Fertilizer Application Patterns and Trends and Their Implications for Water Quality in the Western Lake Erie Basin

February 2018

INTERNATIONAL JOINT COMMISSION • COMMISSION MIXTE INTERNATIONALE
Canada and the United States   Canada et États-Unis

For more information on the International Joint Commission (IJC), please visit the IJC's website: www.ijc.org. Information also can be obtained by contacting any of the following IJC offices:

United States Section Office
2000 L Street NW, Suite 615
Washington, DC 20440
Phone: 202-736-9000
Fax: 202-632-2006
commission@washington.ijc.org

Canadian Section Office
234 Laurier Avenue West
22nd Floor
Ottawa, ON K1P 6K6
Phone: 613-995-2984
Fax: 613-993-5583
commission@ottawa.ijc.org

Great Lakes Regional Office
100 Ouellette Avenue 8th
Floor
Windsor, ON N9A 6T3
Phone: 519-257-6733
Fax: 519-257-6740
OR
P.O. Box 32869
Detroit, MI 48232
Phone: 313-226-2170 x6733
commission@windsor.ijc.org

Ce rapport est également disponible en français.

This report may be cited as: International Joint Commission (2018). **Fertilizer Application Patterns and Trends and Their Implications for Water Quality in the Western Lake Erie Basin.**

February 2018

Print version
ISBN: E95-2/30-2018E
Cat. No.: 978-0-660-24732-8

PDF version
ISBN: E95-2/30-2018E-PDF
Cat. No.: 978-0-660-24731-1

For more information, visit the IJC website (IJC.org)
and follow us on social media.

Subscribe to our newsletter at: http://ijc.org/en_/blog.

INTERNATIONAL JOINT COMMISSION

Lana Pollack

Lana Pollack
Chair
United States Section

Gordon Walker
Chair
Canadian Section

Rich Moy
Commissioner
United States Section

Richard Morgan
Commissioner
Canadian Section

Benoît Bouchard
Commissioner
Canadian Section

Acknowledgments

The International Joint Commission would like to acknowledge the extensive efforts, input and guidance provided by the Great Lakes Science Advisory Board's Science Priority Committee and its project Work Group.

Primary Authors

J. David Allan, Work Group Co-Chair and University of Michigan
Michael W. Murray, Work Group Co-Chair and National Wildlife Federation
with contributions by Matthew Child, International Joint Commission

Work Group Members and Reviewers

Tom Bruulsema, International Plant Nutrition Institute
Patricia Chambers, Environment and Climate Change Canada
Anne Cook, The Andersons Incorporated
Irina Creed, Western University
Steve Davis, U.S. Department of Agriculture, Natural Resources Conservation Service
Joe DePinto, Independent Consultant
Brad Glasman, Upper Thames River Conservation Authority
Pradeep Goel, Ontario Ministry of Environment and Climate Change
Bob Hecky, University of Minnesota – Duluth
Laura Johnson, Heidelberg University
Pamela Joosse, Agriculture and Agri-Food Canada
Joe Kelpinski, Michigan Department of Agriculture and Rural Development
Kevin King, U.S. Department of Agriculture, Agricultural Research Service
Andrea Kirkwood, University of Ontario Institute of Technology
Rebecca Muenich, Arizona State University
Jeff Ridal, St. Lawrence River Institute of Environmental Sciences
Clare Robinson, Western University
Craig Stow, National Oceanic and Atmospheric Administration
Chris Winslow, Ohio State University
Santina Wortman, U.S. Environmental Protection Agency
Matthew Child, International Joint Commission (Great Lakes Regional Office)
Glenn Benoy, International Joint Commission (Canadian Section)
Mark Gabriel, International Joint Commission (U.S. Section)

Contract Team (LimnoTech)

John Bratton
Noemi Barabas
Chelsie Boles
Brian Lord
Dan Rucinski
Derek Schlea

Executive summary

This assessment of fertilizer application and impacts in the western Lake Erie basin (WLEB) was conducted by members of the International Joint Commission Science Advisory Board's Science Priority Committee, with the assistance of an advisory group and a contractor. It considers primarily commercial (or synthetic) fertilizer and manure, and secondarily other nutrient-containing materials applied to agricultural lands.

Nonpoint agricultural release is recognized to be the largest single source of excess nutrients to western Lake Erie. Because phosphorus (abbreviated by its chemical symbol, "P") is the limiting nutrient for algal growth in most freshwater systems, the sources, transformations and effects of excess P were the focus of much of the assessment, although nitrogen (N) is also briefly discussed. Commercial fertilizer sales data, reported rates of commercial fertilizer application to the land surface, and total manure generation based on livestock numbers within watershed boundaries were used to inform the relative importance of these two sources to P loading. Point sources such as wastewater and industrial outfalls as well as urban and other nonagricultural nonpoint sources were not examined as part of this analysis; these sources are currently considered relatively minor (less than 15 to 25 percent combined) at the regional scale in comparison with nonpoint agricultural P loading to western Lake Erie (WLE). The study had a geographic scope of the binational WLEB, including the St. Clair - Detroit River system basin.

In addition to assessing the relative magnitude of P inputs from commercial versus manure fertilizers, this study drew upon published literature and knowledge of the advisory group and contractor team to better understand past, current and possible future influence of nonpoint agricultural runoff on nutrient loads delivered to WLE, and their potential to cause eutrophic conditions and episodic appearances of nuisance and harmful algal blooms (HABs). This included a review of land and nutrient management programs, including the recently adopted 4R nutrient management program; consideration of the capabilities of existing monitoring programs and watershed models to distinguish nutrient loads and impacts from different fertilizer sources and application practices; and assessment of the state of knowledge concerning the potential contribution of each fertilizer type to eutrophic conditions in Lake Erie. This effort helped to identify gaps in spatial coverage, temporal resolution and knowledge related to data, modeling and monitoring; points to continuing and emerging research needs; and identifies issues where future policy development may be important to effect necessary change.

Key findings and recommendations

This study presents numerous findings related to agricultural practices and fertilizer application (Chapter 2), monitoring (Chapter 3), modeling (Chapter 4), and additional factors that deserve consideration (Chapter 5). Chapter 6 identifies numerous data and information gaps and presents the work group's recommendations. A summary of key findings and recommendations is included below.

1. There are no established analytical nor data analysis methods for distinguishing P loads from commercial fertilizer versus manure at the point of delivery to the lake from tributaries, nor can a causal connection be drawn between different sources of P applied to fields and the response of algae in WLE.

Although recent and increasing research using stable isotopes and molecular fingerprinting holds considerable promise to improve our understanding of the fertilizer sources of P to the lake, at this time commercial fertilizer sales, manure generation and application information must be used as a proxy for the relative influence of each major fertilizer source, although prevailing privacy policies limit access to farm data and information. In addition, limited research to date finds no significant differences in P export (either dissolved reactive P [DRP] or total P) from fields receiving manure versus commercial fertilizer. However, findings of this report, supported by current literature, leave little doubt that nutrients lost from agricultural lands are primarily responsible for WLE eutrophic conditions.

Recommendation: Continue emerging research on phosphorus source monitoring, including stable isotope and organic phosphorus fingerprinting research as part of source attribution efforts, and site-based monitoring of P loss by species from fields receiving differing amounts of commercial fertilizer and manure.

2. Estimated overall manure generation and commercial fertilizer application values, converted to elemental P, total 41,687 tonnes (72 percent) for the US watershed and 16,327 tonnes (28 percent) for the Canadian watershed based on the most recent comparable binational data (2006-07), as summarized in Table ES-1 (data from LimnoTech, 2017).

As indicated in the following table, commercial fertilizer is the primary source of phosphorus used for agricultural purposes in the western Lake Erie basin (WLEB) overall and in the United States, while in Canada manure and commercial fertilizer are comparable as sources (52 percent manure and 48 percent commercial fertilizer).

Table ES-1: Amount of phosphorus in manure generated and commercial fertilizer applied in the western Lake Erie basin, 2006/2007

Jurisdiction	Total P (kg)	Total P (kg) as %	Manure Generated P (kg)	Manure Generated P as % of Total P	Commercial Fertilizer Application P (kg)	Commercial Fertilizer Application P as % of Total P
U.S. (2007)	41,687,180	72	7,735,580	19	33,951,601	81
Canada (2006)	16,326,671	28	8,443,129	52	7,883,542	48
Total	58,013,851	100	16,178,709	28	41,835,143	72

Current P application rates from commercial fertilizer are comparable in much of Canada and the United States and have declined in the watershed overall since the 1980s. The total numbers of animals in areas draining to the WLEB have remained fairly constant over the past 30 years, but there is a trend toward higher concentrations of animals per farm. P from generated manure has remained stable with no significant changes since the 1980s (though one analysis estimates gradually increased generation in the Maumee River watershed from the early 1990s to 2010), and it is higher in the upper portions of each domestic watershed. Information on permitted concentrated animal feeding operations (CAFOs) in the United States is publicly available (although not easily aggregated) and data regarding animals per farm in Ontario are generally not available to the public.

The amount of phosphorus entering watersheds due to other agricultural sources – including greenhouses, other agricultural products and pesticides – is small and not likely to contribute substantially to loads or impacts in Lake Erie, although they may have local impacts.

There are fundamental data limitations on estimates of both commercial fertilizer and manure application, with both temporal and spatial limitations, due primarily to program structure (e.g. agricultural censuses carried out only every five years) and prevailing policies that restrict the availability of farm-scale data.

Recommendation: Agencies should obtain (e.g. through surveys, available datasets and any new data as appropriate) commercial fertilizer sales and application data at both higher temporal and spatial resolution to allow for improved understanding of this important source. In addition, agencies should evaluate approaches to making these data broadly available at the highest spatial resolution possible.

Recommendation: Better quantify all major components of manure generation, management, field application, and associated P loss and impacts on local and regional surface water quality and ecosystems.

3. Stored soil P (legacy P) has the potential to contribute to river P loads for years or decades, although evidence indicates that some drawdown of legacy P is occurring. Numerous studies indicate that P fertilizer application exceeded P removal in crop harvest to the 1980s, likely resulting in accumulation of P stored in watershed soils. More recently, fertilizer application of phosphorus in the whole watershed is roughly balanced by P removal in harvested crops, although there is considerable local variation. Because crop yields have in general increased in recent decades while P fertilizer application has held steady or declined, this general pattern implies an ongoing drawdown of soil phosphorus content. However, even a small 'leakage' of excess P may be sufficient to contribute to algal blooms, particularly since the quantities of P added as fertilizer and removed as crop yield are large relative to P exported from the fields.

Phosphorus may also have accumulated to saturation in some nonagricultural compartments (buffer zones, filter strips, wetlands, riparian zones, ditches/drains and ditch/drain sediments and river channels). Because these systems do not have an outlet for phosphorus via crop harvest, it is hypothesized that these compartments of the greater landscape may be shifting from P sinks to slow-release P sources. The role and behavior of legacy P in systems such as this is an area of active research, and is also largely outside of current management and policy consideration.

Further reduction in P fertilizer application, increases in P removal via crop harvest and improvement in P retention on the land (through nutrient management practices such as the 4Rs, or right source, rate, time, and place) may be called for in order to speed the drawdown of stored P and lessen P export.

Recommendation: Agencies should collect and regularly update a statistically representative binational data set of phosphorus concentrations and vertical stratification in agricultural soils (including more consistent protocols for soil test phosphorus), whether through an existing program or a new (agency led, or potentially multi-sector) program.

Recommendation: Improve spatial resolution of data on legacy phosphorus (including reservoirs of legacy P in locations not actively farmed), as well as linkages between P fluxes from reservoirs and lake phenomena including algal blooms and hypoxia.

4. No-till cropping systems contribute to increased Dissolved Reactive Phosphorus (DRP) export from fields.

Sixty-three percent of WLEB cropland has some type of conservation tillage in place (mulch tillage, seasonal no-tillage, or continuous no-tillage), practices that were widely adopted in the region by the early 1990s. The expansion of conservation tillage over the past two decades coincides with the rise of DRP export and thus is considered a contributory factor. No-till leads to accumulation of P in the uppermost layer of soil which is then more available for transport, and may allow the formation of soil macropores that serve as transport pathways for subsurface transport through drain tiles.

Numerous studies have found that no-till plots have a higher DRP load than other conservation and conventional tillage plots.

***Recommendation*:** Support research and monitoring to quantify and better understand the implications of no-till agriculture for P accumulation at the soil surface and P transport through drain tiles, and to explore potential new approaches to minimizing P losses associated with no-till practices.

5. Subsurface artificial tile drains increase conveyance of P through subsurface pathways.

Data from the mid-2000s indicate that most US counties in the WLEB have over 50 percent of acres tile-drained (including 86 percent of agricultural land in the Maumee River watershed), and three of the four tertiary watersheds in the Canadian portion of the WLEB have over 50 percent of hectares tile-drained. Other studies have found that average tile flow can convey up to 50 percent of annual precipitation. Few data exist to quantify trends in tile drainage in the WLEB.

Phosphorus transported through tile drains may be an important contributor to algal blooms. Although dissolved and particulate phosphorus loadings from subsurface tiles are small as a proportion of P applied, the widespread prevalence of tiling suggests a substantial cumulative effect.

Recommendation**:** Agencies should obtain more current data on tile drainage networks and their impact on P form and mass transport, including interactions with tillage practices, commercial fertilizer and manure application, and the relative role and rates of tile discharge of P in comparison with surface runoff.

6. Climate change is expected to influence P export to the lake.

The phosphorus load delivered by rivers to Lake Erie is governed by concentration and discharge. Because discharge varies much more than concentration, years of high precipitation and discharge are also years of high P loads. One study found about one-third of the increased DRP load of the Maumee River since 2002 is attributable to higher runoff volumes, and researchers have noted that a continuing trend of increasing river discharge substantially complicates the ability of nutrient management to reach load reduction targets.

Modeling indicates that the realized benefits of best management practices (BMPs) and related management strategies under a moderate climate may be substantially offset if precipitation and runoff increase in the future. Modeling studies have found that wetter climates will result in longer recovery timeframes, though several recent studies have also indicated the potential for tempered impacts on P export with future climate.

Climate change can influence HAB development in other ways, including through generally warmer water temperatures and effects on lake stratification.

Recommendation: Continue to evaluate climate change impacts on P loads from rivers as a potentially complicating factor influencing how target loads are determined, as well as implications for management actions needed to meet targets.

7. The western basin of Lake Erie and its tributaries are among the most intensively monitored parts of the Great Lakes basin, although shortcomings need to be addressed.

Offshore lake monitoring and lower watershed monitoring are reasonably robust. There are many monitoring programs that include parameters relevant to nonpoint nutrient loading and impacts. Data availability is fair overall, with time lags commonly exceeding a year or more for data release. Real-time gauges and sensors are becoming more common in the region, and most major programs do distinguish between total and dissolved reactive phosphorus, the latter of which is considered more bioavailable. Important monitoring gaps exist in watersheds and lakes in terms of space, time and parameter suite.

Recommendation: Design and implement an optimized and integrated long-term monitoring network for water quality and agricultural practices to support decisions about the best approaches to nutrient load reductions.

Recommendation: Develop stable funding mechanisms and institutional stewards for sustained, long-term binational monitoring and data management.

8. Models (in particular the Soil and Water Assessment Tool or SWAT) provide valuable insights into the effectiveness of various land and nutrient management strategies in reducing P loads, and hold much additional potential as analytical and predictive tools.

Modeling has provided valuable insights into the relationships between agricultural practices and riverine P loads, identified locations where P losses likely are greatest, and shown the potential benefits of various land and nutrient management practices – including management practices that farmers employ. Results suggest that wide implementation of a mix of strategies will be needed to reduce P loads to WLE. As a cautionary note, the extent of existing implementation of most conservation practices is not always modeled (given limited data on current extent of implementation), which must be taken into account in considering modeled benefits of additional implementation.

Recommendation: Develop operational models linked to optimized monitoring networks, and high-resolution surveys of changing agricultural practices and watershed characteristics to support forecasting of evolving conditions, and to inform inter-annual and within-season adaptive management decisions.

Recommendation: Continue financial and policy support for development and application of research models at various scales to improve process understanding of phenomena and dynamics (including improving soil phosphorus routines and addressing other processes noted above), as well as to simulate alternate management scenarios.

9. Broad implementation of a mix of current best management practices, increased evaluation and developing new approaches to address emerging challenges, including the increase in DRP export, are critical to restoring the health of Lake Erie.

Adoption of appropriate management practices (e.g. the 4R nutrient management program) may have a bigger influence on P export from agricultural lands than the type of fertilizer (i.e. commercial versus manure). Adoption of 4R practices can reduce available P, and edge-of-field studies also have found positive outcomes from implementation of 4R practices, although more research on the efficacy of management practices is needed. Models indicate that realizing significant reduction of riverine nutrient loads from Lake Erie tributaries will require multiple conservation practices including nutrient management, reduced fertilizer application and various land management practices.

The lack of detailed information on farm practices at the field level and over time limits our ability to fully document and model fertilizer application, evaluate the effectiveness of changes such as expanding adoption of 4R practices, and to make more realistic models of how changes in practices affect nutrient runoff. Farmer surveys, especially if the survey pool is sufficiently large and representative, can help in this regard, as would more detailed reporting of local practices.

Further expansion and implementation of appropriate management practices ultimately depends on understanding and, where feasible, addressing the socio-economic, policy and cultural drivers of agricultural production and BMP adoption. Although an examination of those issues is beyond the scope of this report, the authors acknowledge their importance and encourage a deeper examination of those drivers considering the science findings included here.

Recommendation: Continue to promote 4R guidelines for fertilizer application through outreach, education and technology to enhance adoption and effectiveness of 4R practices. Expand efforts to evaluate the effectiveness of 4R and other best management practices at the field and watershed scales, and identify areas for improvement.

Recommendation: Support research and monitoring (watershed and lake) to improve process understanding and identify management options best able to reduce export of all forms of P so that P remains onsite and available for crop uptake.

Perspective

Looking to the future, it is likely that management and policy will need to be developed to address the challenges identified in this report. This may require new approaches to offset the presumed influence of no-till crop management and tile drainage on phosphorus runoff, including changes to tillage and drainage practices, keeping in mind other environmental goals of these practices (e.g. erosion control). Should future climates continue a trend to greater precipitation and runoff, it may be necessary to adjust target P loads in the future if the climate becomes substantially wetter.

Fortunately, a number of trends, now more than a decade long (based on most recently available data), are encouraging. P fertilizer inputs are declining while P removal as crop yield has increased. Declines in soil P in at least some locations suggest that fertilization at or below crop needs and drawdown of soil P can be achieved without impacting yields. Models such as SWAT provide insight into the mix of land and nutrient management practices that are likely to be most effective in bringing riverine P loads into the range where extreme algal blooms will become rare events. This report provides a comprehensive assessment of fertilizer practices in western Lake Erie and through synthesis of the most recent literature, identifies research needs, aspects of land and nutrient management that demand attention, and suggests where policies may need to be developed to effect necessary changes.

P control measures enacted in the 1970s demonstrated that Lake Erie eutrophication could be reversed by strategies focused mainly on point sources, resulting in significant reductions in total P loadings, in open lake P concentrations and in algal biomass. The challenge this time is with agricultural nonpoint sources of nutrients, which will require a different set of responses. Lake Erie has benefitted from bold action in the past and requires similar bold action today to ensure its health and value to the people of the basin into the future.

Table of contents

List of Tables

List of Figures

1. Problem statement

Eutrophication – or elevated nutrient levels and associated ecological changes – has plagued Lake Erie and many other water bodies for decades. Following significant harmful algal blooms (HABs), hypoxia and other impacts in Lake Erie in the 1960s, multiple policy, regulatory programs and nonregulatory initiatives were put into place to address these and other problems. The combination of the US Clean Water Act (including the permitting program for point sources), federal and provincial laws and programs on the Canadian side, binational US-Canadian efforts through the Great Lakes Water Quality Agreement (GLWQA), and other nonpoint source reduction programs led to reductions of some nutrient loads, in particular via wastewater treatment plants and agricultural sediment runoff. Since the 1990s, however, resurgence in eutrophic symptoms and especially the increasing presence and severity of Lake Erie HABs have brought new urgency to the need to understand causes and determine effective management responses. As nutrient loads continue to be high and agricultural sources of phosphorus (P) in commercial fertilizer and manure[1] are widely considered to be an important source of P entering Lake Erie (IJC, 2014), there is an urgent need to better understand the influence of agricultural fertilizer and appropriate land and nutrient management strategies to protect the health of western Lake Erie (WLE).

The International Joint Commission (IJC) Science Priority Committee (SPC) was tasked with exploring this issue in depth for the western Lake Erie basin (WLEB) (Figure 1-1). The key objective was to assess the magnitude and relative importance of two broad nutrient sources, commercial fertilizer and manure, and the influence of nutrient management associated with those major sources on nutrient loads and their impacts to the WLEB. This project attempted to address the following questions:

- What are the magnitudes of commercial fertilizer use and manure generation and use in the WLEB? Are data sufficient to understand the relative importance of these sources to phosphorus delivery to WLE?
- What is the extent of best management practices and programs (e.g. 4R nutrient stewardship) in the WLEB and what is their effectiveness in managing phosphorus loss to tributaries from commercial fertilizer and manure?

---

[1] As used in this report, "commercial fertilizer" references all forms of synthetic fertilizer (including inorganic fertilizers and synthetic organic fertilizers). "Commercial fertilizer" does not encompass animal manure that is brokered (sold) in the WLEB. "Manure" references animal manure in any form (i.e. liquid or solid) produced by livestock, and does not include other organic-rich waste material (e.g., biosolids from wastewater treatment plants, compost, or any other material). "Fertilizer" used alone typically references any form of inorganic or organic material added to soil to augment nutrients (through primarily commercial fertilizer and manure).

- What is the extent of existing monitoring programs and are these programs adequate to ascertain the relative importance of commercial fertilizer and manure as phosphorus sources to WLE?
- What are the capabilities of existing models (in particular watershed models) to help ascertain the relative importance of commercial fertilizer and manure as contributors of phosphorus to Lake Erie and also to assess the effectiveness of various management practices?

