Assessment of Fertilizer and Manure Application in the Western Lake Erie Basin

Final Report
Prepared for:
U.S. Dept. of State,
International Joint
Commission

Solicitation Number:
SAQMMA16R0757

August 9, 2017

LimnoTech

Water | Scientists
Environment | Engineers

Cover images courtesy of U.S. Department of Agriculture, Natural Resources Conservation Service, except top center satellite image courtesy of U.S. National Aeronautics and Space Administration .

- Upper right, monitoring flow from a tile drain (USDA-Agricultural Research Service).
- Lower right, precision fertilizer application guided by an electronic field map and global positioning system navigation in a tractor cab (USDA-NRCS, provided by Steve Davis).
- Lower left, deep fertilizer injection with minimal soil disturbance (USDA-NRCS, provided by Steve Davis).
- Upper left, Holstein Friesian dairy cow (USDA image number K11662-1, photo by Peggy Greb).
- Top center, satellite image of algae blooms on Lake St. Clair east of Detroit, which is a connecting waterway between Lake Huron and Lake Erie (image acquired July 28, 2015). NASA Earth Observatory image by Joshua Stevens, using Landsat data from the U.S. Geological Survey.

501 Avis Drive
Ann Arbor, MI 48108
734.332.1200
www.limno.com

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Acronym List

4Rs Right Source, Right Rate, Right Time, Right Place (fertilizer application)
A2EM Advanced Aquatic Ecosystem Model
AAPFCO Association of American Plant Food Control Officials
AAFC Agriculture and Agri-Food Canada
AFO Animal Feeding Operation
AGNPS Agricultural Non-Point Source Pollution Model
AGU American Geophysical Union
AMPA Aminomethylphosphonic acid (a breakdown product of glyphosate herbicide)
APEX Agricultural Policy/Environmental eXtender
ARA Agricultural Retailers Association
ARS Agricultural Research Service (USDA)
AUV Autonomous Underwater Vehicle
BMP Best Management Practice
C Carbon
CAEDYM Computational Aquatic Ecosystem DYnamics Model
CAFO Concentrated Animal Feeding Operation
CANWET Canadian Nutrient and Water Evaluation Tool
CEAP Conservation Effects Assessment Project (NRCS)
CFO Confined Feeding Operations
CILER Cooperative Institute for Limnology and Ecosystems Research
CMIP5 Coupled Model Intercomparison Project #5
CSMI Cooperative Science and Monitoring Initiative
DAP Diammonium Phosphate
DEA Des-ethyl atrazine (a decomposition product of atrazine)
DEM Digital Elevation Models
DEQ Department of Environmental Quality
DHI Danish Hydraulic Institute
DP Dissolved Phosphorus
DRP Dissolved Reactive Phosphorus
ECCC Environment and Climate Change Canada
EFDC Environmental Fluid Dynamics Code
ELCOM- Estuary, Lake and Coastal Ocean Model -
ERCA Essex Region Conservation Authority
ERS Economic Research Service (USDA)
ESA European Space Agency
FEMS Farm Environmental Management Survey
GIS Geographic Information System
GLC Great Lakes Commission
GLEC Great Lakes Environmental Center
GLENDA Great Lakes Environmental Database
GLNPO Great Lakes National Program Office (USEPA)
GLOS Great Lakes Observing System
GLRI Great Lakes Restoration Initiative (U.S.)
GLWQA Great Lakes Water Quality Agreement
HAB Harmful Algal Bloom
HDPE High-Density Polyethylene
HEC Huron-Erie Corridor

HMS Hydrologic Modeling System
HRDC Harrow Research and Development Center (Canada)
HSPF Hydrological Simulation Program--FORTRAN
HUC Hydrologic Unit Code
IAGLR International Association for Great Lakes Research
IFA International Fertilizer Industry Association
IJC International Joint Commission
ILO Intensive Livestock Operations
IPNI International Plant Nutrition Institute
IROWC_P Indicator of Risk of Contamination by Phosphorus
LiDAR Light Detection And Ranging
LSPC Loading Simulation Program in C + +
LTI LimnoTech, Inc.
K Potassium
MAP Monoammonium Phosphate
MDEQ Michigan Department of Environmental Quality
MERIS MEdium Resolution Imaging Spectrometer (satellite instrument)
MIKE SHE MIKE Système Hydrologique Européen
MOC Memorandum of Cooperation
MODIS Moderate Resolution Imaging Spectroradiometer (satellite instrument)
MOECC Ministry of Environment and Climate Change (Ontario; OMECC)
MOUSE MOdel for Urban SEwers
MSU Michigan State University
MT Metric Ton (1,000 kilograms)
N Nitrogen
NAPI Net Anthropogenic Phosphorus Input
NASA National Aeronautics and Space Administration (U.S.)
NASS National Agricultural Statistics Service (USDA)
NCDC National Climatic Data Center (NOAA)
NCEI National Centers for Environmental Information (NCEI)
NCWQR National Center for Water Quality Research
NEMWI Northeast-Midwest Institute
NHD National Hydrography Dataset
NMP Nutrient Management Plan
NOAA National Oceanic and Atmospheric Administration (U.S.)
NPDES National Pollutant Discharge Elimination System (USEPA)
NRC National Research Council (Canada)
NRCS Natural Resources Conservation Service (U.S.)
NSM Nutrient Sub-Modules
NuGIS Nutrient Use Geographic Information System (IPNI)
NWIS National Water Information System
NWQMC National Water Quality Monitoring Council
OEPA Ohio Environmental Protection Agency
OMAFRA Ontario Ministry of Agriculture, Food, and Rural Affairs
OMECC Ontario Ministry of Environment and Climate Change
OMOE Ontario Ministry of the Environment (now OMECC)
OLCI Ocean and Land Colour Instrument
OLI Operational Land Imager
OSU The Ohio State University

P - Phosphorus
P_2O_5 Phosphate (chemical formula)
PDF - Portable Document Format
PSC Phosphorus Source Coefficients
PWQMN Provincial Water Quality Monitoring Network
RCA Regional Conservation Authority
SAB Science Advisory Board
SEDTRAN Sediment Transport Model
SPARROW SPAtially-Referenced Regression On Watershed Attributes
SPC Science Priority Committee (IJC)
SRP Soluble Reactive Phosphorus
SSDA Sub-Sub-Drainage Area (Canada HUC-8 equivalent)
STAR Storage and Retrieval
STEWARDS Agricultural Research Database System
STL Seasonal Trend decomposition using Loess
STORET Storage and Retrieval (EPA)
SWAN Simulating Waves Nearshore
SWAT Soil and Water Assessment Model
TBD To Be Determined
TBP Total Bioavailable Phosphorus
TMDL Total Maximum Daily Load
TP Total Phosphorus
SWAT Soil And Water Assessment Tool
UMWC University of Michigan Water Center
UAS Unmanned Aerial Systems
USDA United States Department of Agriculture
USEPA United States Environmental Protection Agency
USGS United States Geological Survey
WLEEM Western Lake Erie Ecosystem Model
WEP Water-Extractable Phosphorus
WLEB Western Lake Erie Basin
WPCP Water Pollution Control Plant
WQP Water Quality Portal
WTOL Toledo, Ohio CBS TV affiliate, Channel 11
WWTP Wastewater Treatment Plant

1
Executive Summary

This assessment of fertilizer and manure application and impacts in the Western Lake Erie Basin (WLEB) was conducted in cooperation with members of the International Joint Commission Science Advisory Board's Science Priority Committee. Nonpoint agricultural release is understood to be the largest single source of excess nutrients to western Lake Erie. Because phosphorus (abbreviated by its chemical symbol, the sources, transformations, and effects of excess P were the focus of much of the assessment, although nitrogen is also briefly discussed. Because it is not currently possible to distinguish P originating from inorganic fertilizer versus manure at the point of delivery to the lake from tributaries, fertilizer sales data, reported rates of application to the land surface, and total manure generation based on livestock numbers within watershed boundaries are used here as proxies for relative P loading. Point sources such as wastewater and industrial outfalls, as well as urban and other non-agricultural nonpoint sources were not examined in detail 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. The study had a geographic scope of the western Lake Erie basin, including the U.S.-Canada Huron-Erie Corridor basin, and consisted of the following elements:

- compilation and analysis of data on inorganic fertilizer, manure, and related product use;
- distinguishing of the importance and role of nutrient management of fertilizers relative to nutrient transport;
- evaluation of the capabilities of existing watershed models to distinguish nutrient loads and impacts from different fertilizer sources and application practices;
- evaluation of current monitoring programs;
- identification of gaps in spatial coverage, temporal resolution, and knowledge related to data, modeling, and monitoring in this area;
- development and presentation of graphical displays of resulting fertilizer use and other data; and
- assessment of the state of knowledge concerning the potential contribution of each fertilizer type to eutrophic conditions in Lake Erie.

Data-Based Findings

- Inorganic fertilizer is the primary source of phosphorus used for agricultural purposes in the study area, and typically accounts for approximately 70 to 80 percent of the total phosphorus applied, including P from all manure generated by livestock (not all manure generated is applied) in the watershed. Current inorganic P application rates are comparable in much of Canada and the U.S., with some local variation. Canadian data are less accessible, but average manure generation overall appears to slightly exceed inorganic fertilizer P application in the Ontario portion of the watershed (2007 data).
- Recent trends show steady or declining inorganic fertilizer application rates overall, especially in Ontario, although historical application rates commonly exceeded crop needs in both countries with a peak around 1980. Note that source percentages and ratios of P application/generation may not necessarily reflect corresponding percentages of contributions to P loads to Lake Erie due

to differences in chemical form and mobility of P from different types of fertilizer and manure, as well as differences in tillage and application methods.

