, the BMPs that are adopted voluntarily first are those that are relatively low-cost, easy to implement and that lead to on-farm net benefits. What remains are higher-cost BMPs that lead to lower on-farm net benefits (such as cover crops in some scenarios). For these, there may be little or no private financial incentive for adoption even if costs are highly subsidized.

Additionally, a potential barrier to more rapid progress is the lack of timelines associated with interim targets in many of the DAPs. Governments plan to take actions that will increase BMP adoption, and some have specific targets. For example, the Ohio DAP 2020 includes a listing of targets for each 12-digit HU watershed in the Maumee River basin, the Michigan Adaptive Management Plan lists actions and milestones for multiple projects and programs, and the US Lake Erie Action Plan references doubling the number of areas under conservation in the western Lake Erie basin through USDA programs. However, target dates for achieving some objectives are often lacking. While we recognize this is a complex problem, it is difficult to assign accountability for realizing planned outcomes and difficult to assess progress associated with a plan without specific deadlines. Concerning BMP implementation, the Chesapeake Bay TMDL could again offer lessons, in the form of a verification framework to support implementation, tracking, verification and reporting of BMPs in the watershed (Chesapeake Bay Program 2014).

3.0 Synthesis of Findings for Lake Ontario

As discussed in the Introduction, nutrient-related challenges for Lake Ontario are substantially different from those facing Lake Erie. In contrast to Lake Erie where several problems (in particular HABs, central basin hypoxia and eastern basin nuisance algae) are all associated with excessive nutrients in Lake Ontario, the main problems are excessive nutrients and associated impacts in some nearshore areas, and low nutrient levels and impacts in offshore waters. As noted in LimnoTech (2022), given these differences, including differences in scientific understanding and management implications, different approaches may be required to address the challenges, though a number of lessons from Lake Erie may be applicable.

Here we briefly discuss the results of this assessment for Lake Ontario, addressing the current situation concerning nutrients and impacts in the lake, Commission nutrient recommendations, a review of recent nutrients research relevant to the lake, a brief review of programs in place, and a summary of progress and barriers preventing more progress addressing nutrient-related problems in Lake Ontario.

3.1 Overview of the state of nutrients and impacts in Lake Ontario

As is the case for any water body affected by either excessive or low nutrient levels, having solid information on nutrient loads for Lake Ontario is important in understanding the system and making management decisions. Nevertheless, the nutrient loading picture for Lake Ontario appears to be more uncertain than that for Lake Erie. One source of information is the most recent Lake Ontario Lakewide Action and Management Plan (LAMP) report (ECCC and USEPA, 2018).[1] Based on the report, approximately 10 percent of phosphorus loads were from municipal and industrial wastewater discharges, 33 percent from tributaries and other nonpoint sources and 57 percent from the Niagara River (and hence mostly upstream sources in the Lake Erie watershed) (ECCC and USEPA, 2018).

There are ongoing questions about the relative contribution of Niagara River phosphorus loads to Lake Ontario; the most recent Progress Report of the Parties noted that phosphorus loads from Lake Erie via the Niagara River "are much higher than previously estimated, account for a significant portion of phosphorus loading to Lake Ontario and, in some years, exceed the 7,000 metric tonnes per annum Lake Ontario target" (ECCC and USEPA, 2022c).

The LAMP report also notes that *Cladophora* blooms re-emerged in Lake Ontario in the 1990s resulting in shoreline and beach fouling, water intake clogging and impacts to property values. This re-emergence is associated with the impact of invasive zebra and quagga mussels, likely

[1] As is the case with other LAMPs, the purpose of the Lake Ontario LAMP is to summarize the current state of Lake Ontario in relation to the nine General Objectives of the GLWQA and point out key threats; to outline actions that will be taken to address the threats and contribute to restoration and protection of water quality in Lake Ontario; and to engage all groups and individuals in the Lake Ontario basin to take action in protecting the water quality in Lake Ontario.

contributing to excess nearshore nutrient concentrations (and additional light penetration) as discussed above. Other impacts noted in the LAMP report include a re-emergence since 2008 of HABs in some embayments, and continuing issues with low offshore phosphorous concentrations, with implications for the lower food web and productivity of the fishery (ECCC and USEPA, 2018).

Ongoing nutrient-related issues were highlighted in the most recent State of the Great Lakes report. The State of the Great Lakes 2022 report noted that nutrient-related conditions in Lake Ontario vary from *fair* and *unchanging* for nutrients in lakes, to *good* and *unchanging* for HABs, to *poor* and *undetermined* for *Cladophora* (ECCC and USEPA, 2022a.) Of note for Lake Ontario, the long-term trend (1970-2019) for nutrients is *deteriorating*, in particular due to low offshore nutrient levels that may be too low to support a more robust food web and healthy fishery. Indeed, concerning the offshore total phosphorus concentrations, even the upper 5th percentile of values in a given year have mostly been below the Agreement interim total phosphorus objective of 10 µg/L (ECCC and USEPA, 2022b).

HABs are not as common in Lake Ontario as in Lake Erie because of its depth, bathymetry and lower temperatures, but they have occurred in Hamilton Harbour and the Bay of Quinte. In contrast, nuisance levels of *Cladophora* are more common in Lake Ontario, including in sites both near nutrient sources and in more remote locations (in some cases influenced by upwelling), with a pattern of resurgence of the problem over the past two decades (e.g., Hui et al. 2021a). At the same time, spatial and temporal variability in *Cladophora* biomass, coupled with the lack of systematic long-term monitoring has made trend assessment challenging. In addition, there have been challenges in relating *Cladophora* biomass to patterns of phosphorus loadings (ECCC and USEPA, 2022b).