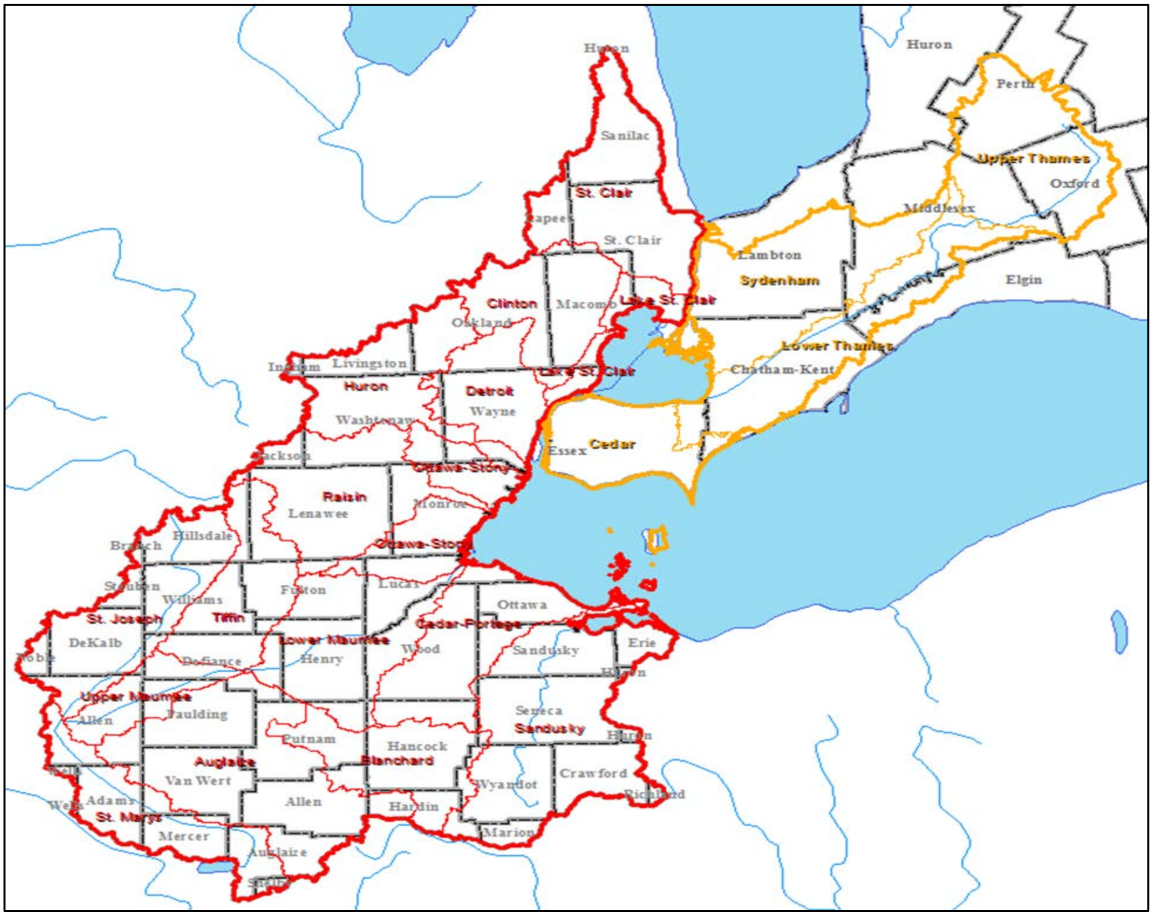

Figure 1-1 Study area. US watershed area (red) = 14,833 sq. miles (38,416 sq. km) or 78 percent of the total; Canada area (yellow) = 4,286 sq. miles (11,101 sq. km) or 22 percent of the total watershed area. (LimnoTech, 2017)

A schematic of key processes and analytical approaches to studying the issue in the WLEB is provided in Figure 1-2. This report summarizes this overall effort, which included meetings of a work group, development of a contract technical report (LimnoTech, 2017) with multiple components, including data acquisition, mapping and summarizing, and assessments of monitoring programs and models, and development of this synthesis report.

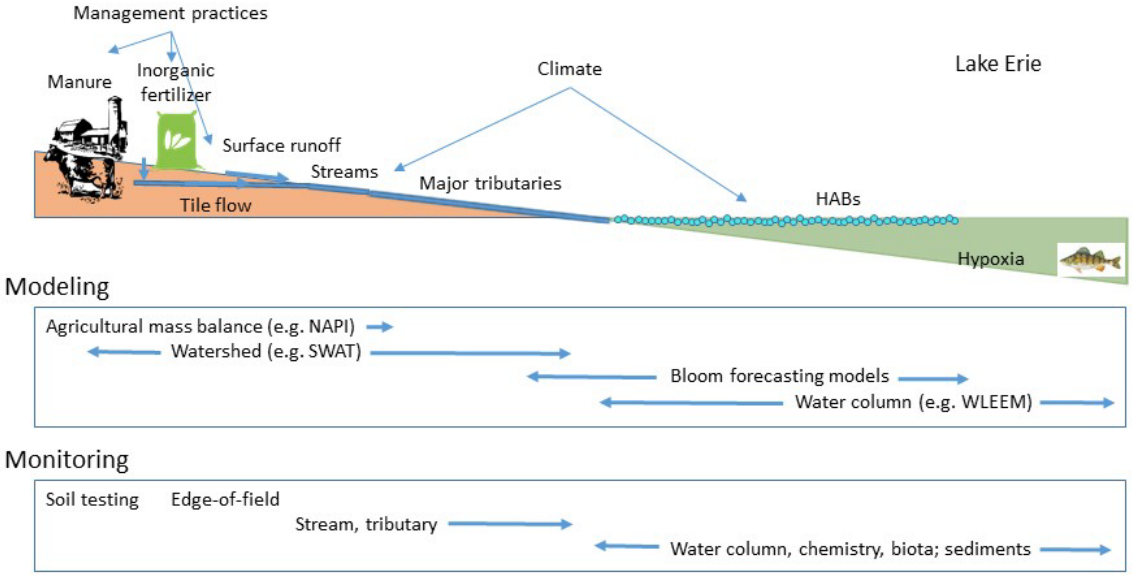

Figure 1-2 Schematic diagram showing selected human activities and components of the hydrologic cycle influencing nutrient loading and lake conditions. Other components (e.g., point source inputs, detailed assessment of groundwater transport of phosphorus, detailed review of in-lake processes) were beyond the scope of this assessment.

2. Agricultural practices, fertilizer application, and factors affecting nutrient runoff in the western Lake Erie basin

The western Lake Erie basin (WLEB) extends over 19,000 square miles (49,000 square kilometers) across parts of Ohio, Indiana, Michigan and Ontario, with approximately 78 percent of the watershed in portions of the three US states (LimnoTech, 2017). The United States and Canadian portions of the watershed are heavily agricultural, with row crops extending over much of both portions, and animal feeding operations in varying locations but often clustered in the upper portions of each watershed (LimnoTech, 2017). Row crops are particularly significant in the Maumee River watershed, amounting to more than three-fourths of the watershed area (Kalcic et al., 2016). The importance of agricultural practices (in particular commercial fertilizer and manure application and subsequent runoff) as a major contributor to nutrient loading to the WLEB has been recognized for a number of years (e.g., Scavia et al., 2014; Smith et al., 2015a; Watson et al., 2016 (and references therein)).

Fertilizer applied to agricultural soils is an important but not exclusive determinant of nutrients carried from the landscape into waterbodies. Fertilizer is applied to fields to increase crop yields, so that crops can grow in greater abundance than the previous natural vegetation growing on unamended soil. Crop needs vary by crop, strain, growing season, weather conditions, water availability, plant health and soil types, among other factors. Nitrogen, phosphorus and potassium are the three main nutrients that are supplied in commercial fertilizers.

Fertilizer in excess of annual crop needs and not otherwise retained in the landscape (e.g., by binding to soil particles or transported to groundwater) can be mobilized in dissolved or particle-bound forms and exported from farm fields by (surface) runoff or tile drain discharge. These excess nutrients are a combination of both newly applied nutrients and nutrients from prior years of fertilizer use and retention. Fertilizers applied to agricultural lands can be described in terms of the amounts, the timing, the methods and the types of fertilizer product chosen to optimize crop production over the short and the long term. Multiple factors can potentially influence the amount of nutrient loss from fields, including type of crop and rotation patterns, tillage practices, soil type and texture, slope, artificial drainage, fertilizer type and application approach (e.g. rate, timing), and hydrology (e.g. related to weather and climate) (Sharpley and Jarvie, 2012).

2.1 Farming practices and trends in the WLEB

Row crops, largely corn and soybeans, predominate in both portions of the WLEB (over 70 percent of all crops for the two crops together), with smaller amounts of wheat, alfalfa and hay, based on five-year agricultural census data for each country. Area planted for the two major crops has not changed substantially since the 1990s, though total area (for all crops) declined slightly from 1996 through 2011 (LimnoTech, 2017). The stability in these two agronomic features, extent of farmed lands and crop type, suggest that the causes of increased loadings of dissolved reactive phosphorus (DRP, considered to be an important contributor to HABs) over the last two decades to Lake Erie must be found in other factors.

Two key farm practices relevant to phosphorus export are extent of artificial drainage and conservation tillage (Jarvie et al., 2017). Subsurface artificial (tile) drains are an important component of agricultural production in poorly drained soils, used to lower the water table thereby improving plant survival through increased root aeration and allowing producers to maintain field access. Due to the substantial extent of clay soils in the WLEB, artificial drainage is common (Kalcic et al., 2016), and though few data exist that quantify actual trends in tile drainage in the WLEB, anecdotal evidence suggests that tiling has increased in recent decades.

Data from the mid-2000s indicated that most US counties in the WLEB have over 50 percent of acres tile-drained, and three of the four major watersheds in the Canadian portion of the WLEB have over 50 percent of hectares tile-drained (LimnoTech, 2017). Indeed, overall, 86 percent of agricultural land in the Maumee River watershed is estimated to have drainage tiles (LimnoTech, 2017). In addition, the recent U.S. Department of Agriculture (USDA) Conservation Effects Assessment Project (CEAP) assessment of the US portion of the WLEB shows 63 percent of WLEB cropland has some type of conservation tillage in place (i.e., either mulch tillage, seasonal no-tillage, or continuous no-tillage), practices that were widely adopted in the region by the early 1990s, with no significant change in tillage practices between 2003-06 and 2012 surveys (USDA NRCS, 2016).

In addition to row crops, the watersheds of the WLEB support substantial populations of livestock, particularly cows, swine and chickens. These generate the manure that is an important nutrient source and, along with commercial fertilizer, the main focus of this report. Total livestock populations have remained relatively stable over the past 30 years in areas draining to the WLEB (LimnoTech, 2017). In the Canadian WLEB drainage area, swine and poultry showed gradual increases over the 30-year period while total cattle population showed a gradual decrease, resulting in an overall relatively stable number of animal units (i.e. individual animals). On the other hand, in the US portion of the watershed, total animal populations increased from 2002 to 2012 for cattle, swine and poultry (in the latter case, using a watershed-based accounting method). Total animal numbers for the 2011-12 period were approximately 900,000 swine in both US and Canadian portions, 375,000 and 170,000 cattle, and 10.8 and 8 million chicken/poultry, in the US and Canadian portions of the WLEB, respectively.[2] In addition, there has been a tendency toward larger farms in particular in the United States, with increases of cattle, swine and poultry in the largest farm categories (for each group) since 1987 (LimnoTech, 2017).

2.2 Commercial fertilizer application

Fertilizer application is one key factor in determining potential magnitude of nutrients lost from watershed soils and entering WLEB tributaries. There are multiple types of

---

[2] LimnoTech, 2017. Note for chicken/poultry, US numbers were based on the watershed-based estimation method.

commercial fertilizer formulations, including fertilizers containing the two key macronutrients phosphorus and nitrogen. Plants take up phosphorus as phosphate (PO_4^{3-}, with the exact form dependent on the soil pH), and there are several measures of the solubility (or ability to dissolve) in water of phosphorus in such fertilizers, with most commercial fertilizers containing at least 50 % water soluble P (OSU, 2006). Table 2-1 gives typical phosphorus and nitrogen levels for several common types of commercial phosphate fertilizers.

Given that sales information is publicly available on a consistent basis (while direct application data are not), commercial fertilizer application across the WLEB and over time is best inferred from sales data at the county and state or province level.[3] Based on agricultural census data (which are offset by one year between the United States in 2012, and Canada in 2011) and additional sales data, fertilizer application amounts by three jurisdictions in the WLEB starting in the mid-late 1980s are provided in Figure 2-1.

Table 2-1: Phosphorus and nitrogen content of several commercial phosphate fertilizers (from OSU, 2017)

Fertilizer Material	% P (as P_2O_5)*	% N
Single superphosphate	16-20	-
Triple superphosphate	44-48	-
Monoammonium phosphate (MAP)	48-61	10-12
Diammonium phosphate (DAP)	46	18
Ammonium polyphosphate	34	10

*: Phosphate is typically measured as P_2O_5.

---

[3] County level (US only: Ruddy et al., 2006; Gronberg and Spahr, 2012); province and state level (Canada, US: Bruulsema et al., 2011; IPNI-NUGIS 2012)

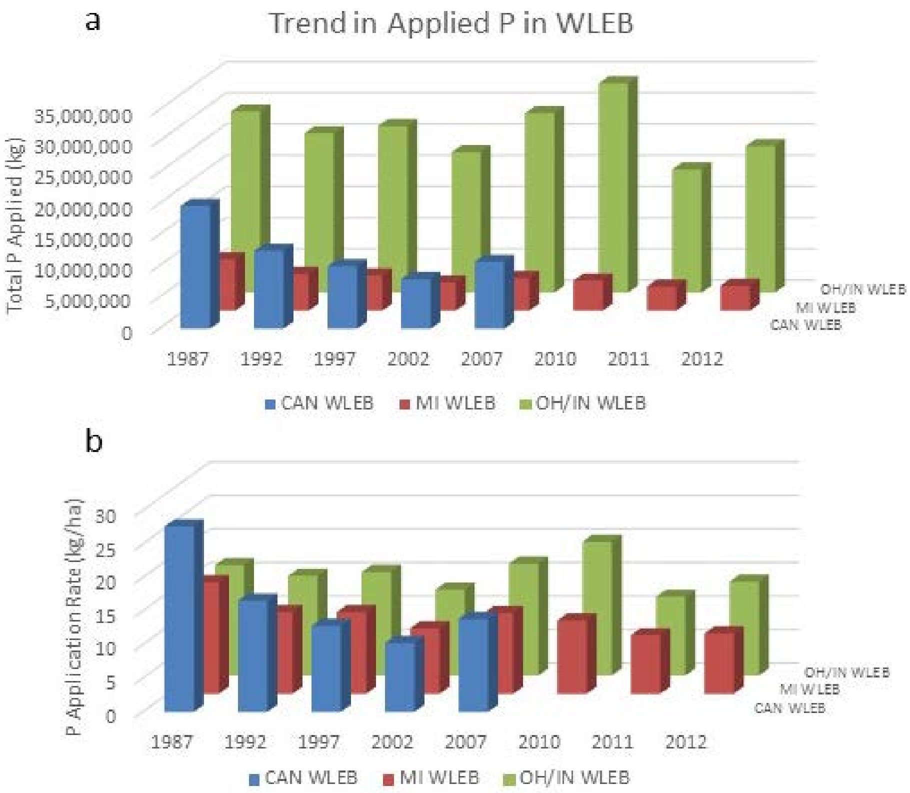

Figure 2-1 Trends in commercial fertilizer phosphorus applied in the western Lake Erie basin. Total phosphorus applied (in kilograms) (panel a), and rate applied (kilograms per hectare (ha), where one hectare is approximately 2.2 acres) (panel b), for commercial fertilizer in the Ohio and Indiana portions, Michigan portion, and Canadian portion of the western Lake Erie basin. Data are drawn from IPNI NuGIS database, and cover census years (i.e., 1987, 1992, etc. for United States, and offset by one year for Canada (e.g. 1986, 1991)), and two additional years (2010, 2011). Note that 2011 census data from Canada were not available at time of compilation. Similar data on nitrogen were not compiled for this project. Figure modified (panel letters, hectare abbreviation) from LimnoTech, 2017, and data available in appendices of technical report.

Total phosphorus (P) application in general shows higher amounts applied in the Ohio and Indiana portions of the watershed. Application rates (kg ha^{-1}, Figure 2-1b) show slight decreases for the Michigan portion of the WLEB, decreasing trends in the Canadian portion (though an increase in 2007), and variable trends for the Ohio and Indiana portion.

Note that data on fertilizer form are not captured in the censuses; however, earlier data in Ohio indicated a gradual shift in the past one to two decades to greater use of monoammonium phosphate and less use of diammonium phosphate (ODA, 2013). In the United States as a whole from 1995 – 2011, use of diammonium phosphate declined by 32 percent, while use of monoammonium phosphate increased by 130 percent (USDA, 2017a).

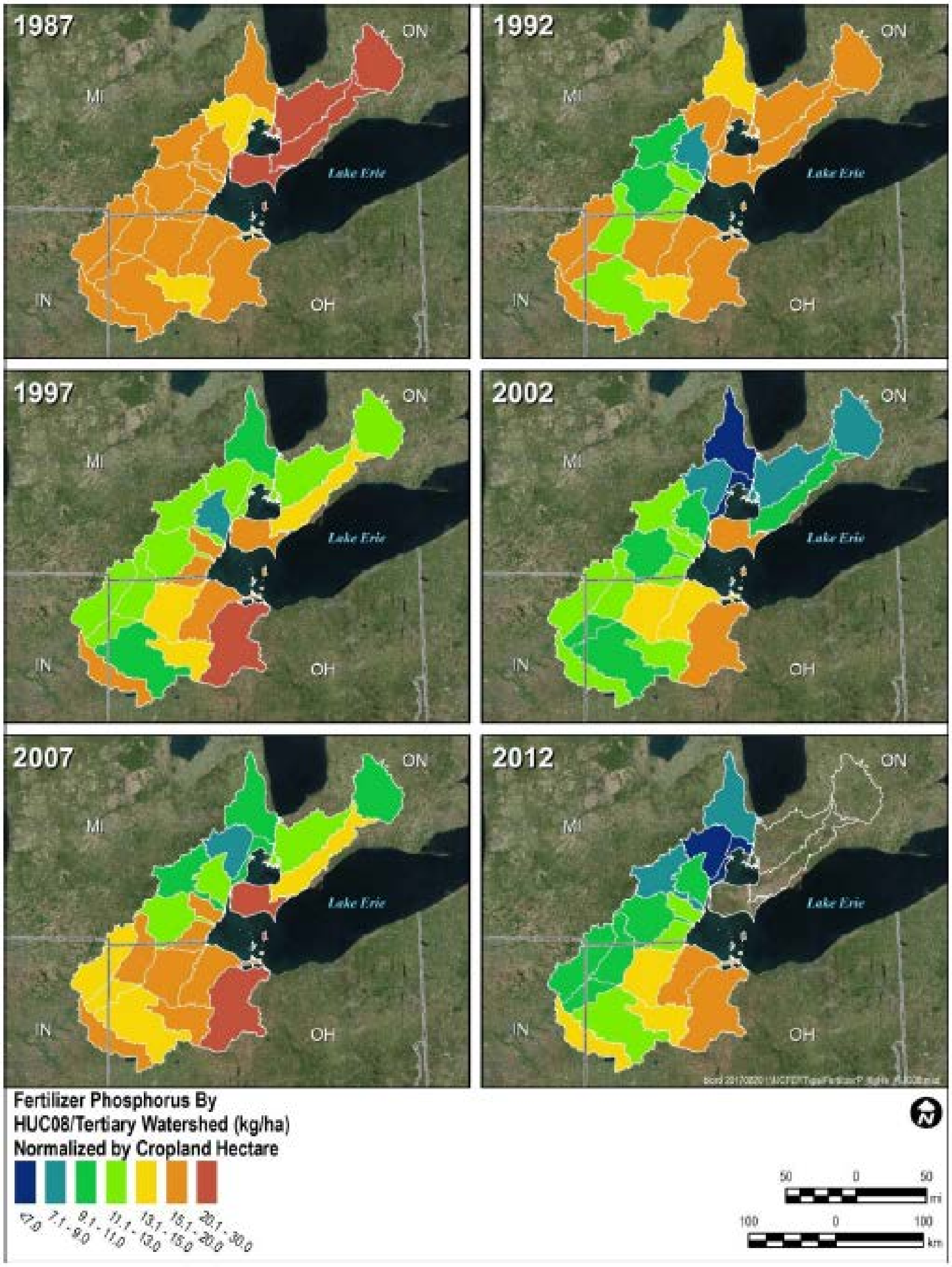

Figure 2-2 Trends in commercial fertilizer phosphorus application intensity (kilograms per hectare) by watershed in the WLEB (with data not available for Ontario for 2012). Ontario data (from the agricultural census in Canada) cover the year prior to those indicated in each panel. (LimnoTech, 2017).

Commercial fertilizer application rate data (on a per area basis, as shown in Figure 2-1) are provided in map form in Figure 2-2. As shown, application rates are higher in the Sandusky, St. Joseph and Cedar-Portage watersheds in the United States, and higher rates (in particular more recently) in the Essex region watersheds on the Canadian side.

The data also show different temporal patterns – application rates are mostly declining in individual US watersheds over the period, whereas in Ontario rates generally declined to 2001 and then increased to 2006 (the most recent data available for Canada).

At the watershed scale, average commercial fertilizer application rates across watersheds in the US portion in 2012 found in this assessment were 11 kg/ha (10 lb./acre), and were highest in the Sandusky watershed at 19 kg/ha (17 lb./acre) (LimnoTech, 2017). Though not directly comparable, the USDA WLEB CEAP assessment for 2012 reported an overall average application rate of 16.4 lb. /acre (USDA, 2016); note that comparing findings between the two assessments would entail several considerations.[4] In the Canadian portion, rates in 2006 (most recent year with available data at the time of technical report preparation) averaged 16 kg/ha (14 lb. /acre), with the maximum in the Essex region watersheds at 26 kg/ha (23 lb. /acre). Across the US WLEB, crop removal ranged from approximately 11 to 22 kg/ha (10 to 20 lb. /acre).[5] This finding, which is consistent with the recent CEAP assessment (USDA, 2016), and which is summarized in the technical report (LimnoTech, 2017) and supported by other recent reviews (e.g., Bruulsema, 2011; Han et al., 2012) indicates that fertilizer application of phosphorus in the whole watershed is roughly balanced by P removal in harvested crops. Because crop yields have in general increased in recent decades while P fertilizer application has held steady or declined, this general pattern implies an ongoing drawdown of soil phosphorus content across the WLEB. Indeed, soil test phosphorus levels (a measure of P available to crops, rather than actual P content of soils) have shown generally decreasing fraction of samples with higher (> 50 parts per million (ppm) P, and increasing fraction of samples with lower P, in counties overall in the three states and Ontario.[6]

2.3 Manure application

Application of animal manure is a longstanding practice in agriculture, which provides organic matter to increase soil health and recycling of nutrients. At the same time, improper application techniques can lead to excessive transport of nutrients, organic matter and other constituents into surface and groundwater. In the WLEB, cattle, swine or pigs and poultry are the dominant farmed animal operations. As noted above, total livestock populations have remained relatively stable over the past 30 years in areas

---

[4] Considerations include different methodologies (e.g., use of surveys in the CEAP assessment vs. fertilizer sales data in the LimnoTech assessment, and ensuring use of same metrics (e.g. cropland acres, etc.); J. Bratton, personal communication.

[5] Based on IPNI-NUGIS, 2012.

[6] Bruulsema, 2016, and reviewed in LimnoTech, 2017.

draining to the WLEB, although there are some differences between the US and Canadian portions of the watershed and increasing consolidation (larger operations) on the US side in particular. The regulatory approach for animal feeding operations differs in the two countries. In the United States, concentrated animal feeding operations (CAFOs) of a certain size are regulated under the Clean Water Act, with implementation typically done by state agencies. In the Canadian portion of the basin, intensive livestock operations (ILOs) are regulated by Ontario agencies (i.e., Ontario Ministry of Agriculture and Rural Affairs, and Ontario Ministry of the Environment and Climate Change).

The quantity and characteristics of manure generated by livestock varies based on several factors, in particular species, age and productivity of the individual animal, as well as nutrient concentrations in and digestibility of its feed (OSU, 2006). Typical phosphorus and nitrogen content in animal manures is provided in Table 2-2. The data show the potentially wide range in P and N content possible within an animal group, though some general patterns as well, including the generally higher P content in poultry manure, and generally lower N:P ratios (not shown) for poultry manure as well. Phosphorus in manure can be in both inorganic form (i.e. as phosphates) and organic form, though most P is in the form of phosphate, and becomes available to plants after application to cropland (Eghball et al., 2002). Further discussion on issues involving P availability in manure is provided below and in Chapter 5.