- Manure accounts for approximately 20 to 30 percent of total agricultural P applied or generated in the study area, but localized concentration of sources and of application increase the relative percentage in some areas, as noted above. Total numbers of animals in the basin have remained fairly constant over time, but there is a trend toward higher concentrations of animals per farm. This trend does not necessarily indicate a corresponding trend of increasing intensity of manure application or P release; research on this aspect of manure generation and use is underway. Information on permitted Concentrated Animal Feeding Operations (CAFOs) in the U.S. is publicly available, although not easily aggregated; Canadian CAFO data are generally not available to the public, nor are farm-specific nutrient management documents.
- Estimated overall application and generation values for fertilizer and manure, converted to elemental P, for the U.S. watershed total 41,687,180 kg (72 percent) and for the Canadian watershed total 16,326,671 kg (28 percent) based on 2007 data.
- Important agricultural trends include gradually increasing yields with gradually decreasing fertilizer application, and an overall reduction of fertilizer application to equal or fall below crop needs; legacy soil P from prior years of excess application has made up the difference where deficits between current-year application and crop needs exist.
- An increasing trend of bioavailable dissolved phosphorus loading from U.S. study area tributaries (but not increased P application to fields), which began in approximately 1995-2000 and has since plateaued somewhat, may be contributing to larger algal blooms in western Lake Erie and large hypoxic areas in central Lake Erie that have been observed in recent years. This increasing trend is coincident with increasing rates of drainage tile installation (limited data are available to quantify this), as well as less intensive tillage practices and wetter spring climate conditions. Substantial changes in the form of P applied in the watershed that would account for the timing and magnitude of the increase in dissolved phosphorus loading to Lake Erie, whether in inorganic or organic (manure) forms, have not been documented.
- Mass balance analyses (e.g., NAPI) indicate that losses of P from new fertilizer and manure may not be sufficient to account for total nonpoint P loads to Lake Erie, and that legacy P may also be an important component of river P export. The role of legacy P in the watershed as a source of annual loading to Lake Erie has been recognized for many years, but has not been well quantified.
- There are some indications that nutrient ratios (e.g., N:P) may be important in initiation, growth, toxicity, and species dominance for algal blooms. Ratios in different fertilizer and manure sources are variable and may play a role in the large variation of ratios observed in different tributaries, different parts of Lake Erie, and different seasons. This is an area of active research.
- No general patterns of greater loss of P from fields where inorganic versus manure P has been applied have been documented. Loss rates tend to be more closely correlated with tillage (incorporation or broadcasting), drainage (soil type and the presence of tile drains), timing of application relative to rainfall, and in the case of manure, water content (i.e., more fluid forms of manure such as lagoon waste are more mobile). Solubility of P in most forms of fertilizer and manure is relatively high until it has become bound to soil particles.

Monitoring and Modeling Assessment Findings

- 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, non-profit, 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.

- Regional-scale, HUC-8/tertiary scale, and field-scale water quality models have been developed or are currently being 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. The code for these programs has been created by government, academic, non-profit, and private sector developers; some programs are freely available while others require payment for use or access. Computing resources and speed are generally sufficient to run the programs in research mode (not necessarily operational mode) at multiple institutions.

Data and Knowledge Gaps

- Numerical models are handicapped by gaps in watershed characterization, monitoring data, and process understanding. Data availability limits their 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.
- Important monitoring gaps exist in watersheds and lakes in terms of space (e.g., less coverage of nearshore lake areas and upper watersheds), time (e.g., sampling frequency is too low to capture important early spring or episodic events at many stations), and parameter suite (e.g., distinction of total vs. dissolved P is not always made in sampling and analysis). Monitoring networks are generally not well integrated and coordinated across agencies and geographies, and are not optimized to support resource management decision-making. Stable funding for sustained monitoring is commonly lacking, even at fairly coarse resolution.
- Important P knowledge gaps include the detailed characteristics and drawdown dynamics of legacy phosphorus pools (soils, stream sediment, lake sediment); and the extent, evolution, and basin-scale impacts of tile drainage networks on P transport (especially in the U.S.); the full influence of manure management and both field-applied and unrecovered manure on local and regional P loading on surface water quality (especially in Canada).
- Data gaps that limit assessment and modeling of sources and impacts include the spatial variability, methods, and timing of inorganic fertilizer and manure application and management (especially in Canada); the spatial and temporal resolution and accessibility of data (e.g., agricultural census only done every five years and not synchronized in both countries, data consolidated to county level, barriers in accessing annual fertilizer sales data [paid access], and time lags in availability of data up to several years).

Recommendations

Recommendations related to water quality and agricultural practice monitoring, in order to sustain and improve awareness of system status, and to fill important data gaps include:

- 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 and government commitments at field to watershed scale (i.e., 40% reduction goal). The network should be sufficient to distinguish changes in water quality due to management actions from natural variability and trends driven by weather and climate change, as well as market-driven variability and trends in agricultural practices.

- Collect and regularly update a statistically representative binational data set of phosphorus concentrations and vertical stratification in agricultural soils, non-agricultural soils, ditch and drain sediments, riparian zones, wetlands, buffers/filter strips, river and harbor sediments, and lake sediments, in order to quantify and monitor changes in these large pools of legacy phosphorus.
- Continue to develop 4R guidelines for fertilizer application, and invest in outreach, education, and technology to enhance adoption and effectiveness of 4R practices.
- Support time-limited and localized programs of research monitoring (watershed and lake) and method development to improve process understanding and characterization of agricultural practices, to inform the geographic focus of watershed management actions, and to increase the accuracy and reduce the cost of monitoring and characterization over time.
- Standardize methods for sample and data collection, processing, analysis, and reporting as much as possible, including across political boundaries, to allow for inter-comparison of data collected by different institutions and agencies. Optimization would include standardization of basic practices including: collecting chemistry and flow data together, developing common analytical procedures and basic analytes (total P and dissolved P), and concentrating resources on priority events (spring storms and snowmelt) and subwatersheds with more intensive agriculture.
- Cross-link sample collection programs more closely with continuous in situ monitoring networks, remote sensing programs (e.g., new satellite instruments and processing algorithms), and operational modeling programs. Investigate emerging imaging technologies such as radio-controlled or autonomous aerial platforms (drones).
- Develop and maintain stable and up-to-date repositories and user-friendly online access portals that effectively serve and integrate accurate data from all monitoring and survey programs.
- Develop stable funding mechanisms and institutional stewards for sustained binational monitoring and data management.

Recommendations related to modeling include:

- As has been done effectively with GLWQA Annex 4 activities related to Lake Erie, continue financial and policy support for development and application of research models at various scales to improve process understanding of field, watershed, and lake phenomena and dynamics, as well as to simulate alternate management and ecological response scenarios.
- Develop operational models linked to optimized monitoring networks, and high-resolution surveys (temporal and spatial) of changing agricultural practices and watershed characteristics, in order to facilitate more rapid data integration, to support forecasting of evolving conditions at various timescales, and to inform interannual or within-season adaptive management decisions that are consistent with current and predicted near-term conditions at multiple spatial scales.
- Create actual or virtual regional modeling centers of excellence to run and maintain operational watershed and lake models, and associated output products, and to facilitate ongoing modeling research and technology transfer.

Recommendations for future research to fill gaps in understanding and to inform policy development include:

- Improve spatial resolution of data on characteristics, and understanding of changes on various timescales, of legacy phosphorus in agricultural soils, groundwater, stream and river sediments, and lake sediments, as well as linkages between these reservoirs or fluxes and lake phenomena, including algal blooms and hypoxia.

- Refine existing data on the current extent, properties, behavior, and multi-scale impacts (field to basin) of tile drainage networks on P form and mass transport, including interactions with tillage practices, forms and methods of fertilizer and manure application, infiltration rates, leaching of legacy P, and the relative role and rates of tile discharge of P in comparison with surface runoff.
- Better quantify all major components of manure generation, management, field application, uptake, soil storage, associated P loss to subsurface and surface water, and relative impacts on local and regional surface water quality and ecosystems.

2
Project Description

LimnoTech, a Michigan based consulting company under contract to the International Joint Commission through the U.S. Department of State, has conducted a compilation and analysis of data on inorganic fertilizer, manure, and related product use in the western Lake Erie basin; identified the importance and role of nutrient management relative to nutrient transport; evaluated capabilities of existing watershed models to incorporate these source sectors; evaluated current monitoring programs; identified knowledge gaps (related to data, modeling, and monitoring) in this study area; developed graphical displays of resulting fertilizer use data; and assessed the state of knowledge concerning the potential contribution of each fertilizer type to eutrophic conditions. A more detailed description of project tasks and associated components of deliverables is included in Table 2-1.

Table 2-1. Detailed Task Descriptions

Task	Description/Deliverable
1a	Compile data on a binational basis by county and watershed on inorganic fertilizer sales and trends with time. This will include acreage of all crops (in particular major commodity crops such as corn, soybean and wheat and typical rotations); farm characteristics (size, number, etc.); artificial drainage (e.g. tiles, density, etc.); inorganic fertilizer sales; and trends in all parameters with time (e.g., over past 20-30 years). This task will rely substantially on existing, publicly available data. In cases where data are not available this will be well documented through communications with relevant agencies, trade associations and/or retailers. It is expected that obtaining the necessary information will require extensive communications and consultations with various organizations on a binational basis, to either obtain available data or to confirm absence of same. In addition this task will require geospatial data processing to re-distribute county-scale data to watershed units.
1b	Compile data on a binational basis on inorganic fertilizer application, including, where available, timing, placement, amounts and typical management practices associated with major crop types and soil types, based on the 4Rs for P management framework, to help clarify the relative significance of various practices. This is likely to require accessing information above and beyond that sought for Task 1a. Using standard GIS approaches, create maps of inorganic fertilizer application by watershed, at the highest resolution possible (e.g. HUC-12 in U.S. portion). The GIS activity is expected to require substantial data processing and interpretation (e.g., potentially based on county-level data in U.S.) to generate maps at a highly resolved spatial scale on a consistent basis for both the U.S. and Canadian sides of the western basin of Lake Erie.