3.2 Summary and synthesis of Commission recommendations for Lake Ontario

As discussed in **Section 2.2**, Commission reports over the past decade addressing nutrients in the Great Lakes are summarized in Table 1. As noted in that section, the emphasis of these Commission nutrient-related recommendations has generally been on issues related to eutrophication and/or Lake Erie. Key recommendations from the reports utilized in the contractor assessment of the extent of reference or adoption in DAPs are identified in the fourth column of the table. While recommendations cut across a wide range of issues related to nutrients in the Great Lakes, there is an emphasis on managing and better understanding the causes and impacts of excessive nutrient loads, in particular to Lake Erie. It is important to note, as discussed in the previous section, that one nutrient-related challenge in Lake Ontario is nearshore eutrophication and impacts, and hence some of the more general Commission eutrophication-related recommendations would have relevance to Lake Ontario.

The Commission report with arguably the most relevance to nutrient-related challenges in Lake Ontario is the report on declining offshore productivity in Lakes Michigan, Huron and Ontario

(International Joint Commission Great Lakes Science Advisory Board 2020). Key recommendations in the report include the following:

- The Great Lakes Executive Committee should explore and implement opportunities and capacities for cooperative application of ecosystem forecasting science addressing nutrient and fisheries management in the Great Lakes.
- The Great Lakes Executive Committee should engage and partner with state and provincial fisheries and environmental agencies as well as other national and binational agencies involved with monitoring and managing Great Lakes aquatic resources.
- The Parties should form (within two years) a multiagency Cooperative Ecosystem Monitoring and Modeling Advisory Committee that should use the Annex 4 assessment on Lake Ontario as a testbed for integrating and instituting coordinated data/information management.
- Outcomes from this work should be shared concerning progress on measures, analysis and outcomes at annual Lake Committee meetings hosted by the Great Lakes Fishery Commission.
- Further reporting should include successes in connecting and adapting nutrient-related actions to fishery management through effective information flow and decision support, modeling and forecasting after the next two consecutive five-year Cooperative Science and Monitoring Initiative cycles (LimnoTech 2022).

Most of these recommendations fall in science or institutional science categories and indicate the importance of advancing understanding of the complicated nutrient-related issues in Lake Ontario to aid in making management decisions. Some recent research efforts addressing Lake Ontario nutrient issues are summarized in **Section 3.3**, and consideration of current programs in light of these Commission recommendations is discussed in **Section 3.4**.

3.3 Literature review: key recent findings on nutrients and Lake Ontario

Consistent with the general emphasis of this project on Lake Erie and a general pattern of more nutrient-related research on Lake Erie than Lake Ontario, the technical report review found fewer papers involving Lake Ontario. However, it should be noted that much research involving nutrient science (including sources, cycling and impacts) with a focus on Lake Erie can have implications for Lake Ontario as well. Key findings from recent research focused on Lake Ontario are summarized here (drawing on LimnoTech 2022).

While research on nutrient dynamics in watersheds has been more extensive in Lake Erie, some efforts have been carried out in the Lake Ontario watershed over the past decade, including regarding siting of BMPs to reduce nutrient loadings (reviewed in LimnoTech 2022). There has been increasing modeling work in Lake Ontario, including to understand *Cladophora* dynamics One recent modeling paper found that although the Niagara River is the major contributor of phosphorus loads to Lake Ontario, loads from smaller tributaries can still have localized impacts on concentrations (Pauer et al. 2022), similar to findings from Howell (2018). A recent whole-lake model has been used to model phosphorus loadings from the Niagara River and other tributaries, upwelling and impacts from invasive dreissenid (zebra and quagga) mussels (Hui et al. 2021b; reviewed in LimnoTech 2022).

The presence and impacts of dreissenid mussels in Lake Ontario (and implications for nutrient cycling) continues to be an important area of research. Recent research has indicated complexities of dreissenid growth in Lake Ontario with, for example, declining densities but increasing biomass at 31-90m depths in recent years (reviewed in LimnoTech 2022).

In spite of a significant amount of recent research on nutrients in Lake Ontario, uncertainties remain. As noted in **Section 3.1**, one important uncertainty concerns the magnitude of phosphorus loadings from the Niagara River, with more recent estimates from ECCC over twice those of earlier estimates. Part of the issue relates to concentration variability within the river, with implications for load calculations to the lake (LimnoTech 2022). A number of other uncertainties concern phosphorus dynamics within the lake, including the fate of phosphorus from the Niagara plume (including how quickly it may be flushed from the lake), changes in dreissenid abundance and implications for nutrient cycling, and physical dynamics including the implications of stratification and upwelling concerning delivery of nutrients to the north shore (reviewed in LimnoTech 2022). These uncertainties are all related to broader nutrient management challenges for the lake, including how to address nearshore impacts of excessive nutrients while addressing (or at least not exacerbating) offshore fishery challenges related to low nutrient levels (LimnoTech 2022).

3.4 Synthesis and review of programs in place and assessment of progress

Although management work involving nutrients in Lake Ontario has been ongoing (e.g., ECCC and USEPA, 2022c, 2018), given ongoing questions about nutrient sources, dynamics and impacts of nutrients in Lake Ontario, much of the emphasis by the Parties and in this review is on science issues, including research and monitoring programs, as briefly described here.

The US Great Lakes Restoration Initiative has supported various research projects in the New York portion of the Lake Ontario watershed. A project database from USEPA[2] indicates that from 2010-2022, 21 projects under Focus Area 3 coordinated by USEPA were carried out in New York state (with some additional projects in multiple states), though it should be noted that the focus of most projects was microbial contamination of beaches, green infrastructure and wetland restoration, and not necessarily nutrient reduction. Additional USDA Natural Resources Conservation Service projects have been funded in New York state, including multiple phosphorus reduction projects on the Genesee River (ECCC and USEPA, 2022c.) On the Canadian side, it is not clear to what extent research and related work focused on nutrients in

[2] The US Great Lakes Restoration Initiative project database can be accessed at: glri.us/projects.

Lake Ontario has been supported through the Great Lakes Protection Initiative (Government of Canada 2022).

The Cooperative Science and Monitoring Initiative involves intensive research and monitoring projects focused on a specific Great Lake each year. The most recent effort addresses Lake Ontario for the 2018 field year, and results have recently been published (Furgal and Collingsworth, n.d.; Watkins et al. 2022 and accompanying papers). Research priorities for the 2018 Cooperative Science and Monitoring Initiative included understanding the magnitude and fate of nutrient loading and understanding nearshore dynamics causing *Cladophora* blooms (Watkins et al. 2022).