Table 2-2: Phosphorus and nitrogen content of several manure types (from OSU, 2005)

Manure Type	% P (as P_2O_5)*		% N*	
	Average	Range	Average	Range
Dairy cattle	1.8	0.7 – 5.2	4.3	2.2 – 14.3
Swine**	4.3	1.4 – 6.8	14.0	2.7 – 24.2
Poultry***	7.0	1.6 – 17.9	3.9	2.3 – 5.6

*: Percentages on a dry weight basis; **: Finishing; ***: Layers

Manure production quantities for the United States were drawn from the IPNI NuGIS project database, which includes estimates based on livestock numbers reported in census data, and reported excretion rates for different livestock (LimnoTech, 2017). Data for the Canadian portion of the WLEB were drawn from a Canadian GIS dataset (LimnoTech, 2017). Like total livestock populations discussed above, manure generation has remained relatively stable, with no significant changes since the mid-1980s (through the 2011-12 censuses), at roughly 8,000 tons of manure phosphorus produced annually in each portion of the WLEB. Multiple studies carried out in the past decade resulted in similar estimates, though the studies would typically rely on the same primary data (i.e., census data on animal numbers and literature data on manure production per animal). One recent review utilizing IPNI NuGIS data for the Maumee River watershed showed a gradually increasing trend of manure production from the early 1990s to 2010 (Powers et al., 2016).

Because livestock operations are not uniformly distributed and manure can be transported (although there is often limited information on manure application), the area receiving this manure (or location alone, in Canada) can only be approximated. In the LimnoTech assessment, the area receiving this manure was distributed to HUC-8 watersheds in the U.S. and tertiary watersheds in Canada and normalized by dividing by total cropland area to illustrate the spatial distribution and variation over time of manure phosphorus production (Figure 2-3). This is an approximation to give a sense of the relative intensity of livestock operations and potential manure application in each watershed; note that the normalization is based on cropland area, not area actually receiving manure. As expected from the location of animal operations (see below), the data do show generally higher manure P production in the upper parts of the US and Canadian portions of the WLEB. Note that this is a coarse estimation, and given the likelihood of shorter distances between manure production and field application, more refined information on actual disposal locations and amounts would likely show significant variation even within HUC-8/tertiary watersheds.

A full accounting of manure generation from animal feeding operations is challenging because smaller operations may not be regulated or reported through regulatory permitting systems, though they would be captured in agricultural censuses. For this project, LimnoTech mapped permitted CAFOs on the US side, and found that dairy CAFOs are much more numerous than beef CAFOs, with the former scattered around the watershed. In contrast, poultry and swine CAFOs tend to be found more in the upper portions of the watershed, and there are also significant numbers of farms just outside the upper reaches of the watershed (LimnoTech, 2017).

In addition, LimnoTech (2017) estimated that permitted CAFOs account for the large majority of layer chicken production, less than one-half of dairy cow production, and less than one-half of hog production (and thus manure generation). As is the case with commercial fertilizer application, data limitations impair a more comprehensive assessment of manure generation and application. Facilities that fall below permitting thresholds will not be captured in regulatory program data, and even for permitted facilities, there would not typically be information on trends of animal numbers, etc., with time. (LimnoTech was not able to readily access data on individual ILOs in Ontario.)

In addition to manure production estimated from animal operations, described above, data exist for estimated manure application *area,* but not quantities, based on county-level agricultural census data. Results shown in Figure 2-4 are consistent with information on manure production (Figure 2-3), showing generally greater area receiving manure in the upper portions of each watershed in both countries. In addition, the figure does not show any widespread, substantial changes with time for periods with available data, though there are increases in areas receiving manure, in particular in upper watersheds on the US side.

Manure is unlikely to be transported great distances, although poultry manure may be more transportable due to its lower moisture content (LimnoTech, 2017), as indicated by a recent study from University of Michigan researchers indicating that approximately 70 percent of CAFO manure was applied within five miles of the generating facilities (Long et al., 2017; LimnoTech, 2017). Sharpley (2006) stated that manure is not typically transported more than 10 miles from point of generation. In any case, as noted by LimnoTech, data accessibility issues and the lack of a single geospatial dataset even for permitted operations makes it very challenging to accurately quantify the amounts and more exact spatial distribution of manure application.

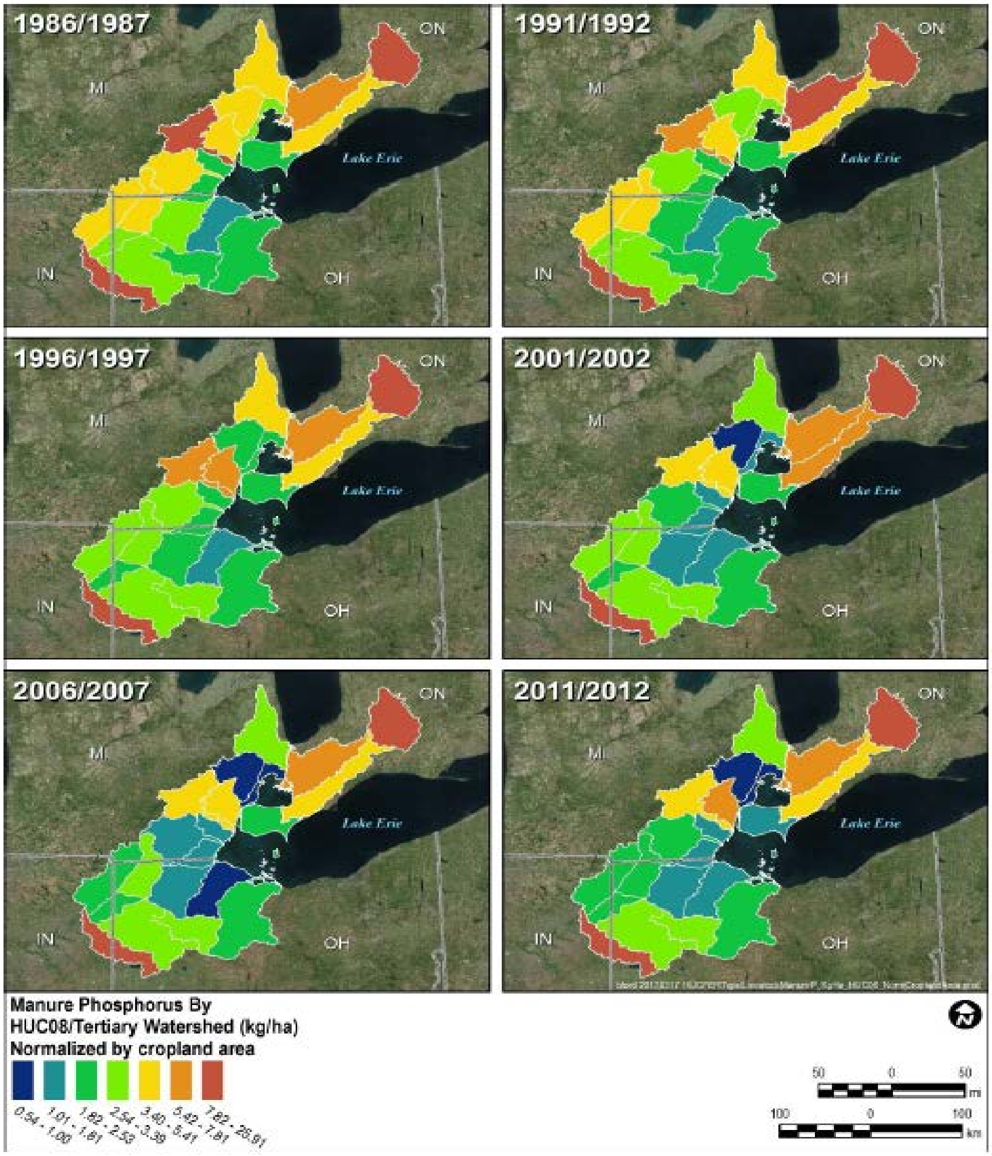

Figure 2-3 Trends in livestock manure phosphorus production by watershed (kilograms per hectare, where normalized by cropland area) in the WLEB. (LimnoTech, 2017)

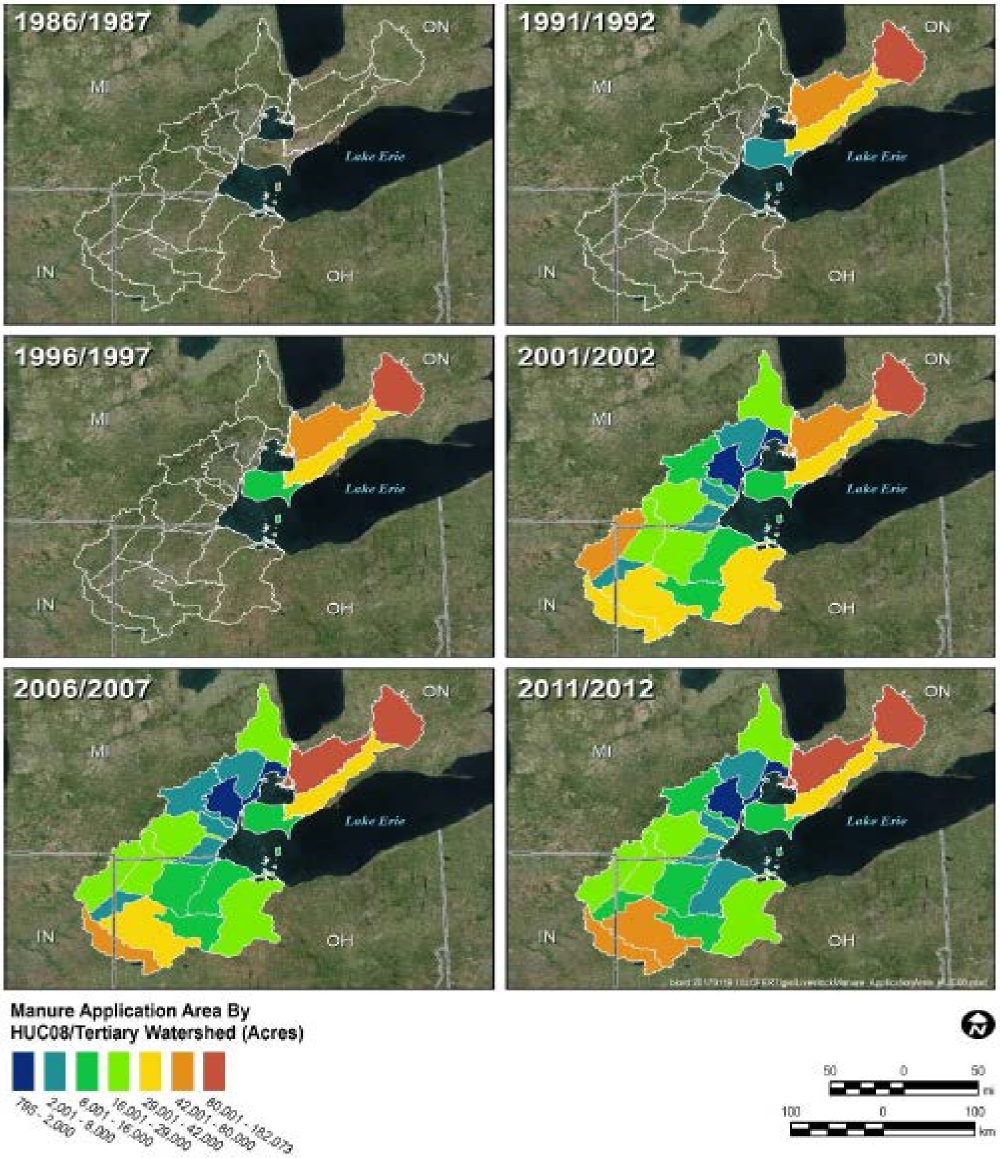

Figure 2-4 Trends in manure application area (acres) by watershed in the WLEB, based on agricultural censuses in both U.S. and Canada. (LimnoTech, 2017)

2.4 Other nutrient sources, Including greenhouses, herbicides and other products

Greenhouse wastewater and nutrient-containing products other than fertilizers can potentially be the source of agricultural phosphorus and nitrogen export in the WLEB. Greenhouse production (e.g. for tomatoes, peppers and cucumbers) has grown appreciably in Ontario in recent decades, in particular in the southern-most county of Essex. Production in the US portion of the WLEB is on a much smaller scale, though anecdotal evidence indicates increasing interest. Excess water or “leachate” from greenhouses can be reused in the facilities. There has been limited research on nutrients in final wastewater disposed of from greenhouses. Although some research has shown elevated phosphorus levels in such wastewater in drains near greenhouses, data are inadequate to estimate total phosphorus loads to major tributaries or Lake Erie from greenhouse production.[7]

Herbicides used in the WLEB that contain nutrients include several that contain nitrogen (e.g. atrazine, metolachlor) and phosphorus-containing glyphosate. In the US portion of the WLEB, atrazine and glyphosate were the predominant herbicides used on corn in recent years, while glyphosate dominated use on soybeans. LimnoTech (2017) estimated less than 500 tons of phosphorus in the form of herbicides was annually applied to fields in the US portion of the WLEB. Glyphosate and its main breakdown product aminomethylphosphonic acid (AMPA) can be routinely detected in surface and groundwater samples, although it appears contributions of phosphorus (even if bioavailable) to total loadings to Lake Erie would be relatively minor. Limited research has explored potential direct impacts of glyphosate on cyanobacteria, finding both promoting (e.g. *Planktothrix*) and inhibiting (*Microcystis*) impacts. Some insecticides (e.g. chlorpyrifos) contain phosphorus (although in amounts that would be quite low in a basin context), and no soil amendments used in the US portion were found to contain phosphorus or nitrogen (LimnoTech, 2017).

One additional potential source of nutrients to the landscape is biosolids, which are sewage sludge from wastewater treatment plants (WWTPs). Though biosolids have measurable P and N concentrations, this potential nutrient source was not considered in this assessment. It is important to note multiple potential disposal options for WWTP dewatered solids – for example, for the Detroit Water and Sewerage Department wastewater treatment plant, the majority of solids disposal is via incineration, with landfill disposal and land application utilized for the remainder at available locations for both within 100 miles of the facility (City of Detroit, 2014).

2.5 The role of nutrient management in affecting nutrient runoff following commercial fertilizer and manure application

There are multiple factors that can affect the potential for nutrient runoff associated with commercial fertilizer and manure application, including static field conditions (e.g., slope, soil texture, depth to water table, soil test P, P sorption capacity, drainage system); dynamic field conditions (e.g., moisture content, temperature (including

---

[7] e.g. OMOE, 2012. Also reviewed in LimnoTech, 2017.

thawed or frozen), soil compaction); precipitation characteristics (e.g., time to next precipitation, amount and intensity of precipitation); field management (e.g. cropping system, tillage extent and type, commercial fertilizer application, manure application); fertilizer characteristics (e.g., type of commercial fertilizer (superphosphate, monoammonium phosphate, etc.); type of manure (e.g. origins, liquid, solid, P content, N:P ratio); and nutrient application approach (e.g., surface application with no incorporation, surface application with incorporation, injection, rate, timing).[8]

While all of these factors can be important in affecting nutrient runoff, nutrient management issues (including consideration of fertilizer characteristics and application approaches) were the focus of much of this project, as pertaining to both commercial fertilizer and manure, and these issues are explored in more detail in the following sections.

2.5.1 Nutrient management and commercial fertilizer application

Recent years have seen the development of both regulatory programs (including Senate Bill 1 in Ohio, with restrictions on fertilizer application, including by season and with wet weather forecasts), and voluntary nutrient management programs. A key example of the latter is the 4R nutrient stewardship program, which was developed conceptually by several organizations, including the International Plant Nutrition Institute, The Fertilizer Institute and Fertilizer Canada (Vollmer-Sanders et al., 2016). The 4R program contains four categories of practices, with a number of individual practices potentially pursued for each (Bruulsema, 2009; LimnoTech, 2017):

- Right source (e.g., consider nutrient form, pursue balanced fertilization (considering nitrogen, phosphorus, potassium))
- Right rate (use soil testing, yield goal analysis, crop inspection, variable rate technology)
- Right time (application timing, controlled release fertilizers)
- Right place (application method, fertilizer incorporation)

The program has had an emphasis on commercial fertilizer, though it is recognized that manure application must be considered even when focusing on the former (IPNI, 2017). In addition to farmers, the program involves a broad range of professionals in its implementation, including agricultural retailers, crop advisors and fertilizer applicators. Implementation of the program has been encouraged by a certification program for nutrient service providers, launched in 2014.

---

[8] Adapted from discussion on manure application, in LimnoTech, 2017 (pp. 54-56).

The certification program standard has multiple components, including a Nutrient Recommendation and Application section, addressing each of the 4R categories. The program's governing body is the Nutrient Stewardship Council, with members divided across four sectors (agricultural business, government, NGOs and universities/research), and with responsibilities that include reviewing changes to the standard, issuing certificates and training auditors.

In the Canadian portion of the WLEB the 4R program is in its initial stages and in 2015 the Government of Ontario, the Ontario Agri-Business Association and Fertilizer Canada signed a 4R Nutrient Stewardship Memorandum of Cooperation. This formal commitment will bring a combined investment of $300,000 over three years (Smith, 2016) to assist Ontario farmers with minimizing their impacts to the environment while maximizing crop yields. The American Society of Agronomy also offers 4R certification within its Certified Crop Advisor Program, and with support of Fertilizer Canada and the Ontario Agri Business Association, this 4R Nutrient Management specialty is offered in the Ontario Certified Crop Adviser Program.

Though the program is also relatively new in the United States, as of April 2016 approximately 35 percent of farmland in the WLEB had been influenced by the 4R certification program (Vollmer-Sanders et al., 2016). Recent research has indicated farmers in the region had been carrying out practices related to 4R elements even before the certification program. For example, in a survey of the Ohio portion of the Maumee River basin, Wilson et al. (2013) found only 15 percent of farmers never test the soil, 68 percent use a nutrient management plan at least part of the time, and 71 percent generally avoid fall or winter application of commercial fertilizer or manure (Wilson et al., 2013; LimnoTech, 2017).

Given the newness of the 4R certification program, evaluation is in its early stages. A broad review of multiple studies across many types of watersheds across eastern North America (including very distinct from the WLEB) over 50 years (and thus numerous studies before formal adoption of the 4R program) did not produce definitive conclusions on effectiveness of timing and method of application in particular on P transport (Christianson et al., 2016). On the other hand, more recent research in the WLEB has shown positive results from nutrient management practices. For example, recent field scale studies in the WLEB have shown reduced P export following implementation of 4R practices, in particular incorporation of surface applied fertilizer (Williams et al., 2016; King et al., 2017). There also have been more landscape-scale modeling efforts examining potential impacts of 4R implementation. In a SWAT modeling study involving input from agricultural and other stakeholders in the WLEB, Kalcic et al. (2016) found that widespread use of multiple best management practices (BMPs) (in particular subsurface fertilizer placement) would be needed to approach phosphorus reduction targets in the WLEB (see further discussion on use of models in Chapter 5). The 2016 CEAP study using survey information on practices and watershed modeling in the WLEB similarly found regular and widespread use of 4R practices would be needed to fully and consistently realize full potential benefits (USDA, 2016; LimnoTech, 2017). Given the relatively limited studies to date on actual effectiveness of 4R practices on phosphorus export, a number of research efforts (including a large multidisciplinary research project) are underway to examine program effectiveness (Vollmer-Sanders et al., 2016; LimnoTech, 2017), and ongoing emphasis in this area is needed.

In spite of relatively limited research on effectiveness of various nutrient management practices in reducing P export in the WLEB, data do show a general long-term trend to reduced P inputs (considering both commercial fertilizer and manure) relative to crop P removal, as discussed above. NuGIS data in particular show the partial phosphorus balance (i.e. phosphate in commercial fertilizer and manure applied minus crop uptake) became increasingly negative across most agricultural acres in the WLEB, from 1997 – 2012,[9] implying a drawdown of soil phosphorus, which should contribute to reduced P loadings to Lake Erie with time (see further discussion in Chapter 5).

2.5.2 Nutrient management and manure application

Manure application methods vary and may differ in potential nutrient loss to waterways. Methods in use include injection of liquid manure and surface application of liquid or solid (or composted) manure, with or without incorporation. Some research shows liquid manure injection and incorporation of surface-applied manure by tillage results in substantially lower loss of TP and DRP when compared with surface application without incorporation.[10] In terms of actual approaches used, application method on the Canadian side is assessed through regular agency surveys, and data from 2006 and 2011 agricultural censuses indicated that 36 percent of manure applied was injected as a liquid, and 30 percent was incorporated (as solid or compost) (LimnoTech, 2017). On the US side, manure application methods have been assessed through individual studies, though different survey methodologies/questions make a

---

[9] NuGIS map data provided in LimnoTech, 2017.

[10] Reviewed in LimnoTech, 2017.

broader synthesis more challenging. Several recent studies indicated a relatively small fraction of farmers in the WLEB reported applying manure (e.g. up to 33 percent in one study of the Maumee and Sandusky River watersheds) (Prokup et al., 2017). Another study found that 34 percent of farmers reported incorporating manure in the Maumee River watershed (Wilson et al., 2013). In terms of cropland area, 12 percent of the US portion of the WLEB, and 16 percent of the Canadian Lake Erie watershed received manure in 2012 (LimnoTech, 2017). It is clear that more systematic collection of data on manure application methods is needed (in particular on US side) to better track the extent of individual practices in the WLEB (LimnoTech, 2017).

Concerning manure generation and potential phosphorus availability, one broader issue is the trend of greater concentration of animals into larger facilities (as noted in Section 2.1), which can result in manure over-application "bullseyes" or "hot spots," given that manure produced is typically not transported long distances (as noted above), and available nutrients may exceed the crop needs of the farm producing the manure and neighboring farms. Unrecovered manure losses (i.e., from spills or from livestock in pastures) and excess fertilizer application near CAFOs and other large livestock aggregations can both lead to increased P export as well as local buildup of P in soils and sediments (Long et al., 2017). As noted above, livestock operations on both sides of the border tend to be found at higher numbers in the upper reaches of the WLEB. Moreover, livestock operations of any size can be concentrated in areas with related operations (e.g. meat processing and packing, egg processing). In addition, note that areas of multiple animal feeding operations (even smaller, unpermitted facilities) can lead to increased availability of phosphorus locally (either stored in soil or transported in runoff), though additional research is needed in this area.