Task	Description/Deliverable
2a	Compile data on a binational basis on livestock and manure production by county and watershed, including size, type, and production data for individual licensed/permitted concentrated animal feeding operations (CAFOs), and any information otherwise available on smaller operations. CAFOs that fall below federal/state/provincial permit thresholds should also be assessed. Differences in the major types of manure (e.g., poultry, swine, and cattle) should be considered. This will include size (e.g. number head), type, and production data for individual licensed/permitted CAFOs, and any information otherwise available on smaller operations. This task will rely substantially on existing, publicly available data. In cases where data are not available that should be well documented through communications with relevant agencies, trade associations and/or retailers. It is expected that obtaining the necessary information will require extensive communications and consultations with various organizations on a binational basis, to either obtain available data or confirm absence of same.
2b	Compile data on a binational basis on manure application, including timing, placement, amounts and typical management practices associated with major crop types and soil types, using the 4Rs for P management framework to the extent possible to better understand the relative importance of manure as a nutrient source (as compared to inorganic fertilizer) including in regard to the rate, timing and placement of manure (as compared with inorganic fertilizer). This is likely to require accessing information above and beyond that sought for Task 2a. Obtain information on locations of manure application (e.g., from CAFO applications and/or permits (U.S.), Nutrient Management Plans (ON)) and using standard GIS approaches, create maps of manure fertilizer application by watershed, again at highest resolution possible. Soil test data may also be helpful in assessing influence of manure application to sites receiving manure. In instances when published information suggests information gaps, follow up communications (potentially including formal or informal surveys) with agricultural experts should be undertaken to confirm information gaps and the nature and extent of related information.
3	Compile data on agricultural production via greenhouses (with an emphasis on larger-scale operations), and any ancillary fertilizer use data. This task is expected to include accessing publicly available data, as well as data only available through producer organizations.
4	Compile data on sales of agricultural nutrient-containing products other than inorganic fertilizers, manure, and greenhouse products, which may include liming material, soil amendments, soil additives, soil conditioners, herbicides, peat, and potting soil. In addition to agency sources, trade organizations and other industry groups are expected to be important sources of information. The assessment should include a consideration of quantities of each product class applied as well as their contribution to nutrient loadings to the receiving environment.

Task	Description/Deliverable
5	Summarize the state of knowledge concerning the potential contribution of each fertilizer type (i.e., inorganic fertilizer, manure, and fertilizer used in greenhouse production) and relative importance of fertilizer application including form, timing, placement, rate to eutrophic conditions in Lake Erie. A synthesis of the data and information collected in the previous tasks will be presented, and will include brief reference to additional issues relevant to manifestations of eutrophication, including potential importance of watershed phosphorus due to natural conditions, legacy content and/or engineering modifications, any differences in phosphorus bioavailability in the water column related to sources (internal and external) and cycling, and influence of loadings of other nutrients (in particular, nitrogen) on toxin production by harmful algae. Information gaps (and an assessment of relative priority in filling them) identified through the earlier tasks should be examined and synthesized as required.
6	Assess the capacity of current Lake Erie tributary and open water monitoring programs, including consideration of data collected in Tasks 1-5, and identify gaps in monitoring data that prevent a more thorough understanding of the relative importance of the major source categories to phosphorus loadings and impacts in Lake Erie, and the influence of the 4Rs on those loadings and impacts. Consider the temporal and spatial extent of monitoring completed through each program and the relevant parameters they measure; identify any novel monitoring approaches that may warrant further investigation in helping shed light on the nutrient source identification issue.
7	Through a review of watershed models commonly used for nutrients (especially SWAT and SPARROW) and consultation with modeling experts, assess the capability of the models (and the availability of necessary input data at appropriate spatial scale) to distinguish nutrient loads based on different fertilizer sources (e.g., inorganic fertilizer vs. manure) and application practices. This includes characterizing the importance of factors such as inputs and transport processes within the western Lake Erie watershed, at a highly resolved spatial scale (including the potential to consider climatological extremes, such as winter vs. summer and low vs. high flows), and factors such as presence and extent of tile drainage. Based on an assessment of their efficacy, the potential of individual models to guide management decisions related to nutrient reductions will be assessed. In addition to briefly reviewing recent application of SWAT and SPARROW (and any other modeling approaches) in the western basin of Lake Erie, this section will also identify models or modelling approaches that have not been applied in the Lake Erie basin, but have good potential to be applied there and address the nutrient source issues of interest.
8	Final Technical Report (with Recommendations), Plain Language Summary, PowerPoint Presentation, and Electronic Appendices (spreadsheets, GIS files). Interim Progress Report #1 and #2 were formatted as annotated drafts of the final technical report, with unresolved questions indicated.

For Tasks 1-5, data and information were drawn largely from agency databases and reports, peer-reviewed literature, as well as from trade associations and interviews in some cases. Sources considered included the U.S. Department of Agriculture (USDA) Census; other USDA databases; Agriculture and Agri-Food Canada (AAFC) Interpolated Census of Agriculture; the U.S. Census Bureau; contacts with state and Ontario fertilizer control offices; and trade associations such as The Fertilizer Institute, the Association of American Plant Food Control Officials, and the International Plant Nutrition Institute. Where necessary, county-level apportioning of data into watersheds has been done following a modified version of standard approaches (e.g., Gronberg and Spahr, 2012). The target time period of interest for each data acquisition task was 1992 through 2012, with a concentration on five-year intervals, and more recent or earlier years where such data were available.

2.1 Project Communication

LimnoTech coordinated with the Fertilizer Work Group (see Appendix A), its leadership, or collaborators on the following:

- in-person kickoff meeting with the Work Group hosted on November 14, 2016,
- conference call with University of Michigan Water Center (UMWC) and collaborators to discuss current modeling projects on December 12, 2016,
- conference call on December 13, 2016 with Work Group leadership to confirm details associated with the study approach,
- conference call on January 20, 2017 with Work Group leadership to discuss mid-term progress,
- conference call with the Work Group on January 27, 2017 to discuss interim progress report #1,
- conference call on March 7, 2017 with Work Group leadership to discuss assessment progress and schedule the next Work Group call and interim progress report #2 delivery (set at March 20, 2017),
- conference call with the Work Group on March 27, 2017 to discuss interim progress report #2 and next steps,
- conference call on May 8, 2017 with Work Group leadership to update progress and confirm timing of draft final report delivery,
- conference call on July 10, 2017 with the Work Group to discuss the draft final reported, which was delivered on June 26, 2017,
- email exchanges to transfer and discuss Work Group review comments on the Draft Final Report between July 10 and delivery of the final report on August 9, 2017,
- conference call with Work Group co-chairs on August 7, 2017,
- informal face-to-face conversations discussing assessment progress and details with Work Group leadership and members in Windsor (UMWC advisory committee meeting, January 18, 2017; and Lake Erie Millennium Network meeting, February 21-22, 2017), Detroit (IAGLR Annual Meeting, week of June 15, 2017), Cleveland (Sea Grant Crude Move Symposium, June 9, 2017), and Chicago (USEPA-Great Lakes National Program Office, June 1-2, 2017).

2.2 Project Deliverables

The following deliverables were completed on the dates noted:

- Study approach: including a description of the proposed activities, data sources and experts/personnel who may be contacted during the course of the project, and discussion of unresolved issues (October 19, 2016).
- Summary spreadsheet of data sources (November 21, 2016).
- Consolidated notes from December 13th conference call (December 19, 2016).

- Interim progress report #1: including narrative summary of progress on all tasks, with particular emphasis on Tasks 1-5, as well as examples of data for each of Task 1-4, and data gaps for Task 6 (January 20, 2017).
- Interim progress report #2: building on interim progress report #1, including additional narrative summary on all tasks and additional figures, with added emphasis on Tasks 6, 7 (March 20, 2017).
- Draft final report: including revised draft narrative text, figures, tables, and maps incorporating workgroup member comments on interim progress report #2; and electronic GIS and data files in spreadsheet format (June 26, 2017).
- Final report: including modifications requested by the Work Group after review of the draft final report, with complete narrative text, figures, tables, maps, and electronic files (August 9, 2017).
- Input and advice on the Work Group summary report during preparation in August and September.

3
Assessment of Fertilizer and Manure

This assessment of fertilizer and manure application and impacts was conducted in cooperation with members of the International Joint Commission Science Advisory Board's Science Priority Committee (Appendix A). Because phosphorus (
systems, the sources, transformations, and effects of excess agricultural P from nonpoint sources were the focus of much of the assessment. Point sources, as well as urban and other non-agricultural nonpoint sources, were not examined in detail as part of this analysis. Nitrogen (N) may become limiting to algal growth later in the growing season, and may also influence bloom toxicity. The study had a geographic scope of the western Lake Erie basin, including the U.S.-Canada Huron-Erie Corridor basin (Figure 3-1).