Other research involving nutrients have been underway in Lake Ontario over the past five years, including a study commissioned by ECCC finding CDN$522 million (US$385 million) in costs to the economy associated with *Cladophora* and cyanobacterial blooms. The recent Progress Report of the Parties also briefly notes work has been underway in New York addressing wastewater treatment, green infrastructure and source water protection (ECCC and USEPA, 2022c). The most recent Lake Ontario LAMP report called for research on nutrient dynamics in Lake Ontario and its watershed, the monitoring of *Cladophora* growth in nearshore areas and tributary nutrient loads, and assessment of waters under a nearshore framework (called for under the 2012 Agreement) (ECCC and USEPA, 2018).

There are multiple monitoring programs addressing nutrients in Lake Ontario, including the long-term ECCC program noted above which has included monitoring of phosphorus and other water quality parameters in the Niagara River. This recent review of data indicates total phosphorus concentrations at Niagara-on-the-Lake increased over the period 1975-2018, although varying patterns were observed within the period, e.g., a rapid increase from 1985-1995, and a general decline from 2005-2018 (Hill and Dove, 2021). Monitoring of nutrient loads to Lake Ontario has been carried out on the United States side by the US Geological Survey, including through a program begun in 2011 covering 30 Great Lakes tributaries, including the Genesee River and Oswego River draining into Lake Ontario (Robertson et al. 2018). Other monitoring programs at the state and provincial levels address nutrients in Lake Ontario (ECCC and USEPA, 2018).

In addition to highlighting research and monitoring developments in recent years, the most recent Progress Report of the Parties identifies policy and management efforts that have occurred or that are in development. An important development has been the initiation of the process to review nutrient concentration and loading targets to meet lake ecosystem objectives for Lake Ontario (ECCC and USEPA, 2022c). The Progress Report of the Parties report also notes other programs addressing nutrient loadings in the Lake Ontario watershed, including wetlands conservation through the Ontario Wetlands Conservation Partner Program, and green infrastructure and other techniques for addressing nutrient loads in the New York portion of the watershed (ECCC and USEPA, 2022c).

In addition to reporting via the Progress Report of the Parties, reporting on nutrient-related issues in Lake Ontario is also carried out through the periodic LAMP and State of the Great Lakes reports, as well as via individual studies in the peer-reviewed literature. However, to date, there is no centralized reporting site similar to ErieStat for Lake Ontario, although some documents are made available through binational.net.

3.5 Summary of progress addressing Lake Ontario nutrient-related problems

Given the lack of domestic action plans for Lake Ontario and a more limited set of Commission recommendations, the LimnoTech (2022) technical report focused on a qualitative assessment of specific issues. The assessment noted that both the Lake Ontario LAMP (ECCC and USEPA, 2018) and the Niagara River Watershed Management Plan addressed most of the relevant issues with the notable exception of manure management. The LimnoTech 2022 technical report noted the importance of developing concentration and loading targets for Lake Ontario, and increasing research, monitoring and related work that can support target development and subsequent implementation work, including work to address the twin challenges of excessive nearshore nutrient concentrations and low offshore concentrations (LimnoTech 2022).

Concerning the status of Commission recommendations and implementation to date in Lake Ontario, the LimnoTech 2022 technical report noted mixed progress. As indicated in Table 1, for the Commission's Great Lakes Science Advisory Board report on declining productivity that is most relevant to Lake Ontario nutrient issues (International Joint Commission Great Lakes Science Advisory Board 2020b), only "little" progress has been made by the Parties in addressing recommendations (LimnoTech 2022). As noted in the LimnoTech 2022 report, much of the reason for the "little" progress made addressing Lake Ontario nutrient issues is that only a short time has passed since release of that Commission Great Lakes Science Advisory Board report. At the same time, some efforts have been underway. For example, the Great Lakes Fishery Commission Committee meetings have reported on measures and outcomes and increasing coordination to link nutrient-related actions to fishery management decisions. Furthermore, discussions are underway within the Agreement Annex 4 Lake Ontario Task Team on an assessment of interim substance objectives and potential next steps (J. Vincent, personal comm.). In addition, the Annex 10 Ecosystem Indicators and Reporting Task Team is also discussing next steps concerning nutrients in Lake Ontario (LimnoTech 2022, Appendix A).

The LimnoTech 2022 technical report emphasizes certain gaps needing to be addressed in order to advance work related to managing nutrients in Lake Ontario. Some knowledge gaps apply to both Lake Erie and Lake Ontario, such as more detailed data on BMP implementation in agricultural watersheds, approaches to incentivize BMP adoption, higher resolution data on *Cladophora* presence in nearshore areas, and a better understanding winter limnology and implications for nutrient cycling. A key issue to address is the uncertainty around balancing impacts of addressing nearshore eutrophic conditions as well as offshore oligotrophic conditions (LimnoTech 2022). One management issue worth noting on the United States side is the fact the New York (and hence the US portion of the watershed) is within USEPA Region 2 rather than Region 5, requiring additional coordination concerning federal agency staff involved in Lake Ontario management.

The LimnoTech 2022 technical report notes the significant differences between Lake Ontario and Lake Erie, including those concerning nutrients and impacts. Nevertheless, the report indicates a short-term goal should be to advance knowledge in Lake Ontario through research, monitoring, and modeling so that appropriate management action commitments (and initial implementation) can be made by 2025 (LimnoTech 2022).

Finally, there are potentially lessons from Traditional Ecological Knowledge involving Indigenous practices and projects addressing water quality concerns that may be relevant to both Lake Ontario and Lake Erie (e.g., Koski et al. 2021). A current project of the Commission's Great Lakes Science Advisory Board-Science Priority Committee is exploring approaches to better integrate Traditional Ecological Knowledge and western science practices in understanding and addressing various Great Lakes issues (International Joint Commission Great Lakes Science Advisory Board 2022).