Phosphorus availability following manure application must consider multiple factors, including form of manure and biogeochemistry of soils. Some recent research has shown that higher water-soluble phosphorus in manure equates with higher phosphorus levels in surface runoff.[11] In addition, manures with high organic matter content can improve soil health and promote infiltration (thus leading to less P loss in runoff) (Sharpley et al., 2002). At the same time, research has shown there can be appreciable variation in water-extractable phosphorus in manure, both across livestock types and depending on the form of manure storage (e.g. liquid vs. solid) (Kleinman et al., 2005; LimnoTech, 2017). More recent research in Canada has led to the development of manure phosphorus source coefficients (based on a combination of manure mixed

---

[11] Reviewed in LimnoTech, 2017.

with soil), which researchers have recommended for incorporation into the Ontario phosphorus risk index (Wang et al., 2016). The intricacies of the issue are further illustrated by potential concerns with liquid manure injection leading to P transport via macropores to tiles (though this is regulated in some jurisdictions). Potential concerns with enhanced subsurface P transport following injection or incorporation were highlighted in a recent review of data compiled in the MANAGE (Measured Annual Nutrient Loads from AGricultural Environments) database;[12] however, it is also important to keep in mind potential differences between soil characteristics in the WLEB and other systems (e.g. texture, development of macropores, soil P saturation and capacity for further retention of P, etc.).[13]

Concerning the issue of P losses from manure vs. commercial fertilizer, a recent review of data compiled in the MANAGE database found that organic P (e.g., manure, leaf litter) was on average applied at higher P rates than inorganic (commercial) fertilizer, and led to higher average corn yields. However, the same data revealed no significant differences in P exports or losses (either DRP or total P) in fields receiving organic vs. inorganic fertilizer, though the number of sites available for the former was small (7).[14]

There is increasing research into field-scale studies on mobility of P as a function of varying fertilizer type more broadly in the region. For example, recent research at the Harrow Research and Development Center in Ontario found significantly increased DRP (but not particulate P) export with leaf compost addition for fields under both long-term conventional tillage and no tillage (2.9 and 5.3 times greater, respectively, compared to fields not receiving leaf compost) (Zhang et al., 2017). Note the study did not include a parallel assessment of potential impact of addition of equivalent P in commercial fertilizer. In addition, current research of the U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) in Ohio is examining P runoff differences between paired fields receiving commercial fertilizer and manure (LimnoTech, 2017).

There have also been additional efforts to develop tools and indicators to estimate the potential loss of phosphorus (or delivery to surface waters), following both commercial fertilizer and manure application. A tool developed by the USDA and validated based on 21 field studies was found to be able to estimate P loss for total, dissolved and

---

[12] Christianson et al., 2016; note that no significant differences in DRP load were found, though data were limited.

[13] Joosse, P., personal communication.

[14] Christianson et al., 2016; note the paper referenced "inorganic" fertilizer (roughly equivalent to commercial fertilizer as used here), and "organic fertilizer" (encompassing both manure and leaf litter).

particulate phases using simple methods and readily available data (Vadas et al., 2009). Canada has been using an indicator termed *indicator of risk of water contamination by phosphorus* (IROWC_P) nationwide, and the tool estimates risk of phosphorus runoff from both resident soil P and applications of commercial fertilizer and manure, as well as assesses P buildup in soils at the landscape scale (Van Bochove et al., 2011; LimnoTech, 2017).

In spite of all of the efforts noted here – including field-scale studies and tool and index development for application at varying scales in the field – the technical review for this project noted that, "There are no analytical methods or data analysis methods for distinguishing contributions to average annual TP loading from manure P vs. inorganic fertilizer P for either the US or Canadian drainage areas to the WLEB" (LimnoTech, 2017). One of the challenges noted was in identifying "rules-of-thumb" for the amount of P exported from soil where manure is applied, given the multiple factors noted in this section potentially affecting P transport. One particular area of uncertainty concerns method and timing of fertilizer application (Long et al., 2017), requiring use of other data (e.g. on manure generation, fertilizer sales and limited application data) and assumptions (e.g., concerning application locations) in order to estimate the relative importance of the two broad fertilizer sources to lake nutrient loads. Given apparent differences in manure application across the WLEB (e.g., higher rates in upper portions of watershed in each country), further investigation is warranted, though such studies (supported by appropriate modeling) would need to account for multiple factors, including estimated manure application at the highest temporal and spatial resolution, potential nutrient transformations following loss from fields, and contributions of other downstream sources.

2.6 Summary of commercial fertilizer application and manure generation in the western Lake Erie basin

Based on the most recent data on commercial fertilizer application and manure generation available through agricultural censuses, and considering the US and Canadian portion of the WLEB, phosphorus in commercial fertilizer exceeds the amount of phosphorus in manure generated. As shown in Table 2-3, the United States supplies the majority (72 percent) of P applied to watersheds of the WLEB from both commercial fertilizer and manure. Commercial fertilizer dominates (81 percent of total) in US watersheds, whereas Ontario watersheds receive slightly more manure P (52 percent) than commercial fertilizer. Note that the values reference manure generated versus commercial fertilizer P applied. However, given available but limited data, as noted above, it is safe to assume that the large majority of manure generated in both portions of the basin is applied within the WLEB.

Table 2-3: Amount of Phosphorus in Manure Generated and Commercial Fertilizer Applied in the Western Lake Erie Basin, 2006/2007 (from LimnoTech, 2017).

Jurisdiction	Total P (kg)	Total P (kg) as %	Manure Generated P (kg)	Manure Generated P as % of Total P	Commercial Fertilizer Application P (kg)	Commercial Fertilizer Application P as % of Total P
U.S. (2007)	41,687,180	72	7,735,580	19	33,951,601	81
Canada (2006)	16,326,671	28	8,443,129	52	7,883,542	48
Total	58,013,851	100	16,178,709	28	41,835,143	72

2.7 Summary and data gaps

Key findings from this portion of the assessment include the following:

- Based on recent census surveys with comparable data, commercial fertilizer phosphorus accounts for 72 percent of the total phosphorus used in agriculture in the WLEB (either commercial fertilizer applied or generated as manure).
- The relative importance of commercial fertilizer vs. manure varies between the two countries, with commercial fertilizer application accounting for over 80 percent of the total used in the US portion, while the two components are similar in the Canadian portion of the watershed.
- Commercial fertilizer phosphorus application intensity (i.e., kg ha^{-1}) has generally declined in the watershed since the 1980s, and data for census years in the US portion of the watershed indicate a general trend towards a negative phosphorus balance (more P removed with crops than added as fertilizer). However, there are still spatial differences, with higher overall application intensity in the Canadian portion of the watershed than US portion, and with generally higher application intensity in the eastern and lower subwatersheds on the US side, and the Essex region watershed on the Canadian side.
- Phosphorus estimates for generated manure (kg ha^{-1}) have shown declines in some watersheds, and essentially no change in other watersheds, in both US and Canadian portions of the WLEB. In addition, phosphorus generated in manure as well as applied (assuming application near sources) is generally higher in the upper portions of both watersheds.

- The amount of phosphorus entering watersheds from other agricultural sources – including greenhouses, other agricultural products and pesticides – is substantially smaller than the two major sources considered here, and not likely to be contributing substantially to loads or impacts in Lake Erie (though local impacts are possible).
- There is increasing application of agricultural phosphorus management strategies, including the 4R nutrient management program, implementation of a recent Ohio law restricting fertilizer application under certain conditions, as well as increased information available (via surveys) on application approaches actually in use.

This assessment has also identified a number of information gaps regarding the relative importance of commercial fertilizer vs. manure phosphorus in the WLEB. Because broad data acquisition on many agricultural components (e.g. crop rotations, commercial fertilizer application, livestock numbers and manure generations, etc.) is only carried out every five years through agricultural censuses, information is lacking on potential year-to-year changes that may have implications for nutrient export and water quality impacts. Furthermore, prevailing privacy policies related to disclosure of farm-scale data means most publicly available data is aggregated at the county (or larger) scale or withheld entirely, requiring assumptions on partitioning values to individual watersheds. Fertilizer application data are not directly available via censuses; commercial fertilizer sales data on an annual basis are obtained from states and aggregated by (and available for purchase from) the Association of American Plant Food Control Officials, though data are not always available for a given state or county and year, and are available after a several-year delay (AAPFCO, 2017). Thus in this assessment, it was not possible to explore any changes in commercial fertilizer application that might have had a bearing on changing nutrient loads and impacts seen in Lake Erie over the past five to six years. On the other hand, some of the patterns driving Lake Erie impacts (in particular increasing DRP loads) have been observed since the 1990s. Hence, it is not clear if more recent estimates of fertilizer application rates would significantly affect the understanding of key drivers affecting WLE water quality that has developed over the past decade.

Data on manure generation and application are even more limited. While county-level data on numbers of farm animals are available through agricultural censuses every five years, obtaining data on individual operations is more challenging. Facilities that fall below permitting threshold numbers would not have any data publicly available, and the numbers of such facilities in the WLEB is unclear (Rissien, 2017). Larger facilities may not require a permit (if not discharging to a water body), or may still be in the process of obtaining a discharge permit. This is further complicated by the varied regulations across the states and province in the WLEB.

In addition, there is often limited information on the fate of manure generated at a particular facility. Though studies have shown that manure is typically not transported long distances, there is potential for movement of manure across county boundaries, and even across the WLEB watershed boundary, which is important given the large number of permitted facilities in or near the upper portions of the watershed (LimnoTech, 2017). Even for permitted facilities, tracking specific information (e.g., amounts, location, timing, etc.) of manure generation and application can entail lengthy public records requests (and document review) from permitting authorities, which even then will not necessarily yield complete information (given that in some cases, information is self-reported).[15] Note that a separate project of the IJC Water Quality Board is examining policy issues around manure generation and application and animal feeding operations in the Great Lakes.[16]

There is clearly a need for more detailed information on both commercial fertilizer and manure application in the WLEB, both on temporal and spatial scales. More detailed and consistent reporting on fertilizer sales at the state and provincial level (including annual data at the county level) would be helpful to better understand trends. It would also be helpful to continue CEAP-type studies that can explore more spatially-resolved data in the watershed that are not publicly available (but can still contribute to understanding processes, including as part of modeling). More detailed data on manure is needed in the WLEB, including more consistent data collection and accessibility for manure generation and use by the states and Ontario, particularly locations of application. In addition, ongoing research efforts may help address these issues, such as attempting to "fingerprint" nutrient sources in the watershed. As noted later in this report, the complexities of nutrient cycling (including transport and fate downstream of farm fields) will likely continue to present challenges to discerning the relative contributions of these two broad nutrient sources to loads and impacts in Lake Erie. Other research efforts that can potentially aid in addressing these issues are noted later in this report.

---

[15] See for example Rissien, 2017; Long et al., 2017.

[16] See IJC, 2017a.

3. What is the capability of tributary, lake and remote monitoring to assess the contributions of different fertilizer sources?

Any investigation of hypotheses related to the causes and severity of eutrophication requires information provided by monitoring programs (Dolan and McGunagle, 2005). Monitoring data have been critical in determining spatial and temporal trends in nutrient loads to all the Great Lakes (Dolan and Chapra, 2012), while long-term monitoring data for key Lake Erie watersheds have enabled researchers to demonstrate the importance of agricultural nonpoint source reduction activities to decreasing trends in flow-weighted total phosphorus concentrations (Richards et al., 2001; Richards and Baker, 1993), and to detect increases in dissolved reactive phosphorus since the mid-1990s (Richards et al., 2010). As described later in this report, monitoring data are essential to various modeling and forecasting efforts, including Soil and Water Assessment Tool (SWAT) calibration, development and scenario-testing associated with phosphorus reduction targets.

Because of the importance of monitoring data in detecting changes and serving as the basis for quantitative assessments, this project described key tributary and open lake monitoring programs, remote sensing monitoring activities, and databases that store and disseminate monitoring information. In addition, a limited number of emerging, experimental or time-limited monitoring programs were reviewed (LimnoTech, 2017).

3.1 Watershed, lake and remote monitoring programs

Dozens of water quality monitoring programs are supported throughout western Lake Erie and its contributing watersheds by federal, state/provincial and watershed agencies, academic entities and nongovernment organizations. A short description of each of the key tributary and open lake monitoring programs is included in the project technical report (LimnoTech, 2017), and are summarized in Table 3-1 below. Recent summaries of ongoing monitoring programs have also been reported by others (e.g., Betanzo et al., 2015).

Table 3-1: Summary of Key Tributary and Open Lake Monitoring Programs for the Western Lake Erie Basin[17]

Organization	Spatial Extent	Select Key Parameters*	Sampling Frequency	Website
Tributary Monitoring Programs				
National Center for Water Quality Research (Heidelberg University)	US portion of WLEB	TP, DRP, ammonia, nitrate	Daily or sub-daily	https://www.heidelberg.edu/academics/research-and-centers/national-center-for-water-quality-research
U.S. Geological Survey	US portion of WLEB	TP, DRP, TKN, ammonia, nitrate, suspended sediments	Monthly plus storm sampling	https://waterdata.usgs.gov/nwis
U.S. Department of Agriculture – Agricultural Research Service	Several edge of field and drain tile sites	Several P and N species, discharge	Sub-daily	http://amarillo.nserl.purdue.edu/ceap/index.php
Ohio Environmental Protection Agency	Maumee River and several tributaries	TP, DRP	5-10+ year intervals	http://www.epa.state.oh.us/dsw/tmdl/maumeeriver.aspx
Michigan Department of Environmental Quality	US side of Huron-Erie Corridor	TP, TKN, nitrate, ammonia	5-year rotating basis	http://www.michigan.gov/deq/0,4561,7-135-3313_3681_3686_3728-32361–,00.html
Province of Ontario – several programs including Provincial Water Quality Monitoring Network (in partnership with Conservation Authorities)	Ontario portion of WLEB	TP, DRP, TKN, nitrate, nitrite	Monthly plus storm sampling	https://www.ontario.ca/data/provincial-stream-water-quality-monitoring-network
Open Lake Monitoring Programs				
U.S. Environmental Protection Agency (several programs)	WLEB	TP, DRP, TKN, nitrate, ammonia, clarity, turbidity, dissolved oxygen	Varies by program; Water Chemistry Program samples spring and summer	https://www.epa.gov/great-lakes-monitoring
Environment and Climate Change Canada (several programs)	WLEB	TP, DRP, TKN, nitrate, ammonia, chlorophyll, clarity,	Varies by program	http://www.ec.gc.ca/scitech/default.asp?lang=en&n=3F61CB56-1

---

[17] Drawn in part from LimnoTech, 2017.

ECCC, cont.		temperature, pH		
National Oceanographic and Atmospheric Administration & Cooperative Institute for Great Lakes Research	WLEB	Microcystin	Continuous to weekly, depending on station	https://www.glerl.noaa.gov/res/HABs_and_Hypoxia/habsMon.html.
Ohio Environmental Protection Agency (several programs)	Nearshore of Ohio portion of WLEB	TP, DRP, TKN, nitrate ammonia, chlorophyll, microcystin	Varies by program	http://www.epa.ohio.gov/Portals/35/lakeerie/2015_Erie_Study_Plan.pdf
Province of Ontario (several programs)	Nearshore of Ontario portion of WLEB	Nutrients (several forms)	Varies by program	https://www.ontario.ca/search/data-catalogue?sort=asc
Lake Erie Center, University of Toledo	Vicinity of Maumee River (nearshore to offshore transects)	TP, DRP, TKN, nitrate, ammonia, chlorophyll	Biweekly, May through September	http://www.utoledo.edu/nsm/lec/
Ohio State University	U.S. portion of WLEB	Nutrients (various forms)	Varies depending on station	https://ohioseagrant.osu.edu/research/live/water

*: TP: total phosphorus; DRP: dissolved reactive phosphorus; TKN: total Kjeldahl nitrogen.

In addition to established monitoring programs, this assessment identified several emerging monitoring or research efforts. The Ohio EPA is initiating a program to intensively sample the Maumee River watershed to identify nutrient loading hotspots. The program will help regulators target the largest sources of loads with watershed improvement programs (WTOL, 2017; OEPA, 2015). This review also identified a project that is examining the sources of phosphorus in the tributaries to Lake Erie using stable isotopes of oxygen in phosphate (Bowling Green State, Heidelberg and Ohio State universities), and another by a group at Ohio State University that will use organic phosphorus fingerprinting to characterize urban and treated wastewater sources.[18] In general, there is increasing research into use of stable isotopes as part of studies on nutrient biogeochemical cycling in watersheds (e.g., Tamburini et al., 2014). For example, a study involving nitrogen and oxygen stable isotopes in a river in England explored sources and the relative importance of biotic versus abiotic processes on nitrogen and phosphorus cycling in the river (Gooddy et al., 2016).

A number of remote sensing programs cover Lake Erie and its watershed and are reviewed in the project technical report (LimnoTech, 2017). NOAA's National Centers

---

[18] Ohio Sea Grant, 2017. Winslow, C., personal communication.

for Coastal Ocean Science program has developed a seasonal HAB forecasting system for western Lake Erie (Stumpf et al., 2012), which became an operational product in July 2017. This forecast is based on bloom intensity measured by four European Space Agency and NASA satellite instruments which measure surface temperature, sediment and chlorophyll concentrations, wind forecasts and current models from NOAA, and phosphorus loading and discharge data from Heidelberg University and the United States Geological Survey (USGS). Twice weekly, as cloud cover permits, the HAB forecast details the current location of Lake Erie HABs during the bloom season, the projected future position, and the intensity of the bloom for the next several days.

This review identified a University of Toledo project that is using remote sensing to characterize field practices, and to map tile drain locations. Outcomes of two workshops held to plan for the future of remote sensing in the Great Lakes and advise NASA on the requirements of future remote sensing systems to address Great lakes issues have been reported (Shuchman et al., 2014).

Several of the watershed, lake and remote sensing datasets generated by numerous organizations are stored and disseminated from a few key databases. The Great Lakes Environmental Database (GLENDA) from U.S. EPA was originally developed for the Lake Michigan Mass Balance study and provides data entry, storage, access, and analysis capabilities for water quality, fish tissue and sediment chemistry data (U.S. EPA, 2016).

The Great Lakes Observing System (GLOS) provides a HABs data page in collaboration with a suite of western Lake Erie partners. In this initial stage, the page provides access to real-time data from stations around the western Lake Erie basin, including measurements of temperature, specific conductivity, turbidity, pH, chlorophyll and blue green algae (or cyanobacteria). Upcoming enhancements will add access to grab sample data, satellite imagery, hydrodynamic model results, and meteorological observations. In addition to the HABs page, the Maumee River tracker webpage is under development by GLOS. This web page's tracking tool sums up nutrient loads day-to-day to show the current year's total nutrient load entering the WLEB through the Maumee River, and charts the cumulative loads in the context of previous (2000-2016) years' ranges.

In addition to the Great Lakes databases, national databases also hold information from the Great Lakes basin. One example is the Water Quality Portal (WQP) maintained by the National Water Quality Monitoring Council (NWQMC). This website is linked to the USGS National Water Information System (NWIS), the EPA STOrage and RETrieval (STORET) Data Warehouse, and the USDA ARS Sustaining The Earth's Watersheds - Agricultural Research Database System (STEWARDS). These databases hold water quality, biological, weather, and other data types. The Government of Canada's Open Data Portal has many national Canadian datasets, including water quality data that are collected in the Great Lakes. In addition, several other national datasets can be found in the database, including biological and sediment data.

Our review confirms that the western basin of Lake Erie and its tributaries are among the most intensively monitored parts of the Great Lakes basin. Offshore lake monitoring and lower watershed monitoring are reasonably robust for the region compared to other parts of the Great Lakes or similar large ecosystems. There are many federal, state/provincial and academic monitoring programs that include parameters relevant to nonpoint nutrient loading and impacts. Data availability is fair overall, with time lags commonly exceeding a year or more from the time of sample or measurement collection to the time of data release. Real-time gauges and sensors are becoming more common in the region, but not all important nutrient-related parameters can be measured by such instruments.

None of the current monitoring programs provide ability to directly differentiate whether phosphorus in tributaries or the lake originate from commercial fertilizer or manure sources. Presently, the tools for fingerprinting phosphorus sources are largely in the development, or research, stage. However, as indicated in Table 3-1, most of the major current monitoring programs include quantification of different phosphorus species, notably DRP, which is important given the recognition of DRP as the key phosphorus parameter relevant to biological uptake and impacts in Lake Erie. Furthermore, remote sensing is now routinely used in mapping cyanobacterial blooms, but available technology focuses on organism or plant pigment (e.g. chlorophyll *a*, etc.) detection, and more traditional measurement approaches are still needed to measure phosphorus concentrations.

3.2 Summary and data gaps

Numerous key watershed, open water and remote sensing monitoring programs are in place for the WLEB. A few databases exist to store and disseminate information from those monitoring programs to Great Lakes users. In sum, these activities help to identify areas of elevated phosphorus loading. Remote sensing, paired with lake monitoring, will continue to document the extent, composition and characteristics of algal blooms.

Our review identified a number of monitoring gaps and limitations. Addressing these gaps and limitations would help to identify priority areas for management attention and track improvements, and enable water quality modelers to better predict and understand nutrient loading and algal blooms.

The spatial distribution and scale of monitoring activities is often inconsistent or lacking. There is less coverage of nearshore lake areas and upper watersheds. Small subwatersheds (HUC-8 or smaller on US side, and tertiary and smaller on Canadian side) are not typically sampled consistently or at a high enough frequency and for sufficient duration to support management decisions (Betanzo, 2015). Additionally, meteorological conditions and tributary flows are monitored at a limited number of separate stations. If this information was available at a higher spatial resolution, more accurate identification and characterization of problem areas and predictive modeling would result. Original analysis completed as part of this review suggests that increased sample size and frequency, and positioning gauges in areas with similar flow distributions, should be considered when using monitoring data to determine future BMP actions (LimnoTech, 2017). Note that in many cases, concentrations are already converted to flow-weighted mean concentrations, which then can be used to compare scenarios with different discharges, such as between tributaries or for a given tributary with time (Jarvie et al., 2017).

Monitoring frequency is often insufficient to support load calculations. Sampling frequency at many stations is too low to capture important early spring or episodic events, and several monitoring programs collect infrequent nutrient concentration data, and without flow data. Stations that collect phosphorus data would be more useful if they collect concurrent flow data, and sample at a frequency greater than once per week (given the recognized importance of precipitation events leading to higher loads). Investments in monitoring that do not provide sufficient temporal resolution to capture runoff events, such as intermittent grab sampling programs, may be of limited value for supporting most management decisions.

Stable funding for sustained monitoring is commonly lacking, and monitoring networks are generally not well integrated and coordinated across agencies and geographies, nor are they optimized to support resource management decision making. As one example, measurement of total as well as dissolved reactive phosphorus is not always performed concurrently due to analytical costs.

Information on P in watershed soils is only available at a very coarse scale (Bruulsema et al., 2011). More spatially resolved soil P data are required, along with improved understanding of the extent and mechanisms of current and legacy soil P contributions to the lake.

For the open waters of Lake Erie reaction rates and fluxes are rarely measured. For example, the accuracy of water quality models would improve with empirically-derived and site specific reaction rate values for water column oxygen depletion, phosphorus mineralization, carbon oxidation and hydrolysis and algal respiration, and flux values for sediment phosphorus deposition or phosphorus release rates (LimnoTech, 2017).

Satellite instruments are limited to measurements on the surface, which prevents an understanding of the true magnitude (total biomass) of a harmful algal bloom when surface agitation and other processes cause mixing of the upper water column. Clouds can also block the view to the lake, rendering half to two-thirds of the imagery unusable for HABs monitoring (Stumpf, 2014). NASA and NOAA are working to overcome these gaps with aircraft-mounted instruments that can see the blooms when satellites cannot because of clouds. Additionally, aircraft have also been fitted with LiDAR, which can be used to characterize plankton density to some depth below the surface in the water column, depending on water clarity.

4. What is the capability of modeling to guide management decisions related to nutrient reductions?

Models are valuable tools that can provide insight into complex systems that may not be generated from field observations alone, as well as make specific predictions about future outcomes under various scenarios, including the outcomes of management interventions. Thus models can guide management decisions that may be beyond the reach of direct observation or experimentation. For example, models relating river P loads to harmful algal blooms informed the recommendation to reduce P export from the Maumee and other WLE watersheds by 40 percent (U.S. EPA, 2015).