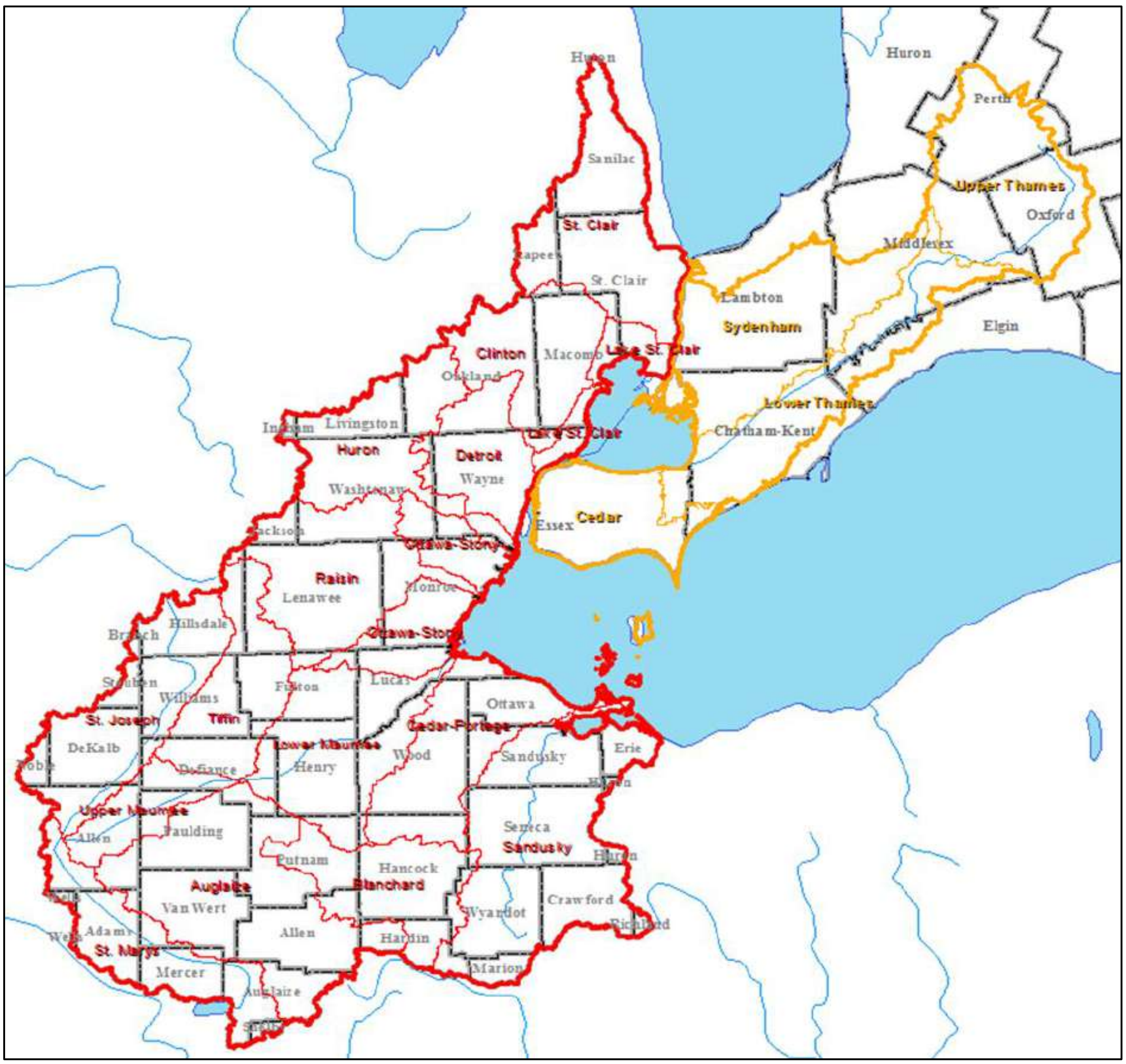

Figure 3-1. Study area: U.S. watershed area (red) = 14,833 sq. miles (38,416 sq. km) or 78% of the total; Canada area (yellow) = 4,286 sq. miles (11,101 sq. km) or 22% of the total watershed area.

3.1 Fertilizer

Lost fertilizer that was originally applied to agricultural land in the watershed (parts of Ohio, Indiana, Michigan, and Ontario) and subsequently released to surface water is agreed by most investigators (e.g., Michalak et al., 2013; Maccoux et al., 2016; Scavia et al., 2017) to be the largest single source of nutrient loading to the western and central basins of Lake Erie. These basins have shown symptoms of eutrophication including harmful algal blooms (west) and hypoxia (central). While substantial actions have been taken to reduce nutrient loss from farmland over the last several decades, negative consequences of the delivery of excess phosphorus to Lake Erie remain, with some indications of a reversal of downward trends in the last 15 to 20 years that began in the 1970s with concentrated efforts to reduce point sources of nutrients. Here we describe the spatial distribution and temporal trends of the application of inorganic agricultural fertilizer in the watershed (also known as commercial fertilizer, as distinct from organic fertilizer or manure), as well as factors that affect its mobility after application.

3.1.1 Fertilizer Sales and Farm Characteristics

Binational fertilizer-related data were compiled by county and HUC-8 watershed (U.S.), or at the highest resolution available, for fertilizer sales, farm characteristics, primary crops, and agricultural practices in the study area. The datasets reviewed are described briefly below. Although other recent studies, particularly geospatial analyses based on soils and hillslopes and modeling investigations such as SPARROW applications, have shown maps of phosphorus source intensities at scales as fine as HUC-12 resolution, no fertilizer sales or application data are publically available in the U.S. or Canada at scales finer than county level, which is comparable to HUC-8 watersheds in the U.S. or sub-sub-watersheds (tertiary watersheds) in Canada.

3.1.1.a Inorganic Fertilizer Sales and Trends with Time

Data indicative of fertilizer sales exist in three main categories: raw distributor sales (as mass of P_2O_5 sold by distributors), farm fertilizer expenditures (as dollars spent by farmers), and compilations of these data into estimates of fertilizer use and application (as mass of P or P_2O_5 applied). Recorded sales in a given county are not necessarily indicative of fertilizer use in the same county, given that purchasers may obtain fertilizer from sources beyond their county borders. Different methods can be employed to apportion sales to counties. Fertilizer expenditures, on the other hand, indicate dollars spent and not amount purchased. In relative terms, fertilizer expenditures have been used in various studies (described below) to allocate state-level sales as phosphate to county level use on the basis of the county expense as a fraction of state expenditures.

3.1.1.b Sales Data (Tons or kg of P_2O_5 Sold)

information from distributors at the county level, records them in a fertilizer tonnage database, and reports these data to the Association of American Plant Food Control Officials (AAPFCO) (Terry, 2006). The AAPFCO processes, summarizes and distributes these data for a fee, with a reporting delay of approximately three years from the fertilizer application year. We purchased a national report of these data for 2011 as part of this study. Sales are recorded in AAPFCO data reports as U.S. tons by grade by county, as normal/single superphosphate (phosphate rock treated with sulfuric acid to improve solubility; 7-9% P), as concentrated/triple superphosphate (phosphate rock treated with phosphoric acid; ~20% P), and as total P_2O_5. No values are reported for MAP or DAP, which are formulations of both nitrogen and phosphorus. For this particular year, Ohio and Indiana data are available at the county level, however, only state level data are included for Michigan for 2011. Most other years, however, are recorded at the county level for Michigan as well. Electronic Supplement folder ES-1 (subfolder Fert1) contains a brief description of the 2011 data, as well as the data and transmittal form from AAPFCO. We did not further evaluate the contents of the 2011 data, nor did we purchase additional years because additional time periods would have to be purchased for a meaningful analysis, and more importantly because the same data have been compiled in more useful forms in studies discussed below. Purchasing additional data would be useful to calculate trends and balances for time periods outside the time frame covered by the studies, including years up to 2014 which is the latest dataset available.

In Ontario, Canada, fertilizer sales have been recorded by several entities over time: Ontario Agri Business Association, Agriculture Canada, Canadian Fertilizer Institute (now Fertilizer Canada), Statistics Canada, which is also known as StatsCan or StatCan (Bruulsema, 2011). At present, Statistics Canada records and reports fertilizer shipment data.
the above sources. These data are reported as metric tonnes of P_2O_5. However, none of the data are reported on the county level. Fertilizer shipment data were downloaded from Statistics Canada from 1967 to 2016 and are described and provided in Electronic Supplement folder ES-1 (subfolder Fert2). We did not further evaluate the contents of these files, because the same data have been compiled in more useful forms in studies discussed below.

3.1.1.c Farm Fertilizer Expenditures

In the U.S., farm expenditures, including fertilizer expenditures, are recorded every 5 years in the USDA Agricultural Census, and the data are available for download via QuickStats queries starting with the year 1992 (USDA-NASS, 2017). Older data are available as PDF tables. Financial data, including farm expenses, are reported in U.S. dollars for the year the data were collected, i.e. they are not inflation adjusted. These data are county based, except where data reporting was suppressed. Lime is included in the fertilizer expenses. Electronic Supplement folder ES-1 (subfolder Fert3) contains and describes these data.

The Canadian Agricultural Census, also at 5-year intervals but offset one year earlier than the USDA census, collects similar data. Canadian Agricultural Census data are also available interpolated to different spatial resolution levels, as the Interpolated Census of Agriculture, a geodatabase from Agriculture and Agri-food Canada (AAFC, 2017). Thus, farm expense data are available directly for the four tertiary or sub-sub-watersheds of interest in Ontario. Electronic Supplement folder ES-1 (subfolder Fert4) contains and describes the Canadian farm fertilizer expense data.

Figure 3-2 shows trends in fertilizer expenses as a proportion of total farm expenses. In Canada, the proportion spent on fertilizers has steadily decreased to 2006. The Canadian data tables do not report expenses for the year 2011. In the U.S., the fertilizer proportion of expenses went up between 2002 and 2012. The available data do not overlap sufficiently between the two countries to know whether there was a reversal of the downward trend in Canada similar to the trend in the U.S. Temporal trends are similar in individual subwatersheds (see Electronic Supplement folder ES-1, subfolders Fert3 and Fert4).

The magnitude of change in fertilizer expenses in the U.S. is likely fairly consistent with the phosphorus application rates, which have been flat. According to Pamela Joosse (AAFC, personal communication, 2017), fertilizer application is more sensitive to commodity prices than fertilizer cost, as farmers may fertilize a crop with good returns more, to ensure that yield is not limited by fertilizer. Although this may be generally true, inorganic fertilizer prices were anomalously high from 2008 through 2013, especially in spring of 2008, which does appear to have affected sales and application rates, especially in 2009 (not resolved in Figure 3-2 data).

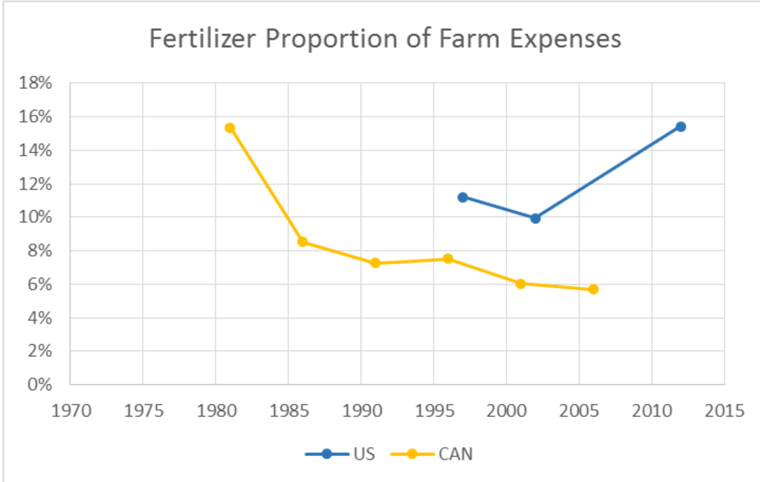

Figure 3-2. Trends in fertilizer expenses as a proportion of total farm expenditures.

3.1.1.d Compiled Fertilizer Sales/Use Data

Several studies have collected and analyzed sales data in the above categories to generate county-level (U.S.: Ruddy et al., 2006; Gronberg and Spahr, 2012) or province and state level (Canada, U.S.: Bruulsema et al., 2011; IPNI-NUGIS 2013) estimates of fertilizer use and phosphorus balance. While the data in these studies are

Bruulsema et al. (2011) for fertilizer application in Canada, the fertilizer tonnages reported for the province are actually sales data. Thus this constitutes a type of fertilizer data that is easily accessible and usable for analysis. The IPNI-NUGIS (2013) data are included in Electronic Supplement folder ES-1 (subfolder Fert2).