4.0 Recommendations

The assessment in this report has found that progress has been made in many areas of federal, state, and provincial programs addressing nutrient-related problems in Lake Erie and Lake Ontario. While recognizing that implementation of DAPs has only been underway for several years, it is also important to emphasize that nutrient-related impacts in the lakes have been present for many years, and there will be a need for more aggressive programs if the reduction targets with near-term deadlines are to be met, such as the 40 percent reduction in total and dissolved reactive phosphorus to western Lake Erie by 2025 identified in the Western Basin of Lake Erie Collaborative Agreement. We offer specific recommendations on approaches to address limitations in DAPs and programs for addressing nutrient-related problems, with an emphasis on recommendations over the short-term for consideration in developing the 2023 DAPs). In the recommendations below, it is assumed that work by the Parties will continue to be coordinated by ECCC and the USEPA.

Given the different nature of the nutrient-related problems in Lake Erie and Lake Ontario, as emphasized on multiple occasions in this report, our recommendations are distinct for the two lakes (though in many cases recommendations would apply to nutrient-related issues in all of the lakes). In addition, following the approach in the Progress Report of the Parties, the recommendations are split into action and science topics. The following recommendations draw on the technical report supporting this project (LimnoTech 2022), previous Commission reports as reviewed in this report, and our identification of needs based on this assessment.

4.1 Recommendations for Lake Erie

The following four action-related and three science-related recommendations are proposed for Lake Erie.

Action-related recommendations

1. **The Parties should work with state, provincial, First Nations, Métis and Tribal governments, and agricultural and nongovernmental partners and stakeholders to incorporate an accountability framework into work under Annex 4 by 2024 that includes reporting on and evaluating progress on Lake Erie nutrients.**

An accountability framework should increase the transparency of the overall process of addressing phosphorus loads to Lake Erie for all Lake Erie water quality stakeholders. The accountability framework, which could be a concise summary of relevant components and actions, should include specific reference to the eight priority river/watershed systems identified by the Parties for phosphorus load reductions (Great Lakes Water Quality Agreement Nutrients Annex Subcommittee 2019). The framework should address all relevant program aspects, including interim targets and timelines, a process for identification and implementation of priority BMPs, roles and responsibilities (including those of agencies and associations), funding needs and commitments, and monitoring and reporting components, all in support of documenting progress in subwatersheds tied into overall load reduction objectives.

The framework should be positioned to best advance progress on overall Lake Erie targets, including through formal incorporation in the adaptive management framework under development by the Parties. The accountability framework should include formal reporting and evaluation of progress (including through increased use of indicators, as noted in the fourth recommendation below), with initial reporting done through the 2025 Progress Report of the Parties and in subsequent progress reports and other avenues as appropriate. The Parties should consider other approaches to ensuring accountability in nonpoint source reduction programs including, for example, through the use of a TMDL-type effort such as the one which has been implemented in Chesapeake Bay for over a decade, and which includes an accountability framework, as noted in **Section 2.4** above (USEPA 2021b).

2. **The Parties should work with state, provincial, First Nations, Métis and Tribal governments, and agricultural and nongovernmental partners and stakeholders to ensure that the 2023 DAPs contain a framework for developing adoption targets for BMPs for the western and central basin watersheds of Lake Erie, and ensure resources are available to increase BMP implementation efforts over the 2023-2025 triennial period.**

In order to meet phosphorus load reduction targets for Lake Erie, aggressive programs in the watershed will be necessary, and establishing a framework for developing BMP targets (e.g., over a triennial cycle) and providing some assurance of implementation will increase the likelihood of success. The Parties, along with states, provincial, First Nations, Métis and Tribal governments, and agricultural and nongovernmental partners should emphasize BMPs that, based on current information, appear to be particularly effective (e.g., subsurface fertilizer placement, fertilizer rate (source) reduction, riparian buffers, and potentially cover crops), use region-specific guidance as appropriate (as noted in **Section 2.6**), and continue to support new research into effectiveness of BMPs, in particular aggregated at the subwatershed scale and larger. This work should draw and build on extensive ongoing work by federal, state, academic, agriculture, and other stakeholders researching and monitoring the effectiveness of BMPs in the western Lake Erie basin.

As part of these efforts to establish a framework for developing BMP targets, it will be important to better track and report at various scales on BMP implementation (e.g., as part of indicator reporting, as noted in Recommendation 4 below). The framework could include a structure where BMP adoption targets are increased periodically (e.g., increasing percentage of acres covered by specific practices in specific subwatersheds thought to be particularly significant phosphorus contributors) while tracking progress in meeting percent phosphorus load reduction targets by specific years (e.g., 2030, as suggested in LimnoTech 2022). The Parties and partners noted here will need to ensure adequate resources are available (e.g., through cost-share programs) and coordinate with non-agency programs (e.g., the 4R Nutrient Stewardship program) to optimize adoption rates, while tracking progress (Recommendation 4).

3. **The Parties should work with state, provincial, First Nations, Métis and Tribal governments, and agricultural and nongovernmental partners and stakeholders in developing and implementing a common framework for assembling, analyzing and making publicly available more comprehensive information on generation and application of manure and commercial fertilizer, and associated phosphorus and other nutrients, at appropriate scales within the western Lake Erie basin, and consider such information in developing any new management regimes for both broad nutrient sources.**

As reviewed in **Section 2** and in several recent Commission-related reports (e.g., International Joint Commission 2018; International Joint Commission Great Lakes Water Quality Board 2019, 2020; LimnoTech 2017), there are both spatial and temporal resolution limitations in reporting on application of phosphorus fertilizers to fields in the western Lake Erie basin. The five-year agricultural censuses have the potential to capture all fertilizer generated or applied, but privacy restrictions often mean some information is withheld, including at the county scale. Surveys can provide information with increased temporal resolution, although it is important that spatial resolution be adequate in order to link application changes to water quality changes. In both cases, the lack of availability of more highly resolved data limits the potential effectiveness of modeling to understand the system. The Parties (and other agencies) should work within existing authorities to consider options to increase the temporal and spatial resolution of data collected, analyzed, and made available, including potentially data at 10- and 12-digit HU levels in the United States (and equivalent in Canada), if such reporting can comply with privacy limitations.