We identify four kinds of models of relevance to WLE algal blooms: (1) watershed nutrient export models that connect land use practices to nutrient loads exported by rivers, (2) eutrophication models that connect river loads to algal blooms, (3) ecosystem (open lake) models that relate nutrients and other ecosystem drivers to lake ecological processes involving multiple components of the food web, and (4) nutrient budget (mass balance) models that compare nutrient inputs to outputs (primarily crop removal and river export) to estimate the extent of over- or under-application of fertilizers. In this review we focus on categories (1) and (4), which provide insight into the consequences of past and current fertilizer applications and land management practices for the quantities of nutrients delivered by WLE tributaries to the lake.

4.1 Watershed Models

Eleven watershed models were reviewed with respect to their hydrologic, phosphorus, and fertilizer or manure application capabilities as well as overall strengths and weaknesses. Details of these models are provided in Table 4-1 with additional details included in the LimnoTech report (2017). The capacity of each model for uncertainty analysis and sensitivity testing were not rigorously assessed, but both are important considerations in model selection and inter-comparison. Models are optimized for particular scales and phenomena and should be used for their intended purposes to simulate watershed-scale, field-scale, particular events, and/or continuous and varying conditions over a longer time period. Two models, SWAT and SPARROW, have received the most use in the WLEB and will be briefly described, focusing primarily on P and including total, particulate and dissolved forms when feasible.

Table 4-1: Comparison of 11 watershed models[19]

Model Name	Hydrologic Capabilities	Phosphorus Capabilities	Fertilizer/ Manure Capabilities	Strengths	Weaknesses
SWAT	Surface runoff, return flow, percolation, evapo-transpiration, groundwater flow. Limited tile drainage capabilities	Mineral and organic P fate and transport	Schedule and content of fertilizer or animal manure applications	Widely used and accepted. Highly customizable	Relatively simple phosphorus cycling. Poor performance in simulating tile drainage
SWATDRAIN/ DRAINMOD	Surface runoff, return flow, percolation, evapotranspiration, groundwater flow. Improved tile drainage capabilities	Only conceptual framework	Fertilizer and manure applications available for nitrogen species, only conceptualized for phosphorus	Improved tile drainage performance (hydrology) compared to SWAT	No phosphorus cycling implemented or applied to WLEB
APEX	Surface runoff volume/rate, subsurface flow, percolation, and potential evaporation. Artificial drainage systems	Soluble P runoff, leaching, mineralization, immobilization of P, and crop uptake of P	Highly customizable fertilizer and manure content and scheduling. Livestock manure production and losses	High resolution, highly detailed and customizable parameters and management practices	Difficult to parameterize with site-specific data
HSPF	Surface runoff volume/rate, subsurface flow, percolation, and potential evaporation. No specific tile drainage capabilities	Organic, soluble, sorbed, and plant phosphorus. Adsorption/ desorption, mineralization, immobilization, plant uptake	Coarse scheduling capabilities for fertilizer and manure applications. Livestock manure production and losses	Widely used and accepted. Standard hydrologic and water quality algorithms that are not overly complex	Limitations on manure/ fertilization customization. No direct tile drainage simulation
LSPC	Surface runoff volume/rate, subsurface flow,	Organic, soluble, sorbed, and plant	Coarse scheduling capabilities for fertilizer and	Simpler to use than HSPF, while maintaining a	The same limitations as HSPF apply. Additionally,

---

[19] Soil and Water Assessment Model (SWAT) and its modification to include tile drains (SWATDRAIN/DRAINMOD), Agricultural Policy/Environmental eXtender Model (APEX), Hydrological Simulation Program-Fortran (HSPF), Loading Simulation Program in C++ (LSPC), USACE Hydrologic Modeling System (HEC-HMS), SPAtially Referenced Regressions On Watershed attributes (SPARROW), AGricultural Nonpoint Source Pollution Model (AGNPS, European Hydrological System Model (MIKE SHE), CAnadian Nutrient and Water Evaluation Tool (CANWET), LandMapR. Drawn from LimnoTech, 2017 (with modifications to description of weaknesses for MIKE SHE and CANWET models, personal communication with J. Bratton).

LSPC, cont.	percolation, and potential evaporation. No specific tile drainage capabilities	phosphorus. Adsorption/ desorption, mineralization, immobilization, plant uptake	manure applications. Livestock manure production and losses	lot of the same functionality	spatial and temporal resolution is coarser and could lead to limitations
HEC-HMS	Surface runoff volume/rate, subsurface flow, percolation, and potential evaporation. No tile drainage capabilities	Simple instream fate and transport based on boundary conditions	No direct inputs for fertilizer or manure	Widely used and accepted. User-friendly graphical interface	No land based production of phosphorus, or water quality, only instream fate and transport
SPARROW	Streamflow	Total phosphorus	Geospatial inputs of areas of fertilization. Constant	Easy to use. Results available for US watersheds in web map-based tool. Based on large quantities of data	Coarse resolution. Not processed based. Lack of detailed nutrient or flow outputs
AGNPS	Surface runoff, subsurface flow, tile drain flow. Ephemeral gullies	Dissolved and sorbed forms. Processes include plant uptake, fertilization, residue decomposition, and transport	Schedule and content of fertilizer or animal manure applications	Highly customizable resolution. Somewhat unique ephemeral gully capabilities. Useful in long-term simulations or land management practice scenarios.	Not widely used. Lack of instream nutrient processes. Not suitable for winter simulations
MIKE SHE	Interception, evapotranspiration, overland and channel flow, unsaturated zone, saturated zone, snowmelt, exchange between aquifer and rivers, snow, advection and dispersion. Tile	Dissolved and sorbed phases. Optional EcoLab package extends to state of the art phosphorus cycling	Not directly incorporated	Highly customizable resolution and capabilities. User-friendly graphical interface	Not widely used (in Great Lakes). Complex, difficult to parameterize with site specific data. Requires expensive licenses

MIKE SHE, cont.	drainage capabilities. Multi-dimensional				
CANWET	Streamflow, surface runoff, subsurface runoff, evapotranspir-ation. Tile drainage spatial coverage	Total phosphorus in surface and groundwater	Spatial and temporal fertilizer inputs	GIS Based and user-friendly. "All-in-one" package for setting up running and post processing model	Not widely used (in Great Lakes). Limited temporal resolution. Simplified parameters and inputs. Lack of documentation
LandMapR	Flow path and storm surface flow	None	None	GIS based tool to guide catchment delineations and flow paths	No real watershed components except topography

4.1.1 SWAT

The Soil Water Assessment Tool (SWAT) is a watershed scale, semi-empirical, semi-spatially explicit, semi-distributed parameter, continuous simulation model that typically operates on a daily time step, although a recent upgrade can allow sub-daily computational time-steps. It should be noted that while the computations are typically performed at a daily time-step, many applications scale the output to monthly or annual aggregates for calibration purposes. The general features of SWAT include simulation of watershed hydrology, sediment loading, nutrient loading, pesticide loading, point sources, and reach routing. Special features include simulation of return flow (i.e., base flow that represents the volume of streamflow originating from groundwater), ponds/reservoirs/wetlands, channel erosion, crop growth and irrigation, tile drains, rural and agricultural management practices, calculation of sediment and nutrient loadings from urban areas, and simulation of bacteria and pathogens. SWAT is a nonproprietary, public domain model with an open source code, allowing researchers to modify algorithms or add additional processes for custom purposes.

The SWAT model has been used extensively for watershed modeling all over the world for many years. The current iteration of the model code is SWAT 2012 (Arnold et al., 2012), while previous versions (released in 2009, 2005 and 2000) are all commonly used. The current version of SWAT incorporates agricultural management practices as part of the algorithms to estimate nutrient and sediment loading. The application of fertilizer or manure to the soil is simulated in SWAT by specifying the timing, type, and amount and depth integration. The type of fertilizer is user-defined, by specifying the fractional content of mineral N, mineral P, organic N, organic P, and mineral N as ammonia. Additionally, the user can specify a bacterial content for manure applications. SWAT allows the user to either define the fertilizer application schedule, or allow the model to automatically determine when fertilizer should be applied, using a nitrogen stress threshold. Figure 4-1a shows the conceptual diagram of the nitrogen processes in SWAT, while Figure 4-1b shows the phosphorus processes.

To produce a working model, SWAT is calibrated in a series of steps to replicate a past data series of daily, weekly or monthly river discharge, and subsequently to the concentration of nutrients (P, N and their fractions) and sediments depending on available data. Due to long-term monitoring on WLE tributaries by the Heidelberg Laboratory (Heidelberg University, 2017), a number of investigators have developed SWAT models using an initial time series of several years to calibrate models, followed by validation against a subsequent time series, resulting in strong applications of this modeling platform. Once calibrated, a SWAT model may then be run under a variety of "what-if" scenarios to identify locations of greatest nutrient and sediment export and explore the consequences of different fertilizer management practices.

To estimate the land management practices required to reduce river export of total phosphorus and dissolved reactive phosphorus by 40 percent from the Maumee basin, five unique SWAT models were developed separately for the Maumee basin (U.S. EPA, 2015; Scavia et al., 2017). The project simulated 11 different land management scenarios including elimination of point source discharges, cropland conversion to grassland, and various levels (25 percent to 100 percent) of infield practices, nutrient management, no tillage and subsurface placement of P fertilizer, along with diversified rotation and wetlands and buffer strips. The key findings of this work suggest that to achieve targeted P load reductions of the order of 40 percent, large-scale implementation of combinations of the 11 different practices would be required, targeted to locations where greatest nutrient loss is estimated to occur.

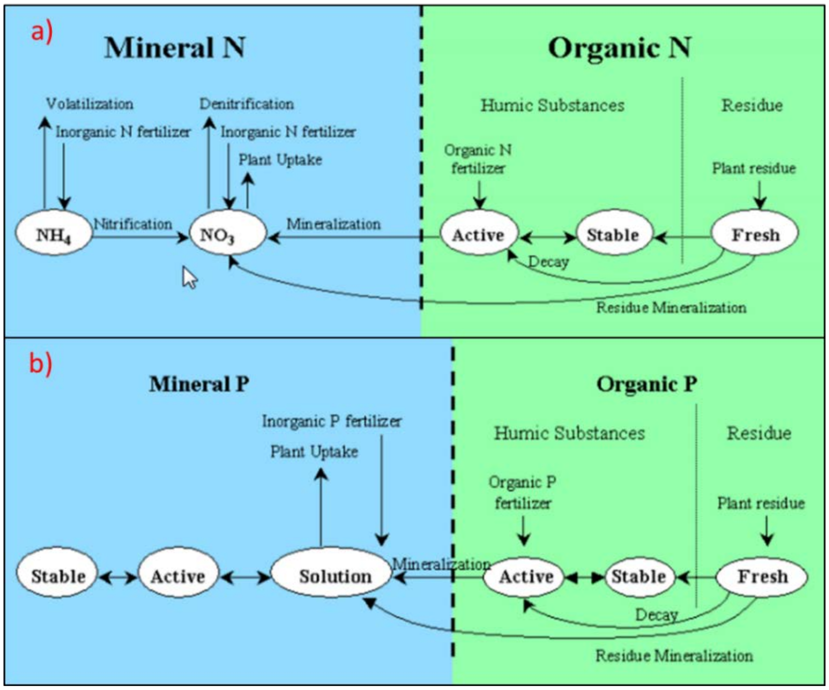

Figure 4-1 Conceptualized nitrogen (a) and phosphorus (b) processes in SWAT. (Reprinted with permission from Neitsch et al., 2011. Copyright 2011 Texas Water Resources Institute)

Using a separate SWAT model of the Huron, Raisin, Maumee, Sandusky, Cuyahoga and Grand watersheds, Bosch et al. (2013) also concluded that multiple management practices would be required to reduce riverine P loads. Modeling also revealed that sub-watersheds with high DRP and TP yields were not uniformly distributed within the larger watersheds, suggesting that management practices targeted at specific locations would be most effective in reducing loading.

Muenich et al (2016) used a SWAT model to explore the timeline of P load reduction for the Maumee River under a range of nutrient and land management scenarios. This analysis found that even if fertilizer application ceased, it may take years to see desired decreases in phosphorus loads under average climate conditions and decades if spring precipitation or snowmelt should increase. This study also found, consistent with Bosch et al. (2013), Kalcic et al. (2016) and Scavia et al. (2017), that multiple agricultural conservation practice with widespread implementation are required to see consistent P-load reductions because no single practice can achieve the target loads every year. However, Muenich et al. (2016) found that DRP loads could drop relatively quickly under average weather conditions, highlighting both the importance of current P-fertilizer applications in driving a given year's loads as well as the importance of hydrology.

Recent years have seen widespread use of SWAT to model nutrient reduction scenarios, and results have important implications for addressing Lake Erie eutrophication:
(1) Realizing significant reduction of riverine nutrient loads from Lake Erie tributaries will require multiple conservation practices, including nutrient management, reduced fertilizer application and various land management practices.
(2) Reduction of nutrient loads may take years to decades, with wetter climates resulting in longer recovery timeframes.
(3) SWAT is a valuable modeling tool for providing specific guidance for nutrient management. Fortunately, ongoing work is intended to maintain the multiple model framework that was developed in Scavia et al. (2017), to assess the 4R nutrient stewardship and certification programs, and to model watershed inputs of nutrients to the Detroit and St. Clair Rivers, including the subbasins for the Clinton, Rouge, Sydenham and Thames rivers, as well as point source discharges.

Finally, it is important to be aware of two limitations of SWAT (and other models). First, because it is not possible to determine what fraction of nutrients at the river mouth are from recent (0-12 months) fertilizer applications vs. nutrients that have accumulated in watershed soils over decades (legacy P), SWAT is calibrated as if all P is recent. This also causes issues with initialization of the model as well, given that data to constrain starting P in soil are generally not available at most scales. A second limitation is the inability to incorporate the extent and locations of existing BMPs due partly to prevailing privacy policies and also to lack of spatially detailed information on fertilizer application practices. As a consequence, model scenarios that explore the benefits of an expansion of conservation practices essentially either assume zero current implementation as a baseline, or require broad assumptions on the state and locations of existing practices. However, a recent study by the USDA NRCS Conservation Effects Assessment Project (CEAP) used farmer survey data to compare extent and impacts of existing conservation practices in 2003-2006 versus 2012 and hypothetical future scenarios, showing benefits of current conservation practices (USDA, 2017b).

4.1.2 SPARROW

SPAtially Referenced Regressions On Watershed Attributes (SPARROW) is a relatively simple watershed model developed by the USGS, and has been applied for the majority of watersheds in the United States to simulate loading of phosphorus, nitrogen, organic carbon and sediment. Spatial resolution of the model has increased in recent years and can operate on the NHD+[20] spatial scale. While most site-specific watershed models are process-based, SPARROW uses non-linear regressions to describe transport of contaminants from point and nonpoint sources. Instream contaminant concentrations, fluxes and yields are simulated based on characteristics of the watershed and contaminant sources. These inputs can include soil, slope, land use, census data, meteorological data, sewer and septic area, agricultural practices and point source discharges. SPARROW allows the user to estimate the relative contribution of each contaminant source to the overall loading estimate, and fertilizer use is accounted for by geospatial data inputs that define where the fertilizer and/or manure are applied.

Robertson and Saad (2011) have developed a regional SPARROW model that covers the US side of the Great Lakes basin, as well as upper Mississippi, Ohio and Red River basins. The model has fairly coarse spatial resolution, operating earlier on the HUC-8 scale, or approximately 1,800 km^2 subbasin size. Based on 2002 input data, the model estimated that farm fertilizer was the source of approximately 26 percent of the delivered phosphorus load to Lake Erie, and approximately 30 percent of the delivered nitrogen. Further, the input from all agricultural practices (including commercial fertilizer, manure and organic matter decomposition) was estimated to be approximately 58 percent of the total load to Lake Erie. The Great Lakes basin SPARROW output was also used as a comparison to SWAT model runs in the Scavia et al. (2016) multi-model project for the Maumee River watershed in the WLEB. Among other findings were differences in export of P from different sources – i.e., SPARROW assumed higher manure application in the upper portion of the watershed, and higher delivery ratio for manure as compared to inorganic fertilizer than did SWAT (Scavia et al., 2016). A binational project between USGS, the IJC and the National Research Council (NRC) of Canada is currently underway, and is working to refine the Great Lakes region SPARROW model to include the basins on the Canadian side as well (IJC, 2017b).

4.2 Western Lake Erie harmful algal bloom forecasting model

Stumpf et al. (2016) refined a previous empirical model to forecast the severity of harmful algal blooms in the western basin of Lake Erie. The model uses the Maumee River discharge, and total bioavailable phosphorus load from March to July of a given year. It also includes a temperature factor, where loads from July are excluded from the independent variables when the June water temperature was below 17^{o} C, the

---

[20] National Hydrography Dataset Plus (NHDPlus) is a national geospatial surface water framework operating at the 1:24,000 resolution or better

temperature threshold for *Microcystis* growth. The model has been used to estimate seasonal HAB severity for 2015 through 2017. Other similar models and forecasting constraints that have been applied in the annual NOAA ensemble forecast for Lake Erie HABs are described by Obenour et al., 2014; Bertani et al., 2016; Ho and Michalak, 2017.

4.3 Mass balance models

Mass balance (nutrient balance, crop balance) models attempt to quantify all major inputs and outputs from a watershed or other spatial unit, typically for P, N or carbon (C), thereby providing an estimate of whether inputs and outputs are in balance (Figure 4-2). An imbalance can indicate whether an element such as P is accumulating or stored material is being depleted. The necessary data are available at various time intervals (often from agricultural censuses every five years) at the county or state level, and can be spatially redistributed to individual watersheds using GIS. Inputs may include fertilizer application, atmospheric deposition and natural weathering (both usually minor and may be excluded), and human inputs (waste, detergents), which can be approximated from human population data and also are minor in sparsely populated agricultural watersheds. A partial P balance that compares fertilizer inputs to crop removal thus provides a reasonable estimate of whether a watershed is accumulating P.

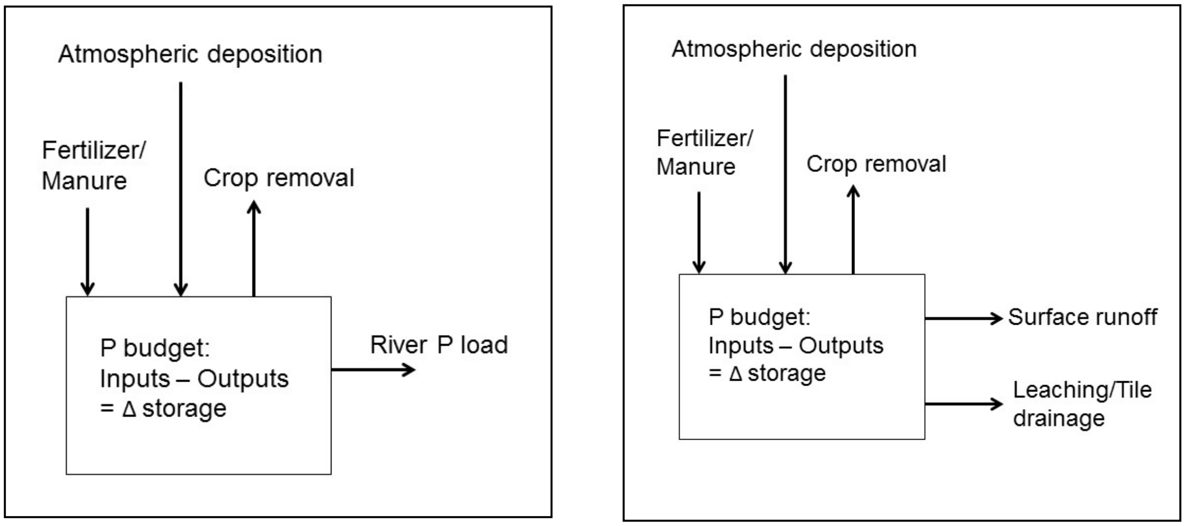

Figure 4-2 A mass balance or P budget diagram showing inputs and outputs. Left: watershed scale. Right: field scale. Note in this conceptual approach, P losses to and transport in groundwater are not explicitly captured.

Several studies have estimated watershed P balances for the watersheds of WLE over past decades. Results are broadly consistent with a global pattern identified by Powers et al. (2016): human-dominated watersheds undergo a prolonged but finite period of P accumulation when P inputs exceed crop demand and crop P yield, often followed by a decline towards a near-zero balance between P inputs and crop P removal. Declining P application and increasing P removal in crops, as described earlier for the WLEB (Chapter 2), are responsible. Although a welcome sign of positive trends in farm management, the P accumulated in earlier years may continue to mobilize long after inputs decline.

Examining P loading trends for 18 Lake Erie watersheds from 1935 to 2007, Han et al. (2012) found a rising P surplus that peaked during the 1970-1980 time period before beginning to decline. The surplus during earlier decades presumably accumulated within the watershed. Studies by Bast et al. (2009) and Bruulsema et al. (2011) likewise found a downward trend in the balance between the major inputs and outputs of P to the soils of this region, noting that in recent years, actual P applications have come much closer to balancing removals while crop yields have increased (Fig. 4.3).

Depending on various assumptions, estimates of the P balance for the region in 2008 range from a surplus equivalent to 1 percent of crop removal to a deficit amounting to 23 percent of the amount of P removed by crops. Most recently, Jarvie et al. (2017) estimated partial P balances for the Maumee, Sandusky and Raisin watersheds. In recent decades mean annual P applied to cropland increased by 4 and 6 percent in the Sandusky and Maumee watersheds and showed an 11 percent reduction in the Raisin. Over the same interval, the average annual P removed in harvested crops increased by 25 percent in the Sandusky and 18 percent in the Raisin and Maumee watersheds. As a consequence, the average annual cropland partial P balance declined: from 3.13 to 0.23 kg P ha^{-1} yr^{-1} in the Sandusky, from 0.97 to −1.38 kg P ha^{-1} yr^{-1} in the Maumee, and from −0.61 to −4.74 kg P ha^{-1} yr^{-1} in the Raisin. Finally, as noted in Chapter 2, new calculations by LimnoTech (2017) found that application rates in 2012 averaged 11 kg P ha^{-1} across US watersheds, with a maximum in the Sandusky watershed at 19 kg ha^{-1}. In Canada, rates in 2007 averaged 16 kg ha^{-1}, with a maximum in the Essex region watersheds at 26 kg ha^{-1}. Crop-removal across the US WLEB (based on IPNI-NUGIS, 2012) ranges from approximately 11 to 22 kg ha^{-1}. Thus, recent phosphorus application rates for fertilizer are similar to crop removal rates. In addition, field-scale P budgets for Ohio fields now ongoing[21] show that P application levels can be substantially above or below the break-even point, and on average are in the negative or drawdown range. It will be important to continue to track this issue. For example, Bruulsema (2016) showed

---

[21] King, K., personal communication.

that though commercial fertilizer application had been relatively flat through the late-2000s in Ontario, there was then a general increase through 2012.