The fertilizer sales data sources described above are the most complete and reliable information of fertilizer distributions at the county (U.S.) and province (Canada) level. Other possible data sources have been considered (e.g. International Fertilizer Association (IFA), Agricultural Retailers Association) but did not yield any data at the required resolution.

3.1.1.e Acreage and Trends of Crops

USDA census data from QuickStats (USDA-NASS, 2017) and Canadian Interpolated Census of Agriculture data (AAFC 2017) were used with the data aggregated to the scale of the watersheds of interest. Figure 3-3 shows the trends in acreage of corn, wheat, soy, and alfalfa combined with hay. Alfalfa and hay are minor crops. Soy is the leading crop by acres, followed by corn, and an increase in acres in one is associated with a decrease in acres in the other; planting in wheat is independent of corn and soy due to the seasonal offset (mostly winter wheat, planted in fall under proper conditions) and accounts for only a quarter of the acreage of these four crop types combined. There has been a gradual slight downward shift in acres of winter wheat through time in the U.S., and an increase in Canada, although winter wheat planting is highly dependent on fall weather conditions and fluctuating prices, so acreage can be quite variable from year to year. Overall trends are fairly flat, with more variation in Ontario watersheds. (The data supporting these plots can be found in Electronic Supplement folder ES-1, subfolder Fert7).

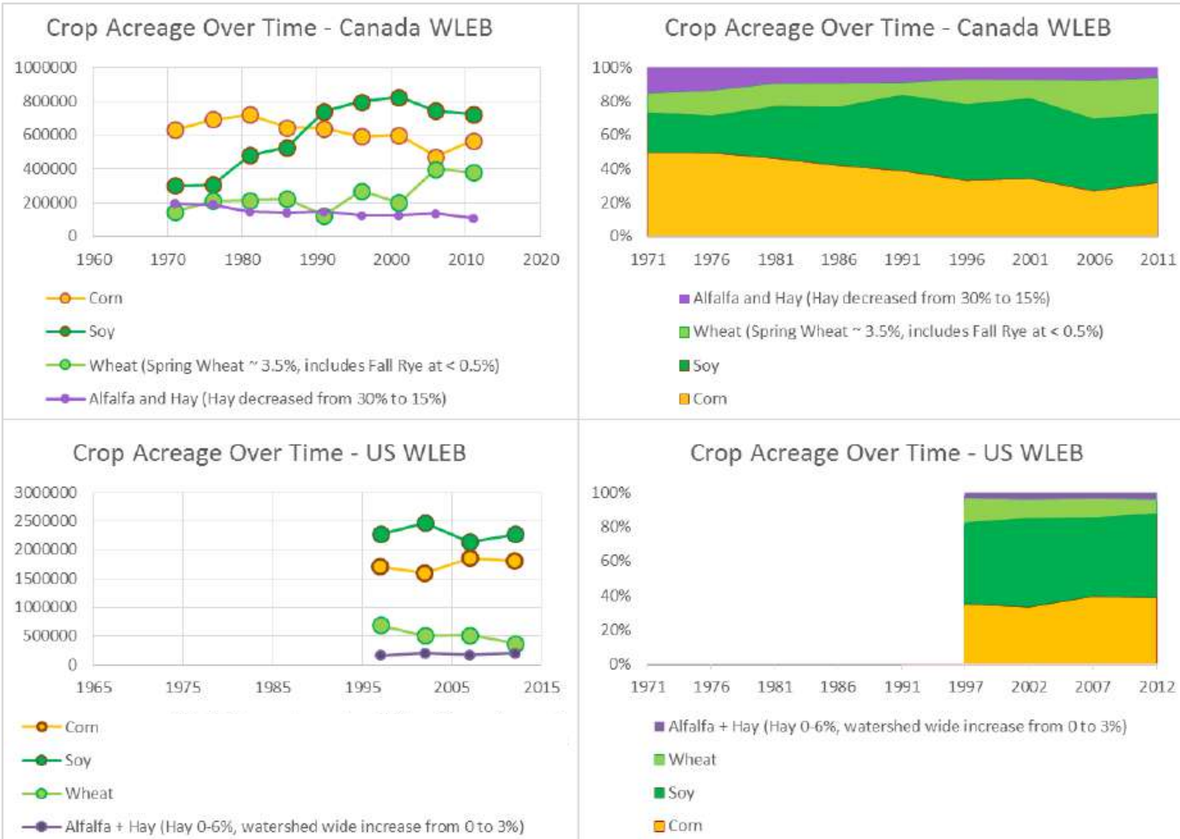

Figure 3-3. Acreage (left) of corn, wheat, soy, and alfalfa/hay in the WLEB, and percentage of total (right). The total of these 4 crops has remained nearly constant in time in the US. In Canada, The strongest trend is an increase in soy and a decrease in corn. Corn dominates in the Upper Thames watershed, but soy dominates in the Lower Thames and Sydenham.

3.1.2 Farm Characteristics and Trends

For much of the 20th century, there has been a strong trend for farm consolidation, with declining numbers of farms, and larger overall farm sizes (Baltensperger, 1987; Ahearn et al., 2002; Han and Allan, 2012). Using USDA census data from QuickStats, Figures 3-4 and 3-5 show that the majority of US WLEB cropland acres are owned by a small number of farms, and that there has been a continuing trend towards fewer and larger farms in both Canada and the US: while farm acreage decreased by 6-7%, the number of farms decreased by 2 to 3 times as much (11 and 20%). Trends as well as the distribution of farm sizes and numbers are comparable in the U.S. and Canada. Trends toward larger farm size suggest that prioritizing policies toward improving nutrient management practices at the largest agricultural operations first may produce the most rapid results. This assumes that current practices and impacts per unit area are similar across farms of different sizes, which is likely not an accurate assumption.

Figure 3-4. Number of farms by size category and total acreage in each size category in the WLEB. The farm size cluster in the 10 to 50 (69 in Canada) acre bin reflects an abundance of 40-acre farms (1/16 square mile). Note that the farm size cut-offs are defined differently in the U.S. and Canadian data sets, and vertical axes also differ in scale. These data are reported only for the 2011 census in Canada. No data for 2007 are in the downloaded U.S. census table.

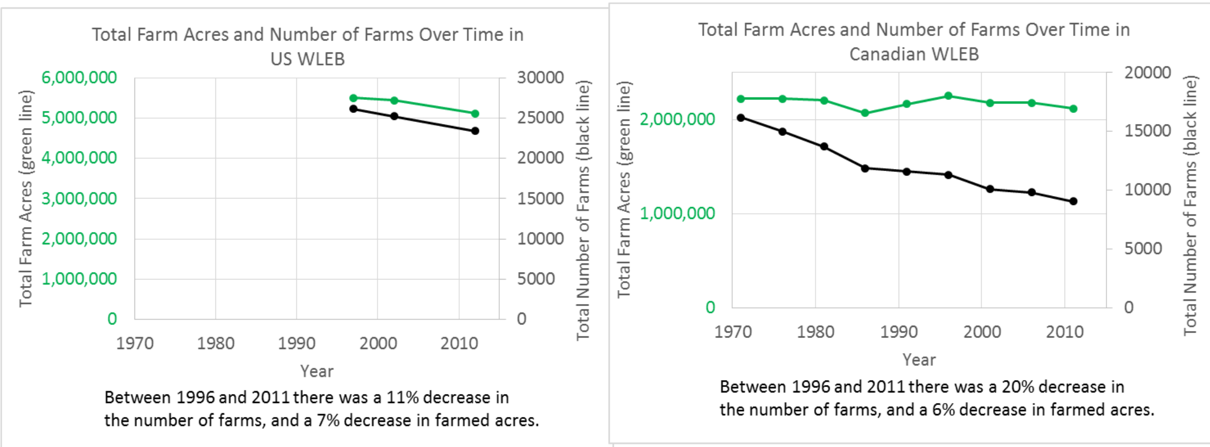

Figure 3-5. Trend in farmed acres and number of farms in the W. Lake Erie watershed.

Using USDA census data from QuickStats and the Canadian Interpolated Census of Agriculture, Figures 3-6 and 3-7 show agricultural land distribution and trends in fertilized acres. There have been more decreases than increases in the last four census years, and trends seen in Figure 3-5 indicate that this is part of a general trend, (urbanization is one likely cause, though this has not been investigated here). The distribution of agricultural land-use between the U.S. and Canada is very similar.

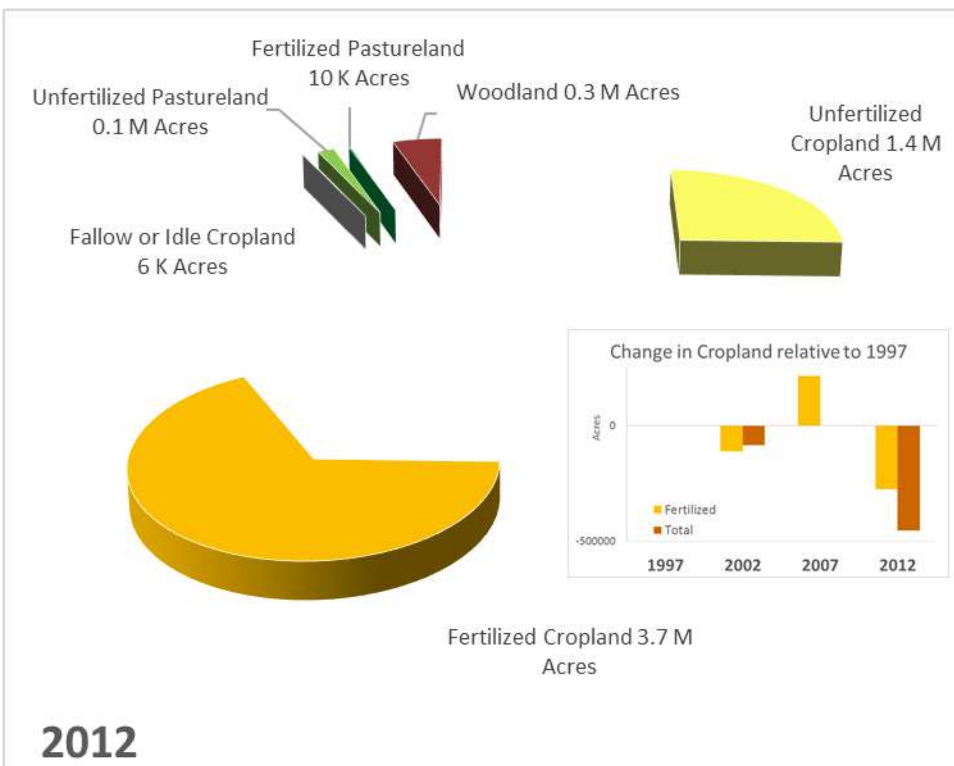

Figure 3-6. Distribution of Agricultural Land Uses in the U.S. portion of the WLEB as reported in the 2012 U.S. Agricultural Census and changes of fertilized and unfertilized acres of the four most recent census years relative to 1997 (inset). Depending on the year, 0.6% or less of total cropland is irrigated. No data for 2007 in downloaded U.S. Census table.