Concerning manure, the Parties should consider approaches to filling information gaps identified through the Commission's Great Lakes Water Quality Board Manure Management project (Arvai 2022). A formal multi-organization collaborative could help identify approaches to collecting, analyzing and making available manure management data, including data on the ultimate fate of manure (and its phosphorus) in distribution and utilization. The Parties could consider development of a similar collaborative, involving agricultural associations, agencies, academic researchers and nongovernmental organizations, to increase availability of commercial fertilizer application data at scales fine enough to be helpful in linking application changes to water quality changes, including in 12-digit HUs and in larger watersheds. Furthermore, the Parties should consider other approaches to increasing availability of information on commercial fertilizer and manure, including under existing right-to-know statutes.

Finally, the Parties, states, and provincial governments should utilize the additional information obtained from implementing these recommended actions to consider additional approaches to managing (including regulating) manure and commercial fertilizer.

4. **The Parties should, within two years, work with states, provincial, Tribal, First Nations and Métis governments, and agricultural and nongovernment partners and stakeholders to develop and/or revisit indicators needed for tracking progress in reducing nutrient loads and improving Lake Erie conditions, including an entire suite of driver, pressure, state, impacts and management-response indicators, and improve indicator communication.**

The presence of comprehensive indicators is essential in documenting progress and utilizing an accountability framework in addressing any environmental problem. In a driver-pressure-state-impacts-response-framework context, current indicator reporting focuses on pressure (e.g., nutrient loads) and state or impacts indicators (e.g., eutrophication and extent of HABs in the western Lake Erie basin), but provides less emphasis on management-response indicators. Reporting on nutrient loads (through ErieStat) is helpful, but tracking and reporting at more refined levels (e.g., 10- or 12-digit HUs) could provide even greater benefits. Concerning indicators in the lake, the Parties should revisit sub-indicators for HABs, and consider use of the NOAA cyanobacterial severity index (or develop a similar science-based index) to track trends in Lake Erie HABs, rather than rely only on the maximum areal extent of HABs in a given season as the indicator. The Parties should also develop a sub-indicator on central basin hypoxia, drawing on extensive monitoring work over decades by USEPA and recent research.

Concerning management-response indicators, there is a clear need to track and report BMP implementation rates at as fine a scale as is feasible, including tracking type, locations, extent and changes with time. Furthermore, there is a clear need to better track manure generation and application at fine scales in the western Lake Erie basin (akin to a driver indicator), which more systematic efforts as outlined in the previous recommendation could help address. These driver and management response sub-indicators could be coupled with other information (e.g., on phosphorus loads, including dissolved reactive phosphorus loads) to help assess the environmental outcomes of these actions (also addressed in Recommendation 7 below).

The Parties should also work to improve indicator reporting, which could include involving more stakeholders in indicator development/revision (increasing the likelihood of broader interest in the system responses), and report more regularly through existing venues, such as ErieStat and the Agreement implementation website (binational.net), while drawing on examples from other efforts, such as the Chesapeake Bay experience (chesapeakeprogress.com).

Science-related recommendations

5. **The Parties should reduce the barriers to voluntary adoption of effective BMPs by undertaking—and completing an initial round by 2025—studies to assess the on-farm costs, benefits and communication barriers to adoption of the BMPs most likely to result in more widespread phosphorus reductions (e.g., subsurface fertilizer placement, fertilizer rate reduction, riparian buffers and potentially cover crops). Ongoing and new research findings, including on the impacts of BMPs on water quality objectives (Recommendation 7), should be synthesized and communicated, including via peer-to-peer communication networks among farmers.**

As noted in **Section 2.3**, research indicates that financial factors are the most critical barrier to voluntary adoption of BMPs by farmers. While this report recommends (see Recommendation 6) that the Parties investigate alternatives to voluntary programs, we also recommend that the Parties investigate the barriers that exist with current programs. Evaluating the on-farm benefits, costs and risks of implementing specific BMPs known to be effective at reducing nutrient exports will shed light on the relative incentives or disincentives facing farmers. Examining on-farm benefits should include, to the extent practical, benefits to soil health of particular BMPs (e.g., Zimnicki et al. 2020). The knowledge and data generated from these investigations will provide information that can be communicated to the farming community and, at the same time, will provide insight into the likely long-term feasibility of voluntary programs to achieve nutrient reduction goals.

At the same time, **Section 2.3** notes the importance farmers place on believing actions will result in environmental benefits (LimnoTech 2022; Liu et. al. 2020; Wilson et al. 2019; Wilson et al. 2018). There is also recognition amongst many of the value of peer-to-peer communication between farmers in considering implementation of specific practices, as noted in the Canada-Ontario DAP (ECCC and Ontario Ministry of Environment, Conservation and Parks, 2018). The Parties should work with all relevant stakeholders (including through the 4R Nutrient Stewardship program) to promote collaborations that can increase BMP adoption rates.

6. **The Parties should set a goal in the 2023 DAPs to undertake a study to examine the feasibility of the group-level economic instrument outlined in Section 2.3 of this report for reducing nonpoint source nutrient loadings in the western Lake Erie basin. The Parties should direct their relevant agencies to fund and support such a study (or studies) and report on results in the 2025 Progress Report of the Parties.**

Continued reliance on voluntary measures alone may not result in the level of BMP adoption that is needed to meet nutrient loading targets to the western Lake Erie basin from nonpoint sources (International Joint Commission 2017). Moreover, the effectiveness of voluntary programs is likely to experience diminishing returns as the opportunities for the least costly BMPs to be adopted become exhausted. The remaining high-cost BMPs (such as grassed waterways or blind inlets) are not likely in some cases to lead to sufficient on-farm benefits to justify the cost to farmers without substantially more favorable cost-sharing arrangements.