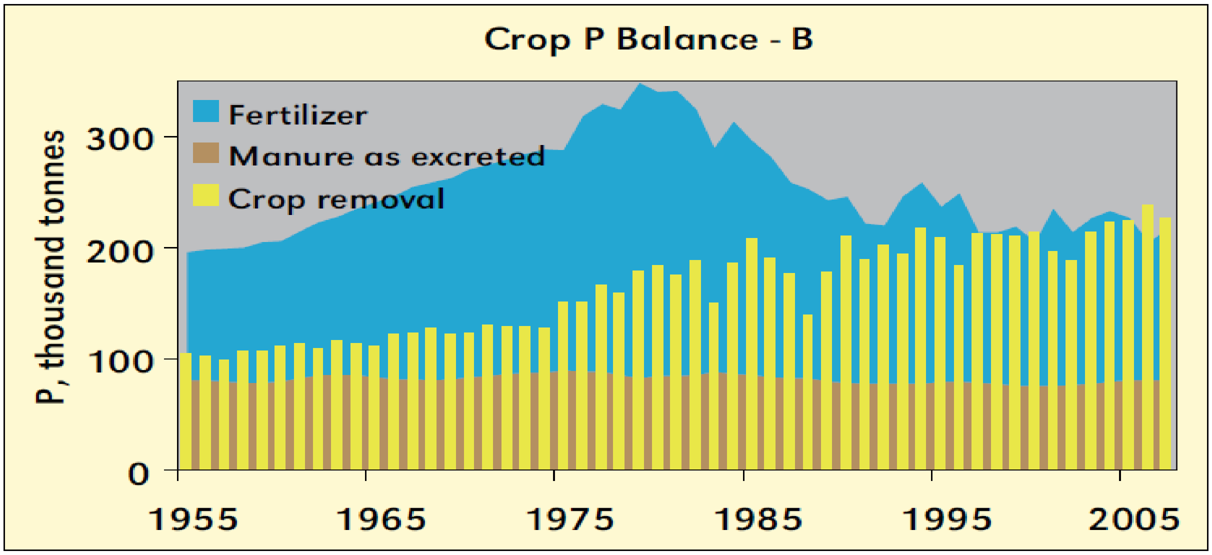

Figure 4-3 Summary of P balance over time for Ontario, Michigan and Ohio (entire state/province, not watershed, and not including Indiana). Note that only about half of manure P excreted is applied to crop fields. (Reprinted with permission from Bast et al., 2009. Copyright 2009 International Plant Nutrition Institute)

Summarizing the above studies, nutrient budget studies generally show a strong and encouraging trend towards P fertilizer application at or below crop removal of P, but two caveats are important:

(1) local-scale studies reveal considerable variation, with some fields in positive and others in negative balance.[22]

(2) Even a small 'leakage' of excess P may be sufficient to contribute to algal blooms, particularly since the quantities of P added as fertilizer and removed as crop yield are large relative to quantities exported from fields. For example, in a study of a watershed in central Ohio, King et al. (2014a) estimated DRP export via drainage tiles at 1.6 percent of applied P to the fields, and earlier research in Illinois indicated an even smaller percentage in runoff. However, P export as a percentage of net inputs (i.e., P application minus crop removal) will obviously be much larger, in considering Figure 4-3.

Data on soil test levels available from IPNI-NuGIS (2012) at the state and provincial level are consistent with the above analysis, as previously noted (Chapter 2). Data indicate the continued existence of a surplus (>50 ppm) in 26 percent of soil samples in the region overall, as well as a downward trend of the proportion of soil test results in

---

[22] King, K., personal communication.

this higher than optimum category, with the largest decreases seen in Michigan and Ontario (Bruulsema, 2016).

In sum, P balances for Lake Erie watersheds agree that fertilizer application rates are moving towards, and in many areas may be in balance with, P removal in crop harvest. In addition, the surplus of soil P as indicated by soil test levels is declining. These findings imply that while soil P concentrations are decreasing and drawdown of legacy P is occurring, the P accumulated in earlier years may still contribute to current riverine P export. If this is the case, then further reduction in P fertilizer application, increases in P removal via crop harvest, and improvement in P retention on the land may be called for in order to speed the drawdown of stored P and lessen P export.

4.4 Summary and data gaps

Water quality models have been developed or are being developed for much of the WLEB at varying degrees of spatial and temporal resolution. A variety of numerical modeling programs (software) exist that simulate agricultural P cycling. Some programs are freely available while others are proprietary. High-speed supercomputers and computing clusters, along with high-bandwidth networking, large data and output storage systems and trained staff, are generally available and capable of running modeling programs in research mode (although not necessarily operational mode) at multiple institutions in the region.

Watershed models, in particular SWAT, have been used to develop deeper understanding of the mix of management practices including source reduction, infield management and BMPs needed to achieve significant reduction in riverine P export and thereby ameliorate the risk of nuisance and harmful algal blooms. It is important to note that other models are available to address issues of concern in this assessment. For example, the Agriculture Policy/Environmental eXtender (APEX) model is a semi-process model operating at the field to small watershed scale, and over time scales ranging from daily to decades (see Table 4-1). The model can examine impacts of conservation scenarios on nutrient export (with significant customization of inorganic fertilizer and manure application information), including consideration of both surface and subsurface (i.e. tile) runoff (Ford et al., 2015).

Watershed modeling using SWAT supports two main inferences:
(1) significant reduction of riverine nutrient loads from Lake Erie tributaries will require wide implementation of multiple conservation practices, and

(2) due to the possible importance of stored P, reduction of nutrient loads may take years to decades, with wetter climates resulting in longer recovery timeframes.

Both SWAT and mass balance approaches have important limitations. Key system inputs and exports in SWAT are based on present-day fertilizer application and river loads, as inputs of P accumulated in soils over past years are not explicitly included (although users can set soil phosphorus levels). In contrast, the IROWC_P framework under development in Canada (though itself not a formal watershed model like SWAT) allows for consideration of both cumulative P additions and degree of soil P saturation in development of the P source component (Van Bochove et al., 2009). In addition, as noted above, the extent of current BMP implementation is often not accounted for (due to data limitations), and thus scenario results with management strategies are in addition to whatever is currently in place (i.e., they may be overestimating the extent of additional implementation that is feasible). A notable exception to this is recent CEAP work in the WLEB, where estimates of conservation practice implementation in 2003-06 and 2012 were utilized in SWAT modeling (USDA, 2017b).

Furthermore, a common limitation in many watershed models (including SWAT, APEX and AGNPS) is general reliance on soil phosphorus routines developed in the 1980s, with only minor updates, in spite of advances in understanding of P availability and transport. Other needs identified to improve model operations include having more information on P availability (i.e., soil characteristics, data beyond agronomic tests); both infield and post-edge-of-field transformation processes; influence of animal diet, manure chemistry and management on P mobilization; and P speciation and transformation in fields following manure application, including translating P data from different analytical approaches into model parameters (Vadas et al., 2014).

Mass balance models and empirically determined nutrient budgets provide insight into the relationship between P inputs as fertilizer and P removal as crops, and provide strong evidence of past surpluses leading to P storage within watershed soils and along the river network. These results also indicate that surplus P inputs in general have been declining for several decades, and soil test P levels similarly show generally declining trends. It will be important to determine whether these trends have continued over the recent past and will continue, in particular given the potential for a relatively small fraction of exported watershed P to contribute to downstream impacts.

5. What additional factors deserve consideration?

It is widely accepted that nonpoint nutrient runoff from agricultural lands of the WLEB is the primary source of excess nutrients delivered to the lake and thus is responsible for present-day eutrophic symptoms (Scavia et al., 2014). The eutrophication of Lake Erie in the 1970s was largely caused by municipal sources, and the lake recovered quickly and substantially following construction of improved water treatment facilities and detergent bans (DePinto et al., 1986). As these point sources were reduced, in recent decades nonpoint runoff from agricultural sources has been understood to be the primary cause of WLE algal blooms and central basin hypoxia. While addressing fertilizer use remains a key priority and is the central focus of this report, additional factors may play a role in either contributing to current problems or making their amelioration more challenging. A recent review highlighted two dozen factors to consider as potential contributors to increased HAB occurrences in the WLEB (Smith et al., 2015a), and several of these are explored in more detail below.

5.1 Increasing DRP in river runoff

For the Maumee and several other WLE tributaries, detailed analyses of nutrient loads and concentrations have been undertaken using approximately daily concentration data for phosphorus, nitrogen and other constituents collected by Heidelberg University since the late 1970s in combination with available United States Geological Survey (USGS) discharge monitoring records (Stow et al., 2015). Analyses of annual phosphorus loads and flow-weighted mean concentrations from the Maumee River revealed substantial increases in bioavailable phosphorus forms (primarily DRP) since the early 1990s, while TP concentrations have changed little or decreased slightly (Baker et al., 2014).

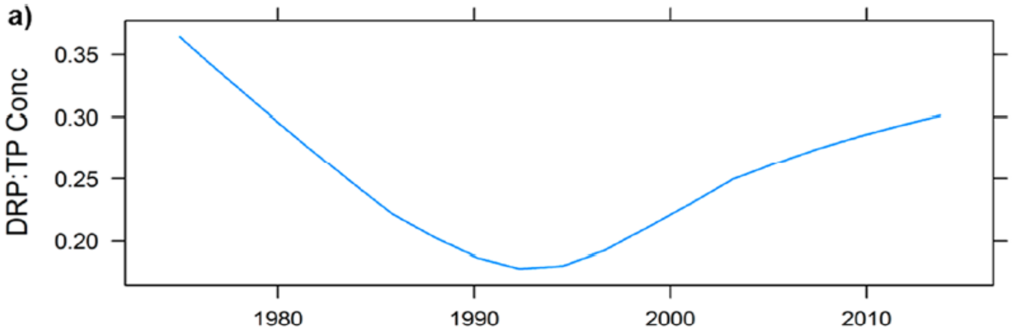

Figure 5-1 Smoothed, long-term trend for the DRP/TP concentration ratio in the Maumee River. (reprinted with permission from Stow et al. 2015. Copyright 2015 American Chemical Society)

Results are further complicated by a long-term increase in precipitation and hence river discharge. TP concentration decreased markedly from 1970 to about 2000, followed by a moderate increase. Maumee River TP loads decreased to about 2000 as well, but have since increased to approximately 1970 levels, due to increased river discharge (load = concentration x discharge). DRP concentration in the Maumee River declined to its lowest level around 1990 and has since increased, and this increasing river discharge has led to even greater quantities of DRP reaching the WLE. The extent to which other river systems show the same trend is uncertain. Monitoring data for the Thames since 1986 show decreasing mean DRP and no trend in TP for the Upper Thames, with DRP steady and TP decreasing for the Lower Thames (Maaskant, 2015).

In addition to increasing DRP loadings in the Maumee River, the ratio of DRP:TP has increased since the 1990s, as shown in Figure 5-1. The increase in DRP loading from the Maumee River in particular coincides with the re-eutrophication of Lake Erie and is a probable cause of increased algal blooms due to the greater bioavailability of DRP relative to particulate P (Baker et al., 2014). Several possible explanations for the pattern shown in Figure 5-1 have been offered, and are considered below.

5.2 Legacy P

Legacy P refers to P that has accumulated in soil due to P fertilizer applied in excess of P removed as crop yield over past years. It does not have a unique chemical signature,[23] and thus any reported measurement of TP, DRP, etc. includes an unknown mix of P applied recently and P that may have been applied years or decades earlier. The existence of catchment stored P is inferred from nutrient budget models (Han et al., 2012; Jarvie et al., 2013; King et al., 2017; Bast et al., 2009), where a positive imbalance implies storage (Figure 4-3), as well as from soil P profiles (Section 5.3) as they change over time. The observation that riverine TP export has shown negligible downward trend (Stow et al., 2015) while fertilizer applications have declined and crop yields have increased (Chapter 2) may also indicate that P applied in previous years and decades is contributing to present-day nutrient export to WLE. Increasing attention is being given to estimating stored P in soils that have accumulated from past nutrient additions (Canadian Water Network, 2017).

Several hydrological and biogeochemical processes delay the responses of streams and rivers to a decrease in nutrient and sediment inputs, potentially for decades (Hamilton,

---

[23] However, note discussion in Chapter 3 on emerging research to potentially distinguish manure versus commercial P sources.

2012). The long travel times associated with groundwater pathways, often over more than a decade, may be partly responsible. While it is well recognized that groundwater pathways can be important with respect to nitrate transport from fields to tributaries, the role of groundwater in delivering P to tributaries has been thought to be negligible due to the tendency of P to associate with minerals or sediment amorphous phases containing aluminum, iron and/or calcium-containing compounds. However, recent evidence suggests that P may be mobile in groundwater, and thus this may be an important transport pathway under some conditions (Holman et al. 2010; Jarvie et al. 2017; Knights et al. 2017). Few studies have directly examined the role of groundwater in P loads to Lake Erie. The tendency of P to associate with minerals and sediment phases can also result in a potentially large yet exchangeable P reservoir in upland soils and alluvial and stream-bed sediments, which may later be released. An additional issue that has not received as much attention in the WLEB is more detailed study of P associated with organic matrices (e.g. soil organic matter), in which P can also be either more stable or available for release back into soil water (Sharpley, 2006).

One indication of the persistent availability of stored P is that DRP is mobilized and peaks with similar intensity in sequential rain events, showing no signs of within-season depletion as would be expected of a more limited current application pool (King et al., 2017). Powers et al. (2016) estimated that the Maumee basin has accumulated over 200 kilotons of P beyond the inventory that existed in 1970; drawdown of this pool has been underway since the 1980s. Modeling the Maumee River watershed and various conservation practice scenarios, Muenich et al. (2016) determined that even if fertilizer application ceased entirely, it may take years to see decreases in phosphorus loads of the magnitude desired. That study also evaluated the effects of fertilizer reductions on crops, and found that with no additional phosphorus, it would take 25 years to significantly affect crop yield, highlighting the capacity of the accumulated phosphorus to support many years of crop growth.

Phosphorus may also have accumulated to saturation in some non-agricultural compartments such as buffer zones, filter strips, wetlands, riparian zones, ditches/drains and ditch/drain sediments, and river channels. Because these systems do not have an outlet for phosphorus via crop harvest, it is hypothesized that these compartments of the greater landscape may be shifting from P sinks to slow-release P sources (Jarvie et al., 2013; Dodd and Sharpley, 2015). As summarized by Sharpley et al. (2013), each type of compartment, dependent in part on spatial scale, has a half-life or lag time of phosphorus reduction spanning from decades to centuries (see Figure 5-2).

The relative importance of background P loading from these compartments is a function of both residence time and effective area, so larger soil or sediment reservoirs that contain P that can be mobilized over time are more important sources than smaller reservoirs, given comparable concentrations and mobility. The role and behavior of legacy P in systems such as this is an area of active research, and is also largely outside of current management and policy consideration.

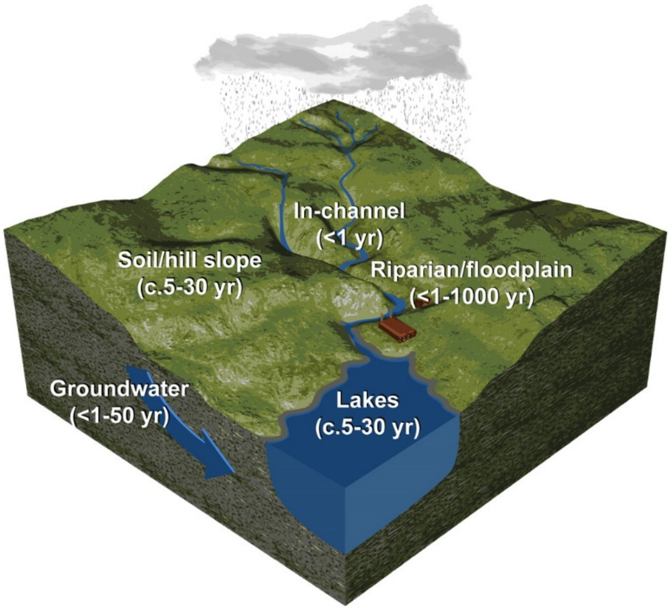

Figure 5-2 Typical time scales for phosphorus (P) retention and recycling in watershed and waterbody legacy P stores. These result in a continued chronic release of legacy P, impairing downstream water quality over time scales of years to decades, or even centuries. (Reprinted with permission from Jarvie et al., 2013. Copyright 2013 American Chemical Society)

While P stored in non-agricultural compartments may be challenging to address, legacy P in agricultural soils can be addressed with 4Rs and other conservation practices, and growth and harvest of crops provide a pathway for significant removal of phosphorus from the system. This approach would address both of the major nutrient sources of interest (commercial fertilizer and manure) in this assessment. Under these conditions of ongoing surplus P in soils, the time lag to water quality improvements and source reduction of elevated soil P is on the scale of a few years to two to three decades (Hamilton, 2012; Sharpley et al., 2013). Stored P in agricultural soils might best be viewed as a valuable resource, and management should focus on how best to ensure that it contributes to crop yields through efforts to minimize transport loss and draw down stored P through crop uptake and harvest. Such an effort would require closer collaboration between researchers, crop advisors and farmers in identifying areas where this approach may be particularly fruitful (Sharpley, 2016).

5.3 Changing farm practices

While about one-third of the increase in the Maumee River's DRP load after 2002 was attributable to higher runoff volumes, the remaining approximately 65 percent increase must be attributed to other causes (Jarvie et al., 2017). Two possible explanations have received considerable discussion: the conversion of land to no-till and minimum till cropping systems, allowing the potential buildup of labile P fractions in the soil surface and the development of macropores due to root decay; and the installation of additional tile drains, thereby increasing the efficiency of runoff conveyance. These farming practices have increased or remained commonplace over the past one to two decades (although trends in tile drain installation are not easily documented), coincident with increased DRP export and occurrence of algal blooms. It is important to note, however, that in addition to no-till and tile drainage, as many as 20 other factors have been postulated to contribute to the increasing algal blooms, including increased soil compaction, decreased soil organic matter, P timings and methods of application, increased intense storms and larger farm sizes, among others (see Section 5.6) (Smith et al., 2015a).

5.3.1 No-till cropping systems

Reduced till and no-till agriculture practices, intended to reduce sediment and particulate P loss due to erosion, have been very successful in reducing TP loads (Dodd and Sharpley, 2015). However, the effects of reduced tillage on the vertical distribution of phosphorus have brought new problems. Reduced tillage leads to accumulation of P in the uppermost layer of soil, which is then more available for transport (Kleinman et al., 2015). In addition, reduced or zero tillage allows the formation and maintenance of soil macropores which efficiently shunt or short circuit the elevated surface P to subsurface P transport pathways, namely tiles (Smith et al., 2015b). In combination with climate change, then, elevated surface P concentrations enhance the probability of increased P losses, especially in dissolved form (Kleinman et al., 2015). Conservation practices such as 4Rs and others have the greatest potential to mitigate the impact of tillage in facilitating P loss via tile drains while continuing the benefits of no-till in reducing P loss in surface runoff (Kleinman et al., 2015).

5.3.2 Tile drains

Subsurface artificial drains are a crucial component of agricultural production in poorly drained soils, many of which are present in the midwestern United States and southern Ontario. Generally, agricultural fields gain subsurface drainage through the installation of field tile, a perforated pipe made primarily of high density polyethylene (HDPE) that can range in diameter from 3 to 6 inches (76 to 152 mm). The small-diameter HDPE tile tubing is laid in either a systematic pattern over the whole field or applied just to certain wet spots within the field. Tiles can drain into either a surface drainage ditch at the field edge or into another larger tile called a 'main.' In the United States, these tiles are typically installed at depths of 3 to 4 feet in the soil profile for soils with moderately low to very low subsoil permeability, and are spaced from 35 to 130 feet apart (Wright and Sands 2001). In the cooler, shallower soils of Canada, tiles are commonly placed at depths of 2 to 3 feet (60 to 90 cm) with spacing of 25 to 60 feet apart (~ 7.5 to 18 meters).[24]

Tile drains are utilized to lower water tables and remove excess water following periods of precipitation or snowmelt. Their installation allows producers to maintain field access and improve plant survival through increased root aeration. These drainage tiles can also carry a substantial amount of flow from the flat or nearly flat fields that are common in much of the western Lake Erie basin (WLEB). A review of tile drainage literature in support of an Indiana SWAT modeling study found that average tile flow amounted to 23.2 percent of annual precipitation on tile drained fields (Boles et al., 2015), and values higher than 50 percent have been measured in Ohio (King et al., 2014a).

Few data exist that quantify actual trends in tile drainage in the WLEB. One exception is the recent USDA CEAP assessment, which reported an increase in tile-drained acreage from 3.4 to 3.8 million acres in the US portion of the WLEB in comparing 2003-06 and 2012 conditions but per acre P drainage rates declined slightly (USDA, 2017b). Anecdotal evidence suggests an interest in tighter spacing of tile lines. Any increase in tile extent or density likely will increase the fraction of runoff moving through the tile system. Since 2008, installation rates may have also been affected by changes to Section 179 of the US tax code through the addition of a 'bonus depreciation,' which allowed producers to more quickly depreciate major purchases, including new drain tile installations. Data on the extent of artificial drainage may be more comprehensive in Canada, with an Ontario assessment indicating nearly 19,000 miles (30,400 km) of new tiles installed annually (Pearce, 2011).

While phosphorus was not historically believed to be prone to tile transport due to soil adsorption, recent research has indicated otherwise. Christianson et al. (2016) reviewed

---

[24] Joosse, P., AAFC, personal communication, 2017

over 400 agricultural drainage publications from locations throughout the United States and Canada. Dissolved and particulate phosphorus loadings from subsurface drainage sites were generally found to be less than 1 kg-P/ha per year, consistent with findings in Ohio edge-of-field studies (King et al., 2014a). Total phosphorus lost in tile drainage water was less than 4 percent of the applied amount in 90 percent of cases. As noted in Chapter 2, no significant differences were observed between commercial and organic fertilizer applications in terms of P loss to tile drainage. No-till plots had a higher dissolved phosphorus load (median 0.12 kg-P/ha) than found with other conservation and conventional tillage plots (median 0.04 kg-P/ha), consistent with other published findings. King et al. (2014b) reported on multiple studies showing subsurface phosphorus transport to be greater under no-till when compared with conventional tillage. This may be because continuous no-till plots do not experience phosphorus mixing within the soil profile that comes with tillage, and there are increased opportunities for preferential flow to tiles via vertical macropores that develop over multiple seasons without tillage. Small-plot studies in Ohio (King et al., 2014a) and Ontario (Zhang et al., 2017) revealed that tile flow total phosphorus concentrations can be even higher at some locations.

P transported through tile drains may be an important contributor to algal blooms. Research by Smith et al. (2015b) on agricultural fields in the St. Joseph River watershed showed rapid hydrological response of tile drains (similar to surface runoff), and reported approximately 50 percent of loading (of both DRP and TP) occurred via tile drains. Kane et al. (2014) showed that Maumee DRP inputs directly drive algae biomass growth in WLE, so the connection between tile drain DRP and Lake Erie algae growth may be quite direct.

Adoption of 4R practices, including subsurface placement, can reduce P losses to some extent, but additional conservation practices are needed (Kleinman et al., 2015). Edge-of-field studies also have found positive outcomes from implementation of 4R practices. Williams et al. (2016) studied the effect of placement on macropore flow and phosphorus transport to tile drains. Findings indicate that incorporating surface-applied P fertilizer, as compared to leaving it on the surface of a no-till field, reduced the dissolved P concentration in tile discharge by 45 percent. King et al. (2017) also found in several edge-of-field studies in the Lake Erie basin that the 4R approach reduced phosphorus losses both in runoff and in subsurface drainage. At this time, however, while some studies suggest an important role for 4R practices, questions remain on their efficacy in improving water quality in a wider variety of watersheds for both P (Christianson et al., 2016) and N (Christianson and Harmel, 2015a) and point to an area where ongoing research is needed.