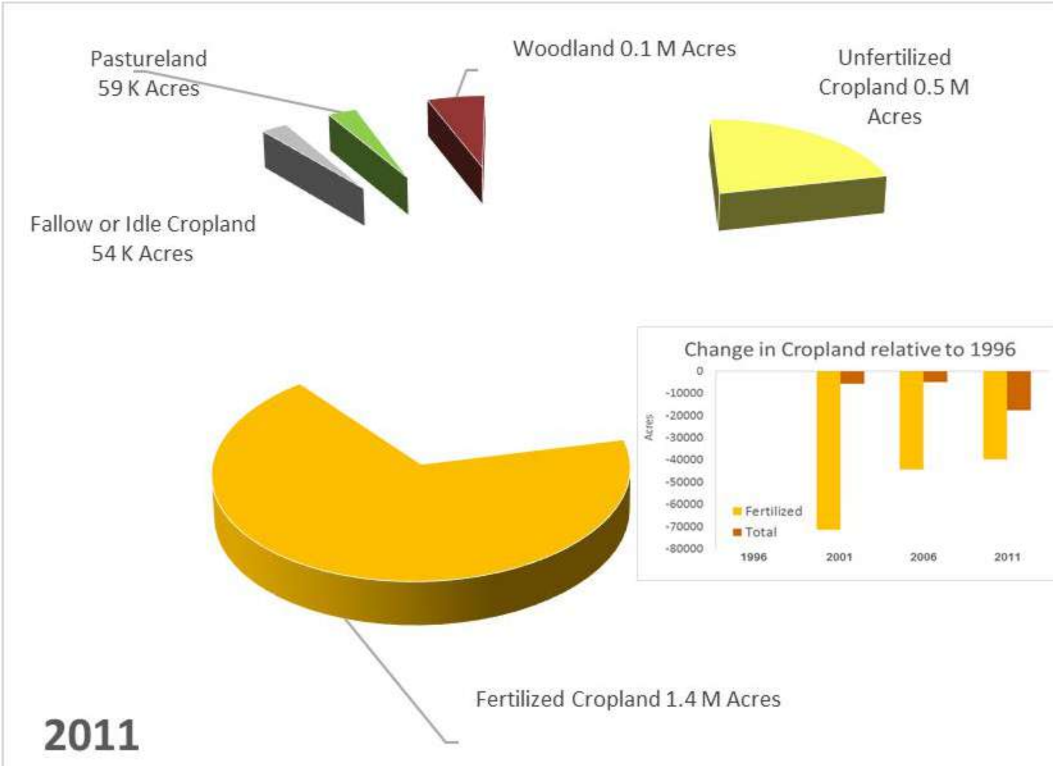

Figure 3-7. Distribution of agricultural land uses in the Canadian portion of the WLEB as reported in the 2011 Canada Census and changes of fertilized and unfertilized acres of the four most recent census years relative to 1996 (inset). Fertilized pastureland is not reported in Canadian data and all fertilization is assumed to be applied to cropland. Irrigated land constitutes less than 1% in each year.

3.1.3 Subsurface Artificial Drainage and Trends

Subsurface artificial drains are a crucial component of agricultural production in poorly drained soils, many of which are present in the Midwestern U.S. 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) which can range in diameter from 3 to 6 inches (76 to 152 mm). Historically, tile lines were made of ceramic or concrete pipe. 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

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) and spaced of 25 to 60 feet apart (~ 7.5 to 18 meters) (Pamela Joosse, AAFC, personal communication, 2017).

Tile drains are utilized to lower the water table following periods of excessive precipitation. This action allows producers to maintain field access and improves 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. A review of tile drainage literature in support of an Indiana SWAT modeling study, Boles et al. (2015) found that average tile flow amounted to 23.2% of annual precipitation on tile drained fields.

Few data exist that quantify actual trends in tile drainage in the Western Lake Erie Basin. Anecdotal evidence suggests that tiling has increased in the recent decade, both in acres tiled and in the relative efficiency of the installed systems. For example, one company (Ag Drainage Inc.[1]) is recommending to customers in Illinois that they consider spacing their tiles as little as 12.5 feet apart in some difficult areas. This will have the effect of increasing the speed with which water can move to the tile system. Since 2008, installation rates may have also been affected by changes to Section 179 of the U.S. tax code through the allowed producers to more quickly depreciate major purchases, including new drain tile installations. Consideration must also be given to commodity prices (particularly for corn) which started the century at around $2 (U.S.) per bushel, before surpassing $8 per bushel in 2012. This commodity has since fallen to levels of $3 to $4 per bushel.

3.1.3.a Phosphorus in Tile Drains, a Review of Current Literature

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 over 400 agricultural drainage publications from locations throughout the United States and Canada. They had several key findings:

- Dissolved and particulate phosphorus loadings from subsurface drainage sites were generally found to be less than 1 kg-P/ha per year. This is consistent with findings in Ohio edge-of-field studies (King et al., 2014a). Van Esbroeck et al. (2016) showed that total TP loss from Ontario measurements was approximately evenly divided between tile drainage and surface runoff.
- Total phosphorus lost in tile drainage water was less than 4% of the applied amount in 90% of cases.
- No significant differences were observed between inorganic and organic fertilizer applications in terms of P loss to tile drainage.
- Some differences were detected with tillage. Conservation and conventional tillage plots had a median dissolved phosphorus load of 0.04 kg-P/ha, while no-till plots had a median dissolved phosphorus load of 0.12 kg-P/ha. This is consistent with other published findings. King et al. (2014b) report on multiple studies which show subsurface phosphorus transport to be greater under no-till when compared with conventional tillage. They highlight a few reasons for this increase, namely that continuous no-till plots do not experience phosphorus mixing within the soil profile that comes with tillage, and that there are increased opportunities for preferential flow to tiles via vertical macropores that develop over multiple seasons without tillage.

While the (Christianson et al., 2016) review cited above was very broad geographically, research is also available which discusses tile phosphorus in regions which are very applicable to the WLEB. King et al., (2014a) made discharge and phosphorus measurements at a small watershed in central Ohio (within the Upper Big Walnut Creek watershed). Their findings indicated tile flow total phosphorus concentrations could reach as high as 5.48 mg/L with annual total phosphorus loading from tiles ranging between 0.28 and 0.77 kg/ha (Table 3-1). Much of this loading was in the form of dissolved reactive phosphorus as annual loadings of this fraction ranged from 0.22 to 0.69 kg/ha. In experimental plots in Ontario, Zhang et al. (2017) found total phosphorus loads from tile drains varied between 1.46 kg/ha for no-till lands and 1.22 kg/ha for conventional tilled lands with no application of additional organic material (only nitrogen).

3.1.3.b Tile Drained Area in the United States and Estimates of P Loading

Because field records are generally not available to the U.S. public due to farm privacy laws, it can be difficult to estimate how many hectares in any given area are drained by subsurface tiles [no map data comparable to that from Ontario has been identified for U.S. tile areas; the Upper Tiffin CEAP report suggested 70-80% tiled]. In their paper, Jarvie et al. (2017) estimates tile drain installation on 86% of agricultural lands in the Maumee and on 92% of agricultural lands in the Sandusky. Sugg (2007) completed a national- -by-county basis using

[1] Use of a specific company name does not imply endorsement.

geospatial data about row crops and soil drainage characteristics.
used, along with the county total area, to prepare a county-by-county map depicting the percent of each county which is tile drained (Figure 3-8).

Table 3-1. Literature summary of total and dissolved phosphorus in tile drains over a variety of geographic areas. Values are reported as loads (kg/ha), concentrations (mg/L), or percentages.