Therefore, the Parties should investigate an alternative approach such as the group-level economic instrument outlined in **Section 2.3**. This instrument can be thought of as a TMDL program supplemented with incentives and enforceability. By rewarding groups that exceed their allocated reductions of nutrient loadings and penalizing excessive group-level loadings, this instrument gives farmers the incentives and the flexibility to adopt cost-effective solutions that are tailored to their specific farming conditions. In this initial exploratory stage, the scope of the study could be limited to examining feasibility and practical considerations. These should include, for example, options for defining and populating groups, determining the associated group shares of phosphorus loadings, considering options for phasing in the allocated shares, payment and fee rates, and implementation with and without a continuation of cost-sharing arrangements for BMPs. The study should be completed in time for reporting in the 2025 Progress Report of the Parties.

7. **The Parties should set a goal in the 2023 DAPs to undertake and/or fund and facilitate new research to advance understanding of the effectiveness of specific BMPs and combinations of BMPs at achieving water quality improvements. As outlined in this report, research should include:**

1. **Edge-of-field studies that measure nutrient export at the field level and variation with BMP implementation and other measures;**
2. **Integrated assessment models that link economic models of farmers' phosphorus-related management practices to biophysical models of the resulting changes in nutrient loadings; and**
3. **Empirical studies that link nutrient concentration data (and other water quality measures) at the watershed or subwatershed level (e.g., 10 or 12 digit HU scale in the United States) with BMP adoption data in the same regions.**

As reviewed in the technical report and noted in **Section 2.3**, there has been increasing research on the effectiveness of different BMPs at reducing phosphorus export from agricultural fields. While certain BMPs appear to be relatively effective at reducing phosphorus losses more generally (e.g., subsurface fertilizer application as noted in LimnoTech 2022), further work at the edge-of-field level is needed across a broader range of field conditions. Such research should also address the benefits of multiple practices.

In addition, the Parties should support the development of integrated assessment models, such as Lupi et. al. (2020) and Liu et. al. (2020) which are reviewed in **Section 2.3**, for key watersheds of the western Lake Erie basin. This type of model helps develop a comprehensive understanding of how policy actions affect the phosphorus-related management practices of farmers and, in turn, the resulting impact on nutrient loadings at the watershed level.

Finally, empirical research that links water quality data at the local or subwatershed scale to past and current BMP adoption practice data at the same scale, using a methodology such as Liu et. al. (2022), also summarized in **Section 2.3** of this report, will shed light on the relationship between BMP adoption rates on actual water quality outcomes in order to provide additional data to guide future management actions.

4.2 Recommendations for Lake Ontario

The following action-related and science-related recommendations are proposed for Lake Ontario.

Action-related recommendation

1. **The Parties should develop and make publicly available a process and timeline for reviewing nutrient objectives and targets for Lake Ontario, revise as appropriate based on a comprehensive review of the science, and identify potential no regrets nutrient reduction actions for nearshore areas.**

The Parties note in the most recent Progress Report of the Parties that they have initiated a process to review nutrient targets for Lake Ontario, a positive development. The 2012

Agreement notes the Parties should review interim substance objectives and loading targets for phosphorus for the open waters of each lake, as well as substance objectives and loading targets for nearshore waters (Canada and the United States, 2012), tasks particularly relevant for Lake Ontario given the different nutrient-related challenges. The Parties should lay out a process and timeline for reviewing objectives and targets in the 2023 DAP, with subsequent revisions as appropriate, while working within an adaptive management framework and drawing on lessons learned in developing the Lake Erie Adaptive Management Framework. The process should also incorporate steps in the identification and implementation of research and assessment work that will be particularly helpful in developing new objectives and targets.

Parallel with developing revised nutrient objectives and targets, the Parties, states, province, and Tribes, First Nations and Métis governments, and agricultural and nongovernmental partners and stakeholders should consider opportunities to implement no regrets actions to reduce nutrient loads in selected nearshore areas subject to HABs or *Cladophora*. Such actions have been identified previously by the Commission as "measures that would be justified under all plausible future scenarios" (International Joint Commission 2011). In usage here, we are also intending to identify actions with limited likelihood of further exacerbating offshore oligotrophication problems.

Science-related recommendation

2. **By 2024, the Parties should identify the best approach to improving science and management of nutrients and related issues in Lake Ontario, whether through existing Annex 4 processes or through a new, multistakeholder committee.**

Given the complexities of nutrient cycling and broader implications in Lake Ontario, it is important that a strategic approach (through a committee) be in place to help identify and direct research, assessment, and monitoring work in support of sound management decisions. It is possible such work could be carried out by an existing Annex 4 committee, though it is important that broader issues and stakeholders (e.g., involving fisheries) be incorporated in these deliberations. The other option to address these broader issues could take the form of a Cooperative Ecosystem Monitoring and Modeling Advisory Committee of the type recommended in the recent Commission's Great Lakes Science Advisory Board declining offshore productivity report (International Joint Commission Great Lakes Science Advisory Board 2020).

Work of the committee would include reviewing ecosystem forecasting science, with an initial emphasis on improving understanding of Lake Ontario, including the benefits and trade-offs of nutrient management actions. This committee could either encompass or work closely with individuals involved in a Lake Ontario adaptive management framework team to ensure Lake Ontario science activities are best informing management actions as noted in the previous recommendation, and continuing to inform as new understanding emerges. The committee could build on recent research efforts and review work (e.g., International Joint Commission Great Lakes Science Advisory Board 2020a) in identifying priority actions to carry out in its first several years.

5.0 Conclusions

In the fifty years since the Great Lakes Water Quality Agreement was first signed, there has been progress in addressing many threats to the Great Lakes. Excessive nutrients and the resulting impacts were a significant motivating factor in the development of the original Agreement, and through the Agreement, federal and other programs, nutrient loads to the lakes were reduced in subsequent years primarily from point sources.

Fifty years later, we are seeing a resurgence of problems related to excessive nutrients in Lake Erie and nearshore areas of the other lakes, and problems with nutrient depletion in offshore waters for Lakes Ontario, Michigan and Huron, and the eastern Lake Erie basin. In some cases, the problems are manifest slightly differently, for example, with one group of cyanobacteria (*Microcystis*) becoming more dominant in HABs in recent decades (e.g., Watson et al. 2016).