5.4 Nutrient ratios

An additional consideration is the ratio of nutrients in fertilizers. Nitrogen:phosphorus ratios are variable in manure as briefly noted in Chapter 2 (e.g., generally lower in poultry litter compared to swine manure), but are lower than the ratio appropriate for major grain and hay crops. Hence, aiming to meet crop needs on a nitrogen basis exclusively by manure can lead to over-application of phosphorus. On the other hand, if farmers restricted manure application to crop demand on a P-basis, there would be an N shortfall, requiring additional commercial fertilizer application (Sharpley and Jarvie, 2012). In general, the application of fertilizers with different nitrogen:phosphorus ratios[25] and subsequent transformation and transport processes that affect certain nutrient forms but not others (e.g., loss of DRP through binding to soil, loss of soil N by denitrification) can lead to varying nitrogen:phosphorus ratios measured throughout the WLEB, including in tributaries and Lake Erie itself (Prater et al., 2017). A related issue is that laboratory and field experiments indicate that nutrient ratios – and even nitrogen concentrations alone, in certain conditions - may be important in cyanobacterial dynamics in Lake Erie, including bloom growth, toxin production and shifts in species populations (Chaffin et al., 2011; Davis et al., 2015).

5.5 Changing climate

The phosphorus load delivered by rivers to Lake Erie is governed by concentration and discharge, and because discharge varies much more than concentration, years of high precipitation and discharge are also years of high P loads. This is the basis for models predicting the severity of HABs for WLE in any given year (Stumpf et al., 2012). The (then) record-setting algal bloom of 2011 occurred following meteorological conditions that produced record-breaking nutrient loads, as a result of a series of large storm runoff events during late winter to early summer. Climate forecasts suggest that similar spring precipitation events may become more common in the future (Michalak et al., 2013). Thus it is important to consider the effects of future climate conditions for nutrient runoff.

Analysis of seasonal and long-term patterns for the Maumee River watershed found that monthly average precipitation was relatively steady from around 1975 into the late 1980s, declined somewhat in the early 1990s, then showed a steady increase from the

---

[25] Inorganic fertilizer can have lower N:P ratios; e.g. Rehm et al. 2002.

mid-1990s through the end of the record (Stow et al., 2015). This trend in precipitation was mostly mirrored in Maumee River discharge trends which, most notably, showed a strong increasing trend from the mid-1990s to the end of the record. Water quality records showed a steady decrease in total phosphorus (TP) concentrations from the mid-1970s until about 2000 before increasing slightly, so that TP concentrations were approximately 20-30 percent lower at the end of the record than at the beginning (Stow et al., 2015). Dissolved reactive phosphorus (DRP) concentrations showed the decrease and subsequent increase, as seen in Fig. 5.1. However, the discharge trend so strongly influenced river export that, though both TP and DRP concentration trends ended at lower points than the beginning of their respective records, their loads to the lake were as high as or higher at the conclusion of the analytical period than at the beginning. In another analysis of Maumee River trends, Jarvie et al. (2017) concluded that about one-third of the increased DRP load of the Maumee River since 2002 was attributable to higher runoff volumes.

A continuing trend of increasing river discharge substantially complicates the ability of nutrient management to reach target goals. As Stow et al. (2015) point out, continued river discharge increases into the future may affect attainment of target P loads even if phosphorus reduction strategies are successful. Thus, achieving substantial reductions in P load may require phosphorus concentrations to be persistently lowered to compensate for increasing discharge. A SWAT application found that river P loads would decline significantly in a few years in response to cessation of fertilizer application under a moderate climate, but such a response could take decades in a future, wetter climate (Muenich et al., 2016). Thus it is concerning that studies in the Lake Erie basin have projected increasing precipitation over the 21st century. A climate simulation by Michalak et al. (2013) indicated that precipitation events which exceed 20 mm are expected to increase in frequency by approximately 50 percent and the frequency of events which exceed 30 mm could be expected to double. The importance of event-based export of P from watersheds calls attention to the need to better understand the efficacy of management practices during short-lived extreme events, as opposed to average conditions (Canadian Water Network, 2017). It is important to note that climate projections for the region remain uncertain (including potential changes in seasonal precipitation patterns), and some recent studies have indicated that multiple factors (e.g. increased evaporation, plant growth) could lead to minimal change or even decreasing discharge and/or P export in the region later this century (e.g., Cousino et al., 2015; Verma et al., 2015; Culbertson et al., 2016; Pease et al., 2017). Finally, in addition to affecting loads, climate change can influence HAB development in other ways, including through generally warmer water temperatures and effects on lake stratification (e.g., Watson et al., 2016).

5.6 Additional factors

Smith et al. (2015a) summarized additional factors that could potentially play a role in the increasing extent of HABs in the WLEB in the past decade. Factors specific to agricultural activities include potentially increased corn or corn-soybean rotations for biofuel production, although crop area data compiled for this assessment do not indicate major changes through 2012 (LimnoTech, 2017); changes in fertilizer source in the mid-1990s to forms that are potentially more available for loss, and that may be more difficult to apply in smaller quantities; greater application of fertilizer during the non-growing season; and issues with soil testing and analysis, including reliance on soil tests developed before conservation tillage was widely adopted, and lack of standard approaches for analysis and reporting in labs (Smith et al., 2015a).

5.7 Summary and data gaps

Because only about one-third of the increase in the Maumee River's DRP load is attributable to higher runoff volumes, two-thirds of this increase must be attributed to other causes. The widespread adoption of no-till and minimum till cropping systems may have contributed by allowing P to accumulate in the soil surface and by allowing macropores to develop and convey dissolved nutrients to sub-surface layers. Tile drains further contribute by increasing the efficiency of runoff conveyance. Both practices have continued to be commonly used over the past one to two decades (although trends in tile drain installation are not easily documented), coincident with increased DRP export and occurrence of algal blooms.

Both no-till and tile drainage practices provide tangible benefits and both interact with one another in complex ways. No-till provides erosion control, reduces surface P losses and reduces runoff amounts, which limits the transport of P and sediment from farm fields. No-till is particularly important during high rainfall events, when much of the P is lost. At the same time no-till may allow more infiltration of dissolved P to tile drains through preferential flow, or may stratify soils with broadcast fertilizer systems. Tile drainage can allow more delivery of DRP loads from fields to the stream system. Conversely, tile can also reduce peak runoff amounts due to lower antecedent moisture conditions and better soil health, and can allow DRP to be better managed through drainage water management. Improvements to these practices may include new adaptations of no-till such as subsurface fertilizer injection, cover crops and others, and new adaptations of tile drainage such as drainage water management, blind inlets, phosphorus filter beds and others.

Large amounts of P applied in previous years have accumulated in watershed soils and in floodplain and river sediments during years of excess fertilizer application. Some drawdown of this legacy P due to plant uptake appears to be underway, and the extent of its contribution to present-day river loads is uncertain.

The prospect of potential future increases in precipitation and runoff poses a serious challenge for meeting P load targets because of the disproportionate influence of river discharge on loads. Models indicate that reduction in river P loads may occur in a short time frame of perhaps a few years under moderate climates and widespread adoption of a mix of nutrient management practices. A wetter climate, coupled with the possible slow release of P stored in watershed soils, could lead to a recovery time of decades.

Further research is needed to better understand the influence of these additional factors on P loss. Advances in understanding the sources and delivery pathways of DRP and its influence upon WLE algal blooms should help to clarify its importance relative to other forms of P. Also important is improved understanding of how to manage currently applied P to reduce losses and how to utilize stored P to take advantage of what is in fact a valuable resource to farmers. New approaches to understanding several phenomena are needed with respect to variable nitrogen and phosphorus ratios in manure compared to commercial fertilizer and potential fertilizer application based on nitrogen needs; any potential increase in fertilizer application (whether commercial fertilizer or manure) during colder months when fields may lack plant cover; changes in commercial fertilizer form, which potentially increases availability of P; and dated and non-standardized soil testing and fertilization recommendation protocols. Many factors will determine whether current load targets are achievable in a reasonable timeframe, and future climates in particular may result in outcomes difficult to anticipate today, and potentially even greater challenges in meeting current load targets.

6. Conclusions and recommendations

Severe eutrophication of Lake Erie in the 1960s and 1970s led to P control strategies primarily addressing point sources that achieved significant reductions in TP loadings, in open lake P concentrations and in algal biomass. The health of Lake Erie was restored only to face new threats since the 1990s, as evidenced by increasing frequency and severity of nuisance and harmful algal blooms in WLE as well as central basin hypoxia. This report analyzes data and recent literature to explore the role of commercial fertilizer and manure in the re-emergence of WLE eutrophication.

A number of trends with respect to fertilizer use, now more than a decade-long, are encouraging. P fertilizer inputs are declining while P removal by crops has increased and declines in soil P in at least some locations suggests that fertilization at or below crop needs and drawdown of stored P can be achieved without impacting yields. Models such as SWAT provide insight into the mix of land and nutrient management practices that are likely to be most effective at bringing riverine P loads into the range where extreme algal blooms will become rare events. This report provides a comprehensive assessment of fertilizer practices in the WLEB and through synthesis of the most recent literature identifies research needs, aspects of land and nutrient management that demand attention, and suggests where policies may need to be developed to effect necessary changes. Lake Erie has benefitted from bold action in the past, and requires similar bold action today to ensure its health and value to the people of the basin.

This report also identifies the need for improved understanding of fundamental processes, improvements in monitoring that can fill critical information gaps, and the need for further exploration via research and modeling of the land and nutrient management approaches needed to ensure that applied fertilizers meet crop needs without contributing to extreme algal blooms and other environmental impacts in downstream aquatic ecosystems.

6.1 Fertilizer application in the WLEB findings

1. At present there are no established analytical nor data analysis methods for distinguishing P loads from commercial fertilizer versus manure at the point of delivery to the lake from tributaries, nor can a causal connection be drawn between different sources of P applied to fields and the response of algae in WLE. Thus, commercial fertilizer sales, manure generation and application information must be used as a proxy for the relative influence of each major fertilizer source, although prevailing privacy policies limit access to farm-scale data and information.
2. Estimated overall annual application and generation values for commercial fertilizer and manure combined, converted to elemental P, total 41,687 tonnes (72 percent) for the United States watershed and 16,327 tonnes (28 percent)

for the Canadian watershed based on the most recent comparable binational data (2006-07). This difference in contributions is comparable to differences in the surface area of the two watersheds.

3. Commercial fertilizer is the primary source of phosphorus used for agricultural purposes in the WLEB overall (72 percent commercial fertilizer and 28 percent manure generated by livestock). However, while commercial fertilizer dominates in the United States (81 percent commercial fertilizer and 19 percent manure), in Canada manure and commercial fertilizer are comparable as sources (52 percent manure and 48 percent commercial fertilizer), based on 2006 comparisons.
4. While manure accounts for approximately 20 to 30 percent of total agricultural P applied or generated in the study area, localized concentration of sources and of application increase the relative percentage in some areas, and overall for the Canadian portion of the WLEB.
5. Total numbers of animals in the basin have remained fairly constant over time, although increases in numbers have occurred on the US side through 2012 using one estimation approach and there is a trend toward higher concentrations of animals per farm. Information on permitted Concentrated Animal Feeding Operations (CAFOs) in the United States is publicly available, although not easily aggregated; Canadian animal feeding operation data were not found to be readily available in this assessment.
6. Though studies are limited, no general patterns of greater loss of P from fields where commercial fertilizer versus manure P has been applied have been documented. Loss rates tend to be more closely correlated with other factors, particularly on-field nutrient management, rather than the type of fertilizer applied.
7. Important agricultural trends include gradually increasing yields with gradually decreasing fertilizer application and an overall reduction of fertilizer application to equal or below crop needs; legacy soil P from prior years of excess application may have made up the difference where deficits between current-year application and crop needs exist.
8. Monitoring data from several WLE tributaries documents an increasing trend of dissolved reactive phosphorus (DRP) loading since the 1990s, whereas total P loading has shown little change. Because DRP is considered to be highly bioavailable, this increase is widely viewed as an important contributor to larger algal blooms in western Lake Erie and large hypoxic areas in central Lake Erie observed in recent years.

9. Changing farm practices concurrent with the rising fraction of DRP in riverine TP loads since the 1990s suggest a connection between algal blooms and rising DRP. As the rise in DRP has not been accompanied by increased fertilizer use, other factors may be responsible. Two have received particular attention: The widespread adoption of conservation tillage practices (no-till in particular) likely has led to accumulation of P at the soil surface, contributing to surface losses, and development of macropores (formed by roots that decay in untilled soil) may allow for increased P export via subsurface tiles. These field tiles increase conveyance through subsurface pathways, and although their extent is not well quantified, indications are that tile extent has increased.
10. P loads are the product of concentrations in river water and river discharge. Although P concentrations have declined somewhat, P loads have remained steady or increased due to increased runoff since about 1990. Years of high precipitation and March-July precipitation produce the greatest P loads and algal blooms.
11. There are some indications that nitrogen: phosphorus ratios may be important in initiation, growth, toxicity and species dominance for algal blooms. Ratios in different fertilizer and manure sources are variable; monitored ratios downstream (including in Lake Erie) will be a function of both these source differences as well as subsequent transport and transformation processes.

6.1.1 Fertilizer data gaps and research needs

1. Data gaps and obstacles that limit assessment and modeling of P sources and impacts include details of commercial fertilizer and manure application and management, insufficient resolution of data, and prevailing privacy policies that limit access to farm-scale data and information. Further research on any differences between results from surveys and the five-year censuses (e.g. in commercial fertilizer application) would be informative. In addition, it is important for all relevant agencies (including Tribal/First Nations) to assess how they can improve data collection and provision to address questions considered in this review.
2. Important P knowledge gaps in agricultural fields include the detailed characteristics and drawdown dynamics of stored phosphorus pools resulting from past P fertilizer in excess of crop demands, the extent of tile drainage

networks, and the full influence of manure management on local and regional P loading on surface water quality.

3. Given the increasing implementation of best management practices and fertilizer management activities, in particular through the 4R program, more research is needed on the efficacy of management actions on P export, including at the field-scale and broader watershed scale (e.g. CEAP-type studies).
4. Important P knowledge gaps at the ecosystem scale include the relative contributions of current commercial fertilizer and manure as well as stored P from previous years to the P load entering the lake and its bioavailable fraction.
5. Important P knowledge gaps exist with respect to management options best able to reduce transport of all forms of P so that P remains onsite and available for crop uptake. This may require finding innovative ways to reduce losses in light of widespread use of conservation tillage practices (that provide other ecological benefits) and field drainage systems.

6.1.2 Fertilizer and broader agricultural practice recommendations

1. Continue emerging research on phosphorus source monitoring, including stable isotope and organic phosphorus fingerprinting research as part of source attribution efforts, and site-based monitoring of P loss by species from fields receiving differing amounts of commercial fertilizer and manure.
2. Agencies should obtain (e.g. through surveys and available datasets) commercial fertilizer sales and application data at both higher temporal and spatial resolution, and make available to the extent allowed by regulations and protocols, to allow for improved understanding of this important source.
3. Better quantify all major components of manure generation, management, field application, and associated P loss and impacts on local and regional surface water quality and ecosystems.
4. Collect and regularly update a statistically representative binational data set of phosphorus concentrations and vertical stratification in agricultural soils (including more consistent protocols for soil test phosphorus), whether through an existing program or a new (agency-led or potentially multi-sector) program.
5. Improve spatial resolution of data on legacy phosphorus (including reservoirs of legacy P in locations not actively farmed), as well as linkages

between P fluxes from reservoirs and lake phenomena including algal blooms and hypoxia.

6. Support research and monitoring to quantify and better understand the implications of no-till agriculture for P accumulation at soil surface and P transport through drain tiles, and to explore potential new approaches to minimizing P losses due to no-till practices.
7. Obtain more current data on tile drainage networks and their impact on P form and mass transport, including interactions with tillage practices, commercial fertilizer and manure application, and the relative role and rates of tile discharge of P in comparison with surface runoff.
8. Continue to evaluate climate change impacts on P loads from rivers as a potentially complicating factor influencing how target loads are determined.
9. Continue to promote 4R guidelines for fertilizer application, including through outreach, education and technology to enhance adoption and effectiveness of 4R practices. Expand efforts to evaluate the effectiveness of 4R and best management practices at the field and watershed scales, and identify areas for improvement.

6.2 Monitoring findings

1. The western basin of Lake Erie and its tributaries are among the most intensively monitored parts of the Great Lakes basin, although significant shortcomings need to be addressed.
2. Offshore lake monitoring and lower watershed monitoring are reasonably robust for the region. There are many monitoring programs that include parameters relevant to nonpoint nutrient loading and impacts. Monitoring of major tributaries in the Ohio portion of Western Lake Erie is comprehensive, including high temporal resolution and quantification of different phosphorus forms (e.g., dissolved reactive phosphorus, particular phosphorus), in particular via certain programs (e.g. Heidelberg University tributary monitoring).
3. Data availability is fair overall, with time lags commonly exceeding a year or more for data release. Real-time gauges and sensors are becoming more common in the region.
4. Remote sensing is increasingly used for regular monitoring of bloom events. Research is ongoing concerning potential use of remote sensing for other applications, including identifying drainage tiles and field practices.

6.2.1 Monitoring data gaps and research needs

1. Important monitoring gaps exist in watersheds and lakes in terms of space, time, and parameter suite. Monitoring networks are generally not well integrated and coordinated across agencies and geographies, and are not optimized to support resource management decision-making.
2. Some programs monitor different phosphorus forms (dissolved, particulate), and others should include monitoring for these species where not already done. There is a clear need for more edge-of-field monitoring, both for routine monitoring and as part of research on effectiveness of different management practices, including 4Rs.

6.2.2 Monitoring recommendations

1. Design and implement an optimized and integrated long-term monitoring network for water quality and agricultural practices to support decisions about the best approaches to nutrient load reductions.
2. Develop stable funding mechanisms and institutional stewards for sustained, long-term binational monitoring and data management.
3. Support research and monitoring (watershed and lake) to improve process understanding and identify management options best able to reduce export of all forms of P so that to the maximum extent practicable, P remains onsite and available for crop uptake.

6.3 Modeling findings

1. Water quality models have been developed for much of the study area at varying degrees of resolution. Numerous numerical modeling programs (software) exist that simulate agricultural and lake processes reasonably well. Computing resources and speed are generally sufficient to run the programs for research purposes.
2. Models, primarily SWAT, provide valuable insights into the effectiveness of various land and nutrient management strategies in reducing P loads. Results suggest that wide implementation of a mix of strategies will be needed to meet reduction targets, and the realized benefits under a moderate climate may be substantially offset if precipitation and runoff increase in the future. As a cautionary note, the extent of existing implementation is not always included in model baseline scenarios, and so the feasibility of additional implementation is uncertain.

6.3.1 Modeling data gaps and research needs

1. Numerical models are handicapped by gaps in watershed characterization, monitoring data and process understanding. Process needs include updating soil phosphorus routines based on more current understanding of P availability and transport, having more refined characterization of soils, better characterizing both infield and post-edge-of-field transformation processes, and several aspects of manure related to manure chemistry, management options and subsequent P transport. Data availability limits model impact for informing many management decisions at the necessary scales. Models can be used to help optimize monitoring programs and field experiments in an iterative cycle, but this is not routinely done.
2. More extensive availability of data on implementation of management practices (e.g. 4Rs) is needed to establish accurate baseline scenarios in SWAT and other models.

6.3.2 Modeling recommendations

1. Develop operational models linked to optimized monitoring networks, and high-resolution surveys of changing agricultural practices and watershed characteristics to support forecasting of evolving conditions, and to inform inter-annual or within-season adaptive management decisions.
2. Continue financial and policy support for development and application of research models at various scales to improve process understanding of phenomena and dynamics (including improving soil phosphorus routines and addressing other processes noted above), as well as to simulate alternate management scenarios.

6.4 Integrated efforts to protect and restore Lake Erie

1. Agencies should work with other partners (including agricultural industry, academics and nongovernmental organizations) to expand research aimed at improving understanding of fundamental nutrient processes in the watershed, understanding the aggregate impact of multiple conservation projects at the field scale and larger on nutrient loading to Lake Erie, and identifying and supporting additional management actions identified as necessary to reduce nutrient-related impacts in Lake Erie.

7. References cited

Akkari, C., Bryant, C.R. 2017. Toward improved adoption of best management practices (BMP) in the Lake Erie Basin: Perspective from resilience and agricultural innovation literature. *Agriculture* 7(54).

Arnold, J. G., Moriasi, D. N., Gassman, P. W., Abbaspour, K. C., White, M. J., Srinivasan, R., Santhi, C., Harmel, R.D., van Griensvan, A., Van Liew, M.W., Kannan, N., Jha, M.K. 2012. SWAT: Model use, calibration, and validation. *Trans. ASABE* 55(4), 1491-1508.

Association of American Plant Food Control Officials (AAPFCO), 2017. Commercial Fertilizer, available from http://www.aapfco.org/publications.html#cf.

Baker, D. B., Confesor, R., Ewing, D. E., Johnson, L. T., Kramer, J. W., Merryfield, B. J. 2014. Phosphorus loading to Lake Erie from the Maumee, Sandusky and Cuyahoga rivers: The importance of bioavailability. *J. Great Lakes Res., 40*(3), 502-517. doi:10.1016/j.jglr.2014.05.001

Bast, L., Mullen, R., O'Halloran, I., Warncke, D., Bruulsema, T. 2009. Phosphorus balance trends on agricultural soils of the Lake Erie drainage basin. *Better Crops*, 93(1), 6-8.

Bertani, I., Obenour, D. R., Steger, C. E., Stow, C. A., Gronewold, A. D., Scavia, D. 2016. Probabilistically assessing the role of nutrient loading in harmful algal bloom formation in western Lake Erie. *J. Great Lakes Res.*, 42(6), 1184-1192.

Betanzo, E.A., Choquette, A.F., Reckhow, K.H., Hayes, L., Hagen, E.R., Argue, D.M. and A.A. Cangelosi, 2015. Water data to answer urgent water policy questions: Monitoring design, available data and filling data gaps for determining the effectiveness of agricultural management practices for reducing tributary nutrient loads to Lake Erie. Northeast-Midwest Institute Report. 169pp. Available from http://www.nemw.org/reports/water-quality/ on August 17, 2017.

Boles, C.M.W., Frankenberger, J.R., Moriasi, D.N. 2015. Tile drainage simulation in SWAT2012: Parameterization and evaluation in an Indiana watershed. *Trans. ASABE* 58 (5), 1201–13.

Bosch, N. S., Allan, J. D., Selegean, J. P., Scavia, D. 2013. Scenario-testing of agricultural best management practices in Lake Erie watersheds. *J. Great Lakes Res.* 39(3), 429- 436.

Bruulsema, T. 2009. Recommendation Development under 4R Nutrient Stewardship. In *Proceedings North Central Extension-Industry Soil Fertility Conference*. Vol. 25. Des Moines, IA. Available from http://www.ipni.net/ipniweb/portal.nsf/0/849509D17481DDDB85257A8C00574254/$FILE/Recommendation%20Development%20under%204R%20Nutrient%20Stewardship.pdf

Bruulsema T.W. 2016. Soil phosphorus trends in the lake erie region. *Better Crops* 100, 4-6.

Bruulsema, T. W., Mullen, R. W., O'Halloran, I. P., Warncke, D. D. 2011. Agricultural phosphorus balance trends in Ontario, Michigan and Ohio. *Can. J. Soil Sci.* 91(3), 437-442.

Canadian Water Network, 2017. Nutrient Management: Research Insights for Decision Makers. Available from http://www.cwn-rce.ca/assets/resources/pdf/CWN-Nutrient-Management-Research-Insights-for-Decision-Makers-2017/CWN-Nutrient-Management-Research-Insights-for-Decision-Makers-2017.pdf.