Reference	P form	Value Desciption	Value (kg-P/ha)	Value (mg/L)	Value (%)	Geographic Area/Site Description
Williams et al. 2016	Dissolved	Average annual DRP load in surface runoff	0.27			Central & Northwest Ohio, USA
King et al. 2016	Dissolved	Average annual DRP load in tile flow	0.46			Central Ohio, USA
Williams et al. 2016	Dissolved	Average annual DRP load in tile flow	0.42			Central & Northwest Ohio, USA
King et al. 2014a	Dissolved	Average annual DRP load in tile flow	0.39			Upper Big Walnut Creek - Central Ohio, USA
Williams et al. 2016	Dissolved	Maximum annual DRP load from surface runoff	2.79			Central & Northwest Ohio, USA
King et al. 2016	Dissolved	Maximum annual DRP load from tile flow	1.97			Central Ohio, USA
Williams et al. 2016	Dissolved	Maximum annual DRP load from tile flow	2.98			Central & Northwest Ohio, USA
King et al. 2014a	Dissolved	Maximum annual DRP load from tile flow	0.69			Upper Big Walnut Creek - Central Ohio, USA
Christianson et al. 2016	Dissolved	Maximum load of dissolved P reported in MANAGE database	36.8			Eastern half of USA, Ontario, & Quebec
Smith et al. 2014	Dissolved	Median soluble P loads from tile over the sampling period	0.03			St. Joseph Watershed, Indiana, USA
King et al. 2016	Dissolved	Minimum annual DRP loss from the studied tile drains	0.08			Central Ohio, USA
King et al. 2014a	Dissolved	Minimum annual DRP loss from the studied tile drains	0.22			Upper Big Walnut Creek - Central Ohio, USA
King et al. 2014a	Total	Average annual TP loss from the entire watershed	0.98			Upper Big Walnut Creek - Central Ohio, USA
King et al. 2016	Total	Average annual TP loss from the studied tile drains	0.57			Central Ohio, USA
King et al. 2014a	Total	Average annual TP loss from the studied tile drains	0.48			Upper Big Walnut Creek - Central Ohio, USA
King et al. 2016	Total	Maximum annual TP loss from the studied tile drains	2.1			Central Ohio, USA
King et al. 2014a	Total	Maximum annual TP loss from the studied tile drains	0.77			Upper Big Walnut Creek - Central Ohio, USA
Smith et al. 2014	Total	Median TP loads from tile over the sampling period	0.34			St. Joseph Watershed, Indiana, USA
King et al. 2016	Total	Minimum annual TP loss from the studied tile drains	0.09			Central Ohio, USA
King et al. 2014a	Total	Minimum annual TP loss from the studied tile drains	0.28			Upper Big Walnut Creek - Central Ohio, USA
Christianson et al. 2016	Total	Conservation tillage, median TP load reported in MANAGE database	0.42			Eastern half of USA, Ontario, & Quebec
Christianson et al. 2016	Total	Conventional tillage, median TP load reported in MANAGE database	0.36			Eastern half of USA, Ontario, & Quebec
Christianson et al. 2016	Total	No-till tillage, median TP load reported in MANAGE database	1.18			Eastern half of USA, Ontario, & Quebec
Christianson et al. 2016	Total	Pasture, median TP load reported in MANAGE database	0.41			Eastern half of USA, Ontario, & Quebec
King et al. 2014a	Dissolved	Maximum measured tile flow concentration of DRP		4.64		Upper Big Walnut Creek - Central Ohio, USA
King et al. 2014a	Dissolved	Annual FWM DRP concentration for the summed tile flow		0.12		Upper Big Walnut Creek - Central Ohio, USA
King et al. 2014a	Total	Maximum measured tile flow concentration of TP		5.48		Upper Big Walnut Creek - Central Ohio, USA
King et al. 2014a	Total	Annual FWM TP concentration for the summed tile flow		0.15		Upper Big Walnut Creek - Central Ohio, USA
Christianson et al. 2016	--	General upper bound for applied P lost in drain water flow, MANAGE			2%	Eastern half of USA, Ontario, & Quebec
King et al. 2014a	--	Percent of discharge ascribed to tile drain flow			47%	Upper Big Walnut Creek - Central Ohio, USA
King et al. 2014a	--	Percent of the dissolved P load ascribed to tile drains			48%	Upper Big Walnut Creek - Central Ohio, USA
King et al. 2014a	--	Percent of the TP exported from the watershed which is from tile drains			40%	Upper Big Walnut Creek - Central Ohio, USA

These area totals and the calculated percent of county in the drainage basin of interest were then used to estimate the hectares of land within the basin which is drained by tile in each county. This estimate assumes that tile drain fields are spread evenly throughout the county, which is acknowledged as a simplification. In addition, though the calculations are reported with the degree of precision necessary for readers to potentially replicate the exercise, these estimates should only be acknowledged as a general approximation of the scale of potential transport (i.e. billions of cubic meters vs. millions of cubic meters).
Thirty-year precipitation norms were then used from stations at the Fort Wayne International Airport, Indiana; Defiance, Ohio; and Ann Arbor, Michigan, to provide annual precipitation estimates for counties in Indiana, Ohio, and Michigan, respectively. Annual precipitation ranged from 937 mm to 973 mm. Following the convention published by (Boles et al., 2015), 23.2% of this precipitation was assumed to leave the fields as tile discharge. With a total of 1,526,910 ha within the basin assumed to be tile drained, based on Sugg (2007) estimates and Ontario data, this resulted in an estimated annual total drain discharge of 3,342,981,115 cubic meters. For comparison, this is roughly 63% of the average annual discharge of the Maumee River at Waterville (data from 1980 to 2010). Using the lowest total phosphorus yield calculated by King et al. (2014a), which was 0.28 kg/ha, a conservative estimate of 427 metric tons
Working backwards from this load, and using the total tile discharge volume calculated above, gives an average tile concentration of total phosphorus of 128 ug/L, which is well within the literature ranges.

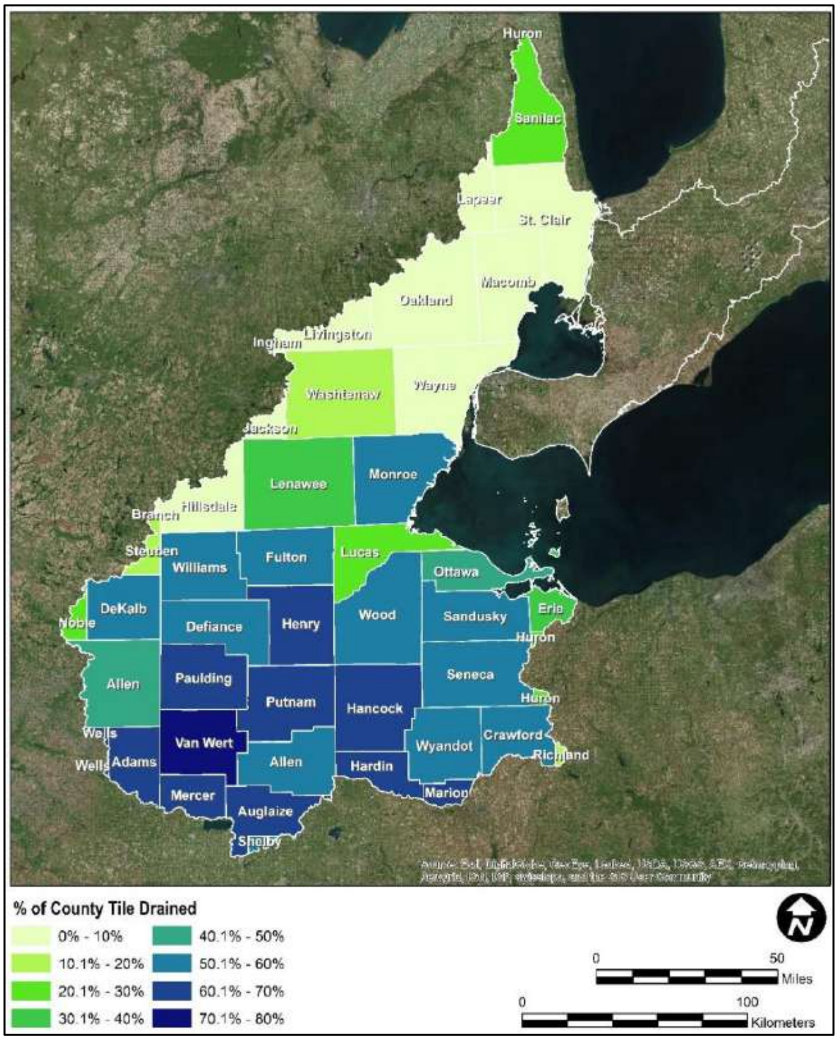

Figure 3-8. Data supplied by Sugg, 2007 and available online at http://www.wri.org/publication/assessing-us-farm-drainage
Supporting geodatabase files can be found in Electronic Supplement Folder ES-3.

3.1.3.c Tile-Drained Area in Canada

Unlike the situation in the U.S., Land Information Ontario collects field level data about tile drains for the purpose of determining whether the field is drained in a random or systematic pattern (Figure 3-9). While these data do not always provide the area of the field which is directly drained, the area of the polygon shapes can

the same fashion as the estimates made for U.S. tile drained areas, a general scale of the phosphorus which is transported by tiles from fields in Canada can be calculated. Again, though the calculations are carried through with the degree of precision necessary to replicate the exercise, these estimates should only be acknowledged as a general approximation of the scale of potential transport. Assuming an annual average precipitation[2] of 882.3 mm, and 23.2% infiltration and discharge through tiles, the 606,718 hectares of fields with tile drains were estimated to produce 1,241,912,916 cubic meters of tile flow

[2] The 1981-2010 climate normal annual precipitation value is from station CHATHAM WPCP, Ontario. Available online at climate.weather.gc.ca.

annually. Using the low estimate from King et al. (2014a), these fields would annually transport approximately 170 metric tons of phosphorus to their local waterways.

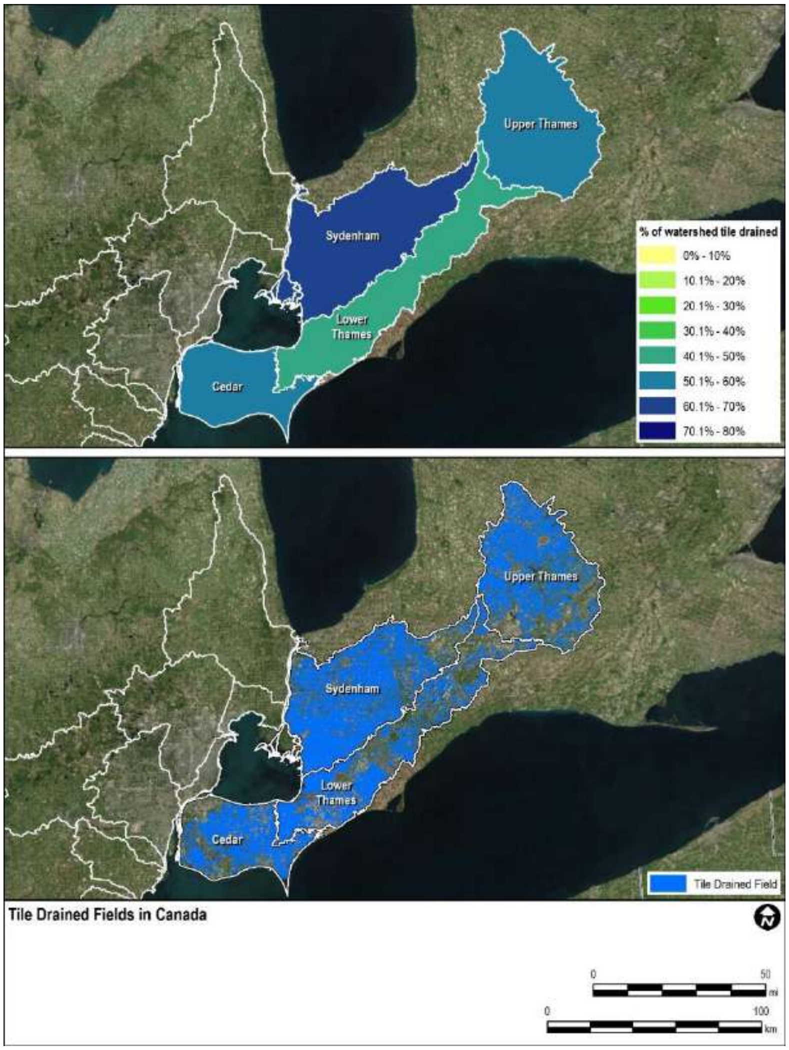

Figure 3-9.Tile drained fields in Ontario; data downloaded from Land Information Ontario