The revised 2012 Agreement and resulting programs, in particular through DAPs, offer the opportunity to address these problems in a comprehensive manner. Multiple Commission reports over the past decade have identified gaps and offered policy and science recommendations across a wide range of topics in support of efforts to reduce nutrient-related problems in Lake Erie and Lake Ontario. Addressing these problems requires comprehensive efforts aimed at reducing agricultural runoff to the western Lake Erie basin and a better understanding and managing of nutrients in Lake Ontario to meet the twin objectives of reducing nearshore eutrophication and offshore oligotrophication.

While there has been progress through the decades on both policy and science aspects of excessive nutrients, including in Lake Erie, this report's assessment found areas for improvement, including increasing the adoption of best management practices on agricultural fields, having more comprehensive information on both manure and commercial fertilizer phosphorus, better tracking and reporting on progress, optimizing use of adaptive management, increasing accountability, and carrying out necessary natural and social science research to better understand opportunities to address nutrient-related problems.

Lake Ontario and its nutrient-related problems are quite different from Lake Erie, but we note there remains a similar need to identify management actions that can be taken now while supporting the research and monitoring work (with the appropriate administrative structure) that can inform actions that can be taken in the short and medium term, including actions taken through an adaptive management process.

Going forward on these recommendations, it is important that the Commission play a role in this work. As noted in the Agreement, the Commission's responsibilities include providing advice as well as assistance on joint activities, advising on objectives for scientific activities, consulting with and raising the awareness of the public, and coordinating with other binational or international institutions to address Great Lakes water-quality issues.

Nutrient-related problems facing Lake Erie and Lake Ontario have been in the making for decades, and it will take a concerted effort by the Parties, states, provinces, First Nations, Métis and Tribal governments, the Commission, the agricultural sector, nongovernmental organizations, and the public to successfully tackle these problems and restore and protect Lake Erie and Lake Ontario.

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7.0 Appendices

7.1 Appendix A: Nutrients Synthesis work group assessment approach

The approach for carrying out the review and assessment work for this project entailed the following steps. The Nutrients Synthesis work group was developed in 2020 following planning work involving several International Joint Commission Science Advisory Board Science Priority Committee members and staff. The work group consisted of subject matter experts from within and outside Commission boards and Commission staff support, with project coordination carried out by the three co-leads of the work group (see Acknowledgments section). A contractor (LimnoTech) was selected to carry out much of the review, summary and assessment work. Key elements of this project included the following:

1. A review and summary of key findings and recommendations in eight IJC reports (insert dates) related to nutrient impairments in Lake Erie.

2. A review and summary of other relevant peer-reviewed literature published since these reports were issued addressing Lake Erie nutrient impairment.

3. An assessment of federal, state, and provincial domestic action plans and their implementation considering their adequacy to meet their objectives.

4. An identification of key issues from Lake Erie that can inform efforts to address nutrient impacts in Lake Ontario.

LimnoTech carried out work in support of the four elements above. Regular videoconference meetings of the work group were held, including to identify key issues, gaps and publications related to the key element as the research was underway and following progress reports. Videoconference meetings with LimnoTech were also held to discuss preliminary drafts of the technical report. In October 2021, we organized a virtual workshop—including additional expert involvement from outside the Work Group—for additional input on the technical report. Some details on input received at the workshop are provided in LimnoTech (2022).

Further revisions to the technical report were done in response to several iterations of review and comment involving the work group and/or co-leads, and the technical report was finalized in spring, 2022. Note this was before the Parties to the Agreement released the Progress Report of the Parties and the State of the Great Lakes 2022 reports (released in July 2022), though this report does reference content from those two reports.

Following receipt of the technical report, the co-leads developed this report, drawing heavily on the technical report while also carrying out additional review (e.g., newer literature) and assessment work. The process includes review by the full work group, the full Commission Science Advisory Board and Water Quality Board, and several external reviewers prior to finalization and submission to the Commissioners of the International Joint Commission.

The work group co-leads carried out an additional qualitative assessment of individual programs, where ten program areas were selected, drawing on the technical report (LimnoTech 2022), the DAPs, the Agreement, and broader understanding of programs addressing nutrients. We aimed to address multiple relevant program areas, recognizing the value of comprehensive programs providing water quality benefits, as has been seen in efforts to address nutrient loadings to the Gulf of Mexico through federally coordinated efforts (e.g., Salk et al. 2021). For the ten program areas utilized here, a qualitative score for each DAP was provided based on the criteria in Table A1 below.

Table A1. Rubric for qualitative assessment of extent Domestic Action Plans address particular program area.[1]

Program Area	Score	Criteria
Point Sources/ Regulatory	1	Minimal discussion on regulatory programs, in particular permitting programs
	2	Discussion of relevant regulatory programs, but limited elaboration on individual sectors
	3	Comprehensive treatment of regulatory programs, including all major sectors
Ag. Nonpoint Source/BMPs	1	Minimal discussion on ag BMPs, implementation
	2	Elaboration on ag BMPs, but limited in explanation of efforts to increase implementation
	3	Comprehensive discussion on ag BMPs, including approaches to increasing implementation
Ag. - Manure Management	1	Minimal discussion on manure management framework, details on implementation
	2	Elaboration on manure management framework, some details, but lack of attention to mid-size facilities
	3	Comprehensive manure management framework, including detailed approach to regulating or otherwise addressing mid-size and large facilities

Program Area	Score	Criteria
Watershed Plans, TMDLs*	1	Minimal discussion on watershed plans, regulatory programs (e.g., TMDLs)
	2	Discussion on watershed plans, but limited on regulatory programs (e.g., TMDLs)
	3	Comprehensive discussion on watershed plans, including regulatory programs (e.g., TMDLs)
Research Programs	1	Minimal discussion on research supported
	2	Discussion on general research programs, but limited details, including on watershed modeling
	3	Comprehensive discussion on research, including watershed modeling, social science research
Monitoring Programs	1	Minimal discussion on monitoring programs
	2	Discussion on monitoring, but limited details on forms, temporal, spatial scales
	3	Comprehensive discussion on monitoring, including multiple P forms, temporal, spatial extent
Human Health	1	Minimal discussion on human health concerns, including drinking water
	2	Discussion on human health, but limited on efforts involving drinking water, including treatment
	3	Comprehensive discussion on human health concerns, including in protecting drinking water quality
AM Framework	1	Minimal discussion on adaptive management
	2	Discussion on adaptive management, but limited on approaches to implementing
	3	Comprehensive discussion on adaptive management, including approaches to implementing