Chaffin, J.D., Bridgeman, T.B., Heckathorn, S.A.,Mishra, S. 2011. Assessment of Microcystis growth rate potential and nutrient status across a trophic gradient in Western Lake Erie. *J. Great Lakes Res.* 37 (1), 92–100. doi:10.1016/j.jglr.2010.11.016.

Christianson, L. E., Harmel, R. D., Smith, D., Williams, M. R., King, K. 2016. Assessment and synthesis of 50 years of published drainage phosphorus losses. *J. Environ. Qual.* 45 (5), 1467–77. doi:10.2134/jeq2015.12.0593.

Christianson, L. E., Harmel, R. D. 2015. 4R Water quality impacts: An assessment and synthesis of forty years of drainage nitrogen losses. *J. Environ. Qual.* 44(6), 1852-1860.

City of Detroit Water and Sewerage Department, 2014. Biosolids Dryer Facility Project Plan, May, 2014.

Cousino, L.K., Becker, R.H., Zmijewski, K.A., 2015. Modeling the effects of climate change on water, sediment, and nutrient yields from the Maumee River watershed. *J. Hydrology: Reg. Studies* 4, 762-775.

Culbertson, A.M., Martin, J.F., Aloysius, N. Ludsin, S.A., 2016. Anticipated impacts of climate change on 21st century Maumee River discharge and nutrient loads. *J. Great Lakes Res.* 42(6), 1332-1342.

Davis, T.W., Bullerjahn, G.S., Tuttle, T., McKay, R.M. Watson, S.B. 2015. Effects of increasing nitrogen and phosphorus concentrations on phytoplankton community growth and toxicity during Planktothrix blooms in Sandusky Bay, Lake Erie. *Environ. Sci. Technol.* 49(12), 7197-7207.

DePinto, J.V., Young, T.C., McIlroy, L.M., 1986. Impact of phosphorus control measures on water quality of the Great Lakes. *Environ. Sci. Technol.* 20, 752–759.

Dodd, R. J., Sharpley, A. N. 2015. Conservation practice effectiveness and adoption: unintended consequences and implications for sustainable phosphorus management. *Nutr. Cycl. Agroecosys.* 104(3), 373-392.

Dolan, D. McGunagle, K.P. 2005. Lake Erie Total Phosphorus Loading Analysis and Update: 1996-2002. *J. Great Lakes Res.* 31(Suppl. 2), 11-22.

Dolan, D. Chapra, S.C. 2012. Great Lakes total phosphorus revisited: 1. Loading analysis and update (1994-2008). *Journal of Great Lakes Research*, 38, 730-740.

Eghball, B., Wienhold, B.J., Gilley, J.E., Eigenberg, R.A. 2002. Mineralization of manure nutrients, *J. Soil Water Cons.* 57(6), 470-473.

Ford, W., King, K., Williams, M., Williams, J., Fausey, N. 2015. Sensitivity analysis of the agricultural policy/environmental extender (apex) for phosphorus loads in tile-drained landscapes. *J. Environ. Qual.* 44, 1099-1110.

Gooddy, D.C., Lapworth, D.J., Bennett, S.A., Heaton, T.H.E., Williams, P.J., Surridge, B.W.J. 2016. A multi-stable isotope framework to understand eutrophication in aquatic ecosystems. *Water Res.* 88, 623-633.

Gronberg, J.M. Spahr, N.E. 2012. County-level estimates of nitrogen and phosphorus from commercial fertilizer for the conterminous United States, 1987–2006. U.S. Geological Survey Scientific Investigations Report 2012–5207, 30 p. Available from https://pubs.er.usgs.gov/publication/sir20125207.

Hamilton, S.K., 2012. Biogeochemical time lags may delay responses of streams to ecological restoration. *Freshwater Biol. 57*(s1), 43-57.

Han, H., Allan, J.D. Bosch, N.S. 2012. Historical pattern of phosphorus loading to Lake Erie watersheds. *J. Great Lakes Res.* 38 (2), 289–98. doi:10.1016/j.jglr.2012.03.004.

Heidelberg University, National Center for Water Quality Research, 2017. Available from https://ncwqr.org/

Ho, J.C., Michalak, A.M. 2017. Phytoplankton blooms in Lake Erie impacted by both long-term and springtime phosphorus loading. *J. Great Lakes Res. 43*(3), 221-228.

Holman I.P., Howden, N.J.K., Bellamy, P., Willby, N., Whelan, M.J., Rivas-Casado, M., 2010. An assessment of the risk to surface water ecosystems of groundwater P in the UK and Ireland, *Sci. Total. Environ*., 408, 1847-1857.

International Joint Commission (IJC). 2014. *A Balanced Diet for Lake Erie: Reducing Phosphorus Loadings and Harmful Algal Blooms*. Report of the Lake Erie Ecosystem Priority, Washington, D.C., and Ottawa, Ontario, 100 pp.

IJC, 2017a. Water Quality Board. Available at http://ijc.org/en_/wqb/Great_Lakes_Water_Quality_Board.

IJC, 2017b. SPARROW. Available from http://ijc.org/en_/IWI/SPARROW.

International Plant Nutrition Institute (IPNI). 2012. A Nutrient Use Information System (NuGIS) for the U.S. Norcross, GA. January 12, 2012. www.ipni.net/nugis

IPNI. 2017. The nutrient stewardship 4r pocket guide. Available from http://www.nutrientstewardship.com/4r-pocket-guide/

Jarvie, H. P., Johnson, L. T., Sharpley, A. N., Smith, D. R., Baker, D. B., Bruulsema, T. W., Confesor, R. 2017. Increased soluble phosphorus loads to Lake Erie: Unintended consequences of conservation practices? *J. Environ. Qual.* 46(1), 123-132.

Jarvie, H. P., Sharpley, A. N., Spears, B., Buda, A. R., May, L., Kleinman, P. J. 2013. Water quality remediation faces unprecedented challenges from legacy phosphorus. *Environ. Sci. Technol.* 47(16), 8997-8998.

Kalcic, M. M., Kirchhoff, C., Bosch, N., Muenich, R. L., Murray, M., Griffith Gardner, J., Scavia, D. 2016. Engaging stakeholders to define feasible and desirable agricultural conservation in western Lake Erie watersheds. *Environ. Sci. Technol.* 50(15), 8135-8145.

Kane, D. D., Conroy, J. D., Richards, R. P., Baker, D. B., Culver, D. A. 2014. Re-eutrophication of Lake Erie: Correlations between tributary nutrient loads and phytoplankton biomass. *J. Great Lakes Res.* 40(3), 496-501.

King, K.W., Williams, M.R., Fausey, N.R. 2014a. Contributions of systematic tile drainage to watershed-scale phosphorus transport. *J. Environ. Qual.* 44 (2): 486–94.

King, K.W., Williams, M.R., Macrae, M.L., Fausey, N.R., Frankenberger, J., Smith, D.R., Kleinman, P.J.A., Brown, L.C. 2014b. Phosphorus transport in agricultural subsurface drainage: A review. *J. Environ. Qual.* 44(2), 467–85.

King, K. W., Williams, M. R., Johnson, L. T., Smith, D. R., LaBarge, G. A., Fausey, N. R. 2017. Phosphorus availability in western Lake Erie basin drainage waters: legacy evidence across spatial scales. *J. Environ. Qual.* 46(2), 466-469.

Kleinman, P. J., Wolf, A. M., Sharpley, A. N., Beegle, D. B., Saporito, L. S. 2005. Survey of water-extractable phosphorus in livestock manures. *Soil Sci. Soc. America J. 69*(3), 701-708.

Kleinman, P. J., Sharpley, A. N., Withers, P. J., Bergström, L., Johnson, L. T., Doody, D. G. 2015. Implementing agricultural phosphorus science and management to combat eutrophication. *Ambio* 44(2), 297-310.

Knights, D., Parks, K. C., Sawyer, A. H., David, C. H., Browning, T. N., Danner, K. M., Wallace, C. D. 2017. Direct groundwater discharge and vulnerability to hidden nutrient loads along the Great Lakes coast of the United States. *J. Hydrology, 554*(Supplement C), 331-341. doi:https://doi.org/10.1016/j.jhydrol.2017.09.001

LimnoTech, 2017. Assessment of Fertilizer and Manure Application in the Western Lake Erie Basin. Completed for the International Joint Commission Science Advisory Board's Science Priority Committee. 120 pp. + appendices. Available from http://ijc.org/files/publications/LimnoTech_IJC_Fertilizer.pdf

Long, C.M., Muenich, R.L., Kalcic, M.M., Scavia, D. 2017. Impacts of Concentrated Animal Feeding Operations and manure on nutrient inputs in a watershed. IAGLR 2017 Annual Meeting, Detroit, Michigan, Abstracts, p. 244.

Maaskant, K. 2015. Water Quality Assessment in the Thames River Watershed: Nutrient Trends. Slides presented at the Lake St. Clair Conference: Understanding and Managing Lake St. Clair, Chatham, Ontario, October 21, 2015. Available from https://www.scrca.on.ca/wp-content/uploads/2015/11/LSC-Maaskant.pdf.

Muenich, R.L., Kalcic, M., Scavia, D. 2016. Evaluating the impact of legacy P and agricultural conservation practices on nutrient loads from the Maumee River Watershed. *Environ. Sci. Technol.* 50(15), 8146-8154.

Neitsch, S. L., Arnold, J. G., Kiniry, J. R., Williams, J. R. 2011. Soil and water assessment tool theoretical documentation version 2009. Texas Water Resources Institute.

Obenour, D. R., Gronewold, A. D., Stow, C. A., Scavia, D. 2014. Using a Bayesian hierarchical model to improve Lake Erie cyanobacteria bloom forecasts. *Water Resour. Res.* 50(10), 7847- 7860.

Ohio Department of Agriculture (ODOA), Ohio Department of Natural Resources, Ohio Environmental Protection Agency, Ohio Lake Erie Commission. 2013. *Ohio Lake Erie Phosphorus Task Force II Final Report*, November 2013.

Ohio Environmental Protection Agency (OEPA) Division of Surface Water, 2015. Enhanced Tributary Monitoring in the Western Lake Erie Basin. Columbus, Ohio. Available from http://epa.ohio.gov/Portals/35/documents/2015_Enhanced_WLEB_Trib_StudyPlan.pdf.

Ohio Sea Grant, 2017. Tracking Harmful Algal Blooms from Source to Impact. Available from https://ohioseagrant.osu.edu/news/2016/530zz/habri-series-1.

Ohio State University (OSU) Extension, Ohio Agronomy Guide, 14th Edition, 2005.

Ohio State University (OSU) Extension, Ohio Livestock Manure Management Guide, 2006.

Ohio State University (OSU) Extension, Ohio Agronomy Guide, 15th Edition, 2017.

Ontario Ministry of the Environment (OMOE), 2012. An Analysis of Nutrients and Select Metals Within Wastewater (Pond Discharges) (2007–2011) from Greenhouse Operations in and around Leamington, Ontario, Technical Memorandum.

Pearce, R., 2011. Drainage statistics reveal some interesting facts about Ontario, Drainage Contractor, Nov. 13, 2011.

Pease, L.A., Fausey, N.R., Martin, J.F., Brown, L.C., 2017. Projected climate change effects on subsurface drainage and the performance of controlled drainage in the Western Lake Erie Basin. *J. Soil Water Cons.* 72(3), 240-250.

Powers, S. M., Bruulsema, T. W., Burt, T. P., Chan, N. I., Elser, J. J., Haygarth, P. M., Howden, N. J. K., Jarvie, H. P., Lyu, Y., Peterson, H. M., Sharpley, A. N., Shen, J. B., Worrall, F., Zhang, F. 2016. Long-term accumulation and transport of anthropogenic phosphorus in three river basins. *Nature Geosci.* 9(5), 353-356.

Prater, C., Frost, P. C., Howell, E. T., Watson, S. B., Zastepa, A., King, S. S. E., Vogt, R. J. Xenopoulos, M. A. 2017. Variation in particulate C:N:P stoichiometry across the Lake Erie watershed from tributaries to its outflow. *Limnol. Oceanogr.* doi:10.1002/lno.10628

Prokup, A., Wilson, R. Zubko, C. Heeren, A. Roe, B. 2017. 4R Nutrient Stewardship in the Western Lake Erie Basin. Columbus, OH: The Ohio State University, School of Environment & Natural Resources.

Rehm, G., Schmitt, M. Lamb, J., Randall, G., Busman, L. 2002. Understanding phosphorus fertilizers. University of Minnesota Extension. Available from https://www.extension.umn.edu/agriculture/nutrient-management/phosphorus/understanding-phosphorus-fertilizers/

Richards, R.P., Baker, D.B., Crumrine, J.P., Stearns, A.M. 2010. Unusually large loads in 2007 from the Maumee and Sandusky Rivers, tributaries to Lake Erie. *J. Soil Water Cons.* 65(6), 450-462.

Richards, P.R., Baker, D.B., Kramer, J.W., Ewing, E.D., Merryfield, B.J. Miller, N.L. 2001. Storm discharge, loads, and average concentrations in Northwest Ohio Rivers, 1975-1995. *J. Am. Water Resour. Assoc.* 37(2), 423-438.

Richards, R.P., Baker, D.B. 1993. Trends in nutrient and suspended sediment concentrations in Lake Erie tributaries, 1975-1990. *J. Great Lakes Res.* 19(2), 200-211.

Rissien A. 2017. Ohio's concentrated animal feeding facilities: A review of statewide manure management and phosphorus applications in the Western Lake Erie Watershed.

Robertson, D.M., Saad, D.A., 2011. Nutrient inputs to the Laurentian Great Lakes by source and watershed estimated using SPARROW watershed models. *JAWRA J. Am. Water Resour. Assoc. 47*(5), 1011-1033.

Ruddy, B.C., Lorenz, D.L., Mueller, D.K. 2006. County-Level Estimates of Nutrient Inputs to the Land Surface of the Conterminous United States, 1982–2001. U.S. Geological Survey Scientific Investigations Report 2006-5012

Scavia, D., Allan, J. D., Arend, K. K. Bartell, S., Beletsky, D., Bosch, N. S., Brandt, S. B., Briland, R. D., Daloglu, I., DePinto, J. V., Dolan, D. M., Evans, M. A., Farmer, T. M., Goto, D., Han, H. J., Hook, T. O., Knight, R., Ludsin, S. A., Mason, D., Michalak, A. M., Richards, R. P., Roberts, J. J., Rucinski, D. K., Rutherford, E., Schwab, D. J., Sesterhenn, T. M., Zhang, H. Y., Zhou, Y. T. 2014. Assessing and addressing the re-eutrophication of Lake Erie: Central basin hypoxia. *J. Great Lakes Res.* **40,** 226-246.

Scavia, D., Kalcic, M., Logsdon Muenich, R., Aloysius, N., Boles, C., Confesor, R., DePinto, J., Gildow, M., Martin, J., Read, J., Redder, T., Robertson, D., Sowa, S., Wang, Y-C., Yen, H. 2016. *Informing Lake Erie Agriculture Nutrient Management via Scenario Evaluation*, Final Report, April 2016.

Scavia, D., Kalcic, M., Muenich, R.L., Read, J., Aloysius, N., Bertani, I., Boles, C., Confesor, R., DePinto, J., Gildow, M., Martin, J., Redder, T., Robertson, D., Sowa, S., Wang, Y. C., Yen, H. 2017. Multiple models guide strategies for agricultural nutrient reductions. *Front. Ecol. Environ.* 15, 126-132.

Sharpley A. 2006. Agricultural phosphorus management: Protecting production and water quality, lesson 34. (Livestock and Poultry Environmental Stewardship (LPES) Curriculum).

Sharpley, A. 2016. Managing agricultural phosphorus to minimize water quality impacts. *Scientia Agricola, 73*(1), 1-8. doi:10.1590/0103-9016-2015-0107

Sharpley, A.N., Kleinman, P.J.A., McDowell, R.W., Gitau, M., Bryant, R.B., 2002. Modeling phosphorus transport in agricultural watersheds: Processes and possibilities. *J. Soil Water Cons. 57*(6), 425-439.

Sharpley, A., Jarvie, H. 2012. *Agricultural management, water quality & ecology: Putting practice into policy.* Paper presented at the National Agricultural Biotechnology Council Conference Proceedings.

Sharpley, A., Jarvie, H.P., Buda, A., May, L., Spears, B., Kleinman, P. 2013. Phosphorus legacy: Overcoming the effects of past management practices to mitigate future water quality impairment. *J. Environ. Qual.* 42 (5), 1308–26.

Shuchman, R., Liou, L., Grimm, A. 2014. Great Lakes Workshop Series on Remote Sensing of Water Quality: Executive Summary and Final Report on 2014 Series. Michigan Technological University. Available from http://mtri.org/workshops/nasagreatlakes2014/assets/for_website/NNX14AC90G_2014_Report.pdf.

Smith, D.R., King, K.W., Williams, M.R. 2015a. What is causing the harmful algal blooms in Lake Erie? *J. Soil Water Cons.* 70, 27A-29A.

Smith, D.R., King, K.W., Johnson, L., Francesconi, W., Richards, P., Baker, D., Sharpley, A.N. 2015b. Surface runoff and tile drainage transport of phosphorus in the Midwestern United States. *J. Environ. Qual.* 44, 495-502.

Smith, E. 2016. Ontario Farmers Making Important Progress for Water Quality in Great Lakes. Available from http://www.newswire.ca/news-releases/ontario-farmers-making-important-progress-for-water-quality-in-great-lakes-585866371.html.

Stow, C. A., Cha, Y.K., Johnson, L.T., Confesor, R., Richards, R.P. 2015. Long-term and seasonal trend decomposition of Maumee River nutrient inputs to Western Lake Erie. *Environ. Sci. Technol.* 49 (6), 3392–3400.

Stumpf, R. 2014. Remote Sensing of Lake Harmful Algal Blooms, What We've Learned. presented at the NOAA National Ocean Service Webinar, January 14. Available from https://www.epa.gov/sites/production/files/2014-01/documents/remote_sensing_of_lake_harmful_algal_blooms_what_weve_learned_richard_stumpf_noaa.pdf.

Stumpf, R. P., Wynne, T.T., Baker, D.B., Fahnenstiel, G.L. 2012. Interannual variability of cyanobacterial blooms in Lake Erie. *PLOS ONE* 7 (8): e42444. doi:10.1371/journal.pone.0042444.

Stumpf, R.P., Johnson, L.T., Wynne, T.T., Baker, D.B. 2016. Forecasting annual cyanobacterial bloom biomass to inform management decisions in Lake Erie. *J. Great Lakes Res.* 42(6), 1174-1183.

Tamburini, F., Pfahler, V., von Sperber, C., Frossard, E., Bernasconi, S.M. 2014. Oxygen isotopes for unraveling phosphorus transformations in the soil-plant system: A review. *Soil Sci. Soc.Am. J.* 78, 38-46.

U.S. Environmental Protection Agency (U.S. EPA), 2015. Phosphorus loading targets for Lake Erie. Annex 4 Objectives and Targets Task Team Final Report to the Nutrients Annex Subcommittee May 11, 2015. Available from https://www.epa.gov/sites/production/files/2015-06/documents/report-recommended-phosphorus-loading-targets-lake-erie-201505.pdf. Accessed 16 August 2017.

U.S. EPA, 2016. Great Lakes Environmental Database (GLENDA). Collections and Lists. October. Available from https://www.epa.gov/great-lakes-legacy-act/great-lakes-environmental-database-glenda.

U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS). 2016. Effects of conservation practice adoption on cultivated cropland acres in western lake erie basin, 2003-06 and 2012.

USDA, NRCS, 2017a. Fertilizer Use and Price, Available from https://www.ers.usda.gov/data-products/fertilizer-use-and-price.aspx.

USDA, NRCS, 2017b. Conservation practice adoption on cultivated cropland acres: Effects on instream nutrient and sediment dynamics and delivery in Western Lake Erie Basin, 2003-06 and 2012. 77 pp.

Vadas, P. A., Good, L. W., Moore, P. A., Widman, N. 2009. Estimating phosphorus loss in runoff from manure and fertilizer for a phosphorus loss quantification tool. *J. Environ. Qual.* 38 (4), 1645–1653.

Vadas, P., Bolster, C., Good, L. 2013. Critical evaluation of models used to study agricultural phosphorus and water quality. *Soil Use Manage.* 29, 36-44.

Van Bochove, E., G. Thériault and J.-T. Denault (editors). 2009. Indicator of Risk of Water Contamination by Phosphorus (IROWC_P). A Handbook for presenting the IROWC_P Algorithms. Research Branch. Agriculture and Agri-Food Canada. Quebec. Contribution No. AAFC/AAC, 94 pp.

Van Bochove, E., Denault, J.T., Leclerc, M.L., Theriault, G., Dechmi, F., Allaire, S.E., Rousseau, A,N., Drury, C.F. 2011. Temporal trends of risk of water contamination by phosphorus from agricultural land in the Great Lakes watersheds of Canada. *Can. J. Soil Sci.* 91, 443-453.

Verma, S., Bhattarai, R., Bosch, N.S., Cooke, R.C., Kalita, P.K., Markus, M. 2015. Climate change impacts on flow, sediment and nutrient export in a Great Lakes watershed using SWAT. *Clean-Soil Air Water* 43, 1464-1474.

Vollmer-Sanders, C., Allman, A., Busdeker, D., Moody, L.B., Stanley, W.G. 2016. Building partnerships to scale up conservation: 4R Nutrient Stewardship Certification Program in the Lake Erie Watershed. *J. Great Lakes Res.* 42 (6), 1395–1402.

Wang, Y.T., Zhang, T.Q., Hu, Q.C. Tan, C.S., 2016. Phosphorus source coefficient determination for quantifying phosphorus loss risk of various animal manures. *Geoderma*, 278, 23-31.

Watson, S.B., Miller, C., Arhonditsis, G., Boyer, G.L., Carmichael, W., Charlton, M.N., Confesor, R., Depew, D.C., Hook, T.O., Ludsin, S.A., Matisoff, G., McElmurry, S.P., Murray, M.W., Richards, R.P., Rao, Y.R., Steffen, M.M., Wilhelm, S.W. 2016. The re-eutrophication of Lake Erie: Harmful algal blooms and hypoxia. *Harmful Algae* 56, 44-66.

Williams, M. R., King, K. W., Ford, W., Fausey, N.R. 2016. Edge-of-field research to quantify the impacts of agricultural practices on water quality in Ohio. *J. Soil Water Cons.* 71 (1), 9A–12A.

Wilson, R., Burnett, L., Ritter, T., Roe, B., Howard, G. 2013. Farmers, Phosphorus and Water Quality: A Descriptive Report of Beliefs, Attitudes and Practices in the Maumee Watershed of Northwest Ohio. Columbus, OH: The Ohio State University, School of Environment & Natural Resources.

Wright, J., Sands, G. 2001. Planning an Agricultural Subsurface Drainage System. BU-07685-S. Agricultural Drainage Publication Series. St. Paul, MN: University of Minnesota: Extension Service. http://www.extension.umn.edu/agriculture/water/planning-a-subsurface-drainage-system/.

WTOL. 2017. Ohio Moves Forward with Strategy to Combat Lake Erie's Algae. Accessed March 15. Available from http://www.wtol.com/story/34500188/ohio-moves-forward-with-strategy-to-combat-lake-eries-algae.

Zhang, T. Q., Tan, C. S., Wang, Y. T., Ma, B. L., Welacky, T. 2017. Soil phosphorus loss in tile drainage water from long-term conventional-and non-tillage soils of Ontario with and without compost addition. *Sci. Total Environ.* 580, 9-16.