Program Area	Score	Criteria
Interim Targets/Deadlines	1	No or minimal discussion on interim targets and deadlines
	2	Discussion on interim targets and deadlines, but limited in scope
	3	Comprehensive discussion on interim targets and deadlines, including in scope
Tracking and Reporting	1	Minimal discussion on tracking and reporting progress
	2	Discussion on tracking and reporting, but few details on scope, time frame
	3	Comprehensive approach to tracking and reporting
Roles Delineated	1	Minimal discussion on roles of different agencies, industry/ag, private sector, NGOs
	2	Discussion on various partners, but limited elaboration on roles
	3	Comprehensive discussion on multiple partners and their roles
Funding Expenditures Available	1	Minimal information on resources directed to nutrients problems
	2	Discussion on resources directed to nutrients problems, but lacking details
	3	Comprehensive discussion on resources directed to nutrients problems, including details on various programs

1: Qualitative assessment provided as shadings for particular program areas by DAP jurisdiction in Table 3, where 1 indicates minimal if any attention to particular program (no shading), 2 indicates some attention, and 3 indicates relatively comprehensive coverage within a DAP.

References

LimnoTech, 2022. Synthesis of Recommendations and Assessment of Action to Reduce Great Lakes Nutrient Impacts. Prepared for: International Joint Commission Great Lakes Science Advisory Board and Water Quality Board Work Group on Nutrient Synthesis, March, 2022.

Salk, K. R., et al. 2020. The role of policy in social-ecological interactions of nitrogen management in the Mississippi River basin. Journal of Environmental Quality 49(2), 304-313.

7.2 Appendix B: Watershed terminology

Given the importance of processes on land affecting nutrient loads to Great Lakes waters, it is critical to have a clear understanding of the delineation of lands in the Great Lakes basin. This delineation is important in all aspects of the nutrient problem, including monitoring, modeling, and identifying and implementing management actions. A further complicating factor in the Great Lakes is the binational nature of the basin.

A watershed can be defined as a land area draining water to a particular stream, river or lake (usgs.gov/special-topics/water-science-school/science/water-science-glossary#W). A common approach for decades to delineate watersheds is through use of nested hydrologic units, whereby smaller land areas related hydrologically are aggregated to larger units constituting a larger hydrological basin. The current approach in the United States through the Watershed Boundary Dataset (WBD) involves use of hydrologic unit (HU) names and unit codes, starting with two digits and adding two digits for each finer scale drainage area (Jones et al., 2022). Examples of the system as applied in the western Lake Erie basin are provided in Table B1.

Table B1. Hydrologic Units in United States Watershed Boundary Dataset[1]

Hydrologic Unit Name	Example Hydrologic Unit Code	Watershed/Region Name	Recommended Size Range (acres)
2 digit	04	Great Lakes	
4 digit	0410	Western Lake Erie Subregion	
6 digit	041000	Western Lake Erie	
8 digit	04100011	Sandusky River	
10 digit	0410001106	Honey Creek	40,000 – 250,000
12 digit	041000110601	Broken Knife Creek	10,000 – 40,000

[1]: Hydrologic unit name, recommended size ranges from Jones et al. 2022. Example hydrologic unit codes and watershed/region names from ODNR, 2018 and USDA, 2017. Note the WBD system also includes two optional finer units (14 and 16 digit), although such delineations have mostly not been completed.

The WBD until recently included general terms for hydrologic unit levels, including *watershed* for the 10-digit HU, and *subwatershed* for the 12-digit HU. Currently, the WBD convention is to simply reference the number of digits – e.g., a 10-digit HU (Jones et al. 2022).

Ontario has developed its own hydrographic system, which involves nested units similar to the US WBD. Starting from the largest area are primary, secondary, and tertiary hydrologic units, generally corresponding to other categories used nationally by Natural Resources Canada. Then there are three finer scale units which have entailed coordination with the United States--quaternary, fifth level, and sixth level, which correspond with 10-digit, 12-digit, and 14-digit HUs in the US WBD, respectively. As in the United States for 14-digit HUs, very few sixth level hydrologic units have been delineated in Ontario (Ontario Ministry of Natural Resources and Forestry 2022).

One important issue in working with hydrologic units is recognition that a hydrologic unit is not necessarily synonymous with a watershed, and thus has implications for understanding processes such as nutrient transport. As noted in a recent review, HUs can contain units that drain to segments of streams, remnant areas, and coastal or frontal units that can include multiple watersheds. In one of their two case studies in the United States, the authors found that only 47 percent of 12-digit HUs in South Carolina were watersheds. In analyzing two sets of three HUs in one ecoregion, the authors found substantial water quality differences between the three that were actual watersheds vs. the three that were downstream segments of larger watersheds (Omernik et al. 2017).

In the context of excessive nutrients and Lake Erie, it would be useful to have information at the finest scale possible (e.g., 12-digit HUs or smaller), including parameters such as spatial variations in soil test phosphorus levels; locations, types, and amount of manure application, and locations, types, and amount of commercial fertilizer application. Intensive studies in multiple locations of 12-digit HUs (that include detailed information on agricultural practices, including fertilizer application, as well as modeling and monitoring) could increase understanding of key factors driving changes in phosphorus export off the land, including changes in major tributary loads (e.g., for 8-digit HUs).

In this report, where reference is made to subwatershed, unless otherwise indicated, we are referencing the equivalent of 12-digit HUs.

References

Jones, K.A., Niknami, L.S., Buto, S.G., and Decker, D. 2022. Federal standards and procedures for the national Watershed Boundary Dataset (WBD) (5 ed.): US Geological Survey Techniques and Methods 11-A3, 54 p. doi.org/10.3133/tm11a3.

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