3.1.3.d Tile Drain Phosphorus Estimates in Context

Recently completed work by Maccoux et al. (2016) estimates the total loading of phosphorus into Lake Erie, partitioned into the Huron-Erie corridor, and the Western, Central, and Eastern basins (Figure 3-10). Figure 4 of that work (redrawn here in Figure 3-10) shows the mean total annual phosphorus loadings in metric tons using data from 2003 to 2013. The Huron-Erie corridor is expected to contribute 2,259 MT of total phosphorus with 43% (971 MT) coming from nonpoint sources; of this, the total annual contribution from the Thames River is approximately 342 MT, with 187 MT of this in the form of DRP (Maaskant, 2015). In the Western Basin (excluding the Detroit River), average total loading was estimated to be 3,234 MT per year with 89% (2,878 MT) coming from nonpoint sources. This puts the average total nonpoint loading at 3,849 MT of total phosphorus (971 + 2,878). The conservative Canadian plus United States estimates calculated above for tile drain inputs amount to approximately 15% of this nonpoint total; actual values are likely higher, and possibly substantially higher.

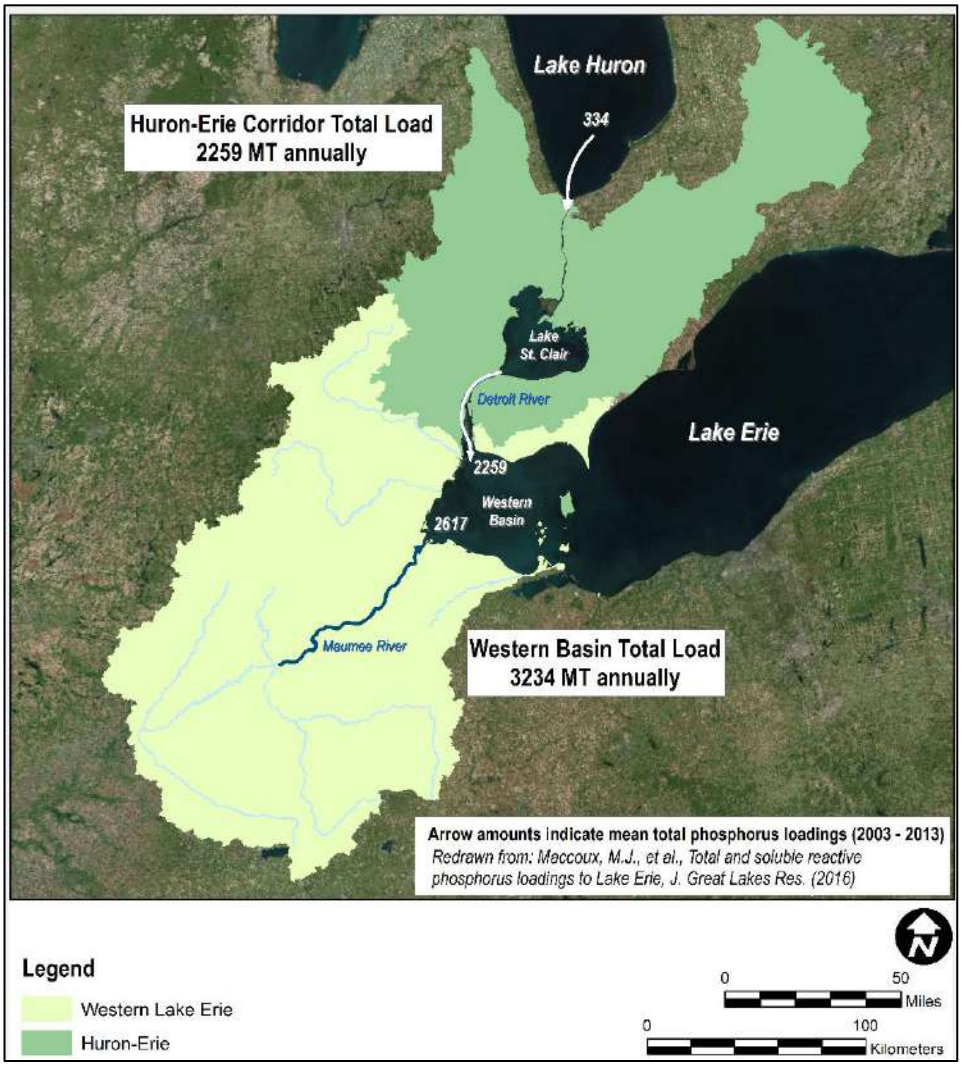

Figure 3-10. Total phosphorus loading into the Western Basin of Lake Erie, redrawn from Maccoux et al., 2016. Note that while our assessment generally considers the Sandusky River watershed to be part of its analysis, Maccoux et al. did not, and thus it has been removed from the study area shown in this figure.

3.1.4 The Effect of Climate on Phosphorus Loads to Lake Erie

As the phosphorus load to Lake Erie is governed by both concentration and discharge, it is important to consider the effects of changing precipitation patterns on the presence of HABs in the lake. Stow et al. (2015) completed a seasonal trend decomposition using loess (STL) to analyze seasonal and long term patterns in data from the Maumee River and surrounding area. Monthly precipitation running from 1895 to 2013 was obtained from NOAA for Ohio Region 1 from the Midwest Regional Climate Center. Discharge data was obtained from the USGS gage in Waterville, OH (USGS04193500) and included data from 1974 to the present. The National Center for Water Quality Research (Heidelberg, OH) was queried for water quality data. Data sets were smoothed with windows of 48 and 250 months for seasonal and long term trends.

Findings indicated that precipitation trends were relatively steady from around 1975 into the late 1980s (Stow et al., 2015). After declining somewhat in the early 1990s, the trend showed a steady increase from the mid-1990s through the end of the record. This trend in precipitation was mostly mirrored in the discharge trends which, most notably, showed a strong increasing trend from the mid-1990s to the end of the record.

Analysis of the water quality records indicate that total phosphorus (TP) concentrations experienced a steady decrease from the beginning of the analysis until about 2000 before experiencing a very slight increase (Stow et al., 2015). The overall effect is that TP concentrations are approximately 20-30% lower at the end of the record than at the beginning. Dissolved reactive phosphorus (DRP) concentrations have also experienced an overall decrease since the beginning of the record, however, this water quality constituent experienced a stronger increase from the mid-1990s to the end of the record. Monitoring data for the Thames show trends since 1986 of decreasing flow-weighted mean DRP and no trend in TP for the Upper Thames, with DRP steady and TP decreasing for the Lower Thames (Maaskant, 2015).

Even though the overall concentrations in the Maumee River have decreased from the beginning of the record to the present time, the authors analysis concluded that the long term trend for TP and DRP load shows strong increases for TP from the year 2000 and strong increases for DRP from about the mid-1990s (Stow et al., 2015). The effect of the discharge trend so strongly influenced loading that, though both TP and DRP concentration trends ended at lower points than the beginning of their respective records, their loads to the lake are as high or higher at the conclusion of the analysis period than at the beginning.

Other studies in the Lake Erie basin have projected increasing precipitation as we approach the end of the 21st century. Michalak et al. (2013) reviewed spring precipitation at a daily time step using several Climate Model Intercomparison Project Phase 5 (CMIP5) climate models. Their findings indicated that events which exceed 20 mm increase in frequency by approximately 50% and the frequency of events which exceed 30 mm could be expected to double.

After reviewing the analysis completed by Stow and others, LimnoTech obtained data for several stations throughout the Maumee from the NOAA National Centers for Environmental Information[3] (https://gis.ncdc.noaa.gov/maps/ncei/cdo/daily).
watershed (a tributary to the Maumee) and have been previously referenced during modeling activities for these watersheds as they provide a long period of record. It is not expected that, as individually analyzed stations, they will be perfectly representative of trends in other parts of the Western Lake Erie Basin.

These stations were processed first to remove any year which contained less than 355 data points (i.e. each year was at least 97% represented). Daily precipitation was summed to provide spring totals, where spring was considered any date between March 1st and July 31st
period has been shown to have the greatest impact on late summer HABs). Each station contained at least 75 years of data after processing. These spring precipitation values were plotted chronologically as points and fitted with a loess smoothing curve using the default span of 0.75[4] and a 95% confidence interval. As can be seen in Figure 3-11, both the Berne WWTP station and the Decatur 1 N station exhibit slight upward trends in spring precipitation beginning in around the mid-1980s. The station at the Fort Wayne International Airport, which had the shortest period of record, showed only a mildly increasing long term trend from the beginning to the end of its record. This brief, high-level analysis serves to confirm that the annual trends identified by Stow et al. (2015) also are likely to apply to the spring precipitation (and thus discharge) which drives HABs in the lake. However, it should be noted that the changes in spring precipitation discussed here do not necessarily indicate changes in total annual precipitation. In addition,

[3] NCEI, formerly the National Climatic Data Center (NCDC)
[4] The span variable controls the amount of smoothing, a low number means fewer points are considered. For span < 1, the neighborhood includes proportion of the points, and these have tricubic weighting (proportional to (1 - (dist/maxdist)^3)^3). For more information, see (Ripley 2017).

it is also important to note that Jarvie et al. (2017) analyzed long-term water quality data for several watersheds within the Western Lake Erie Basin and found that only 35% of the increases in SRP loading observed after 2002 were due to higher runoff volumes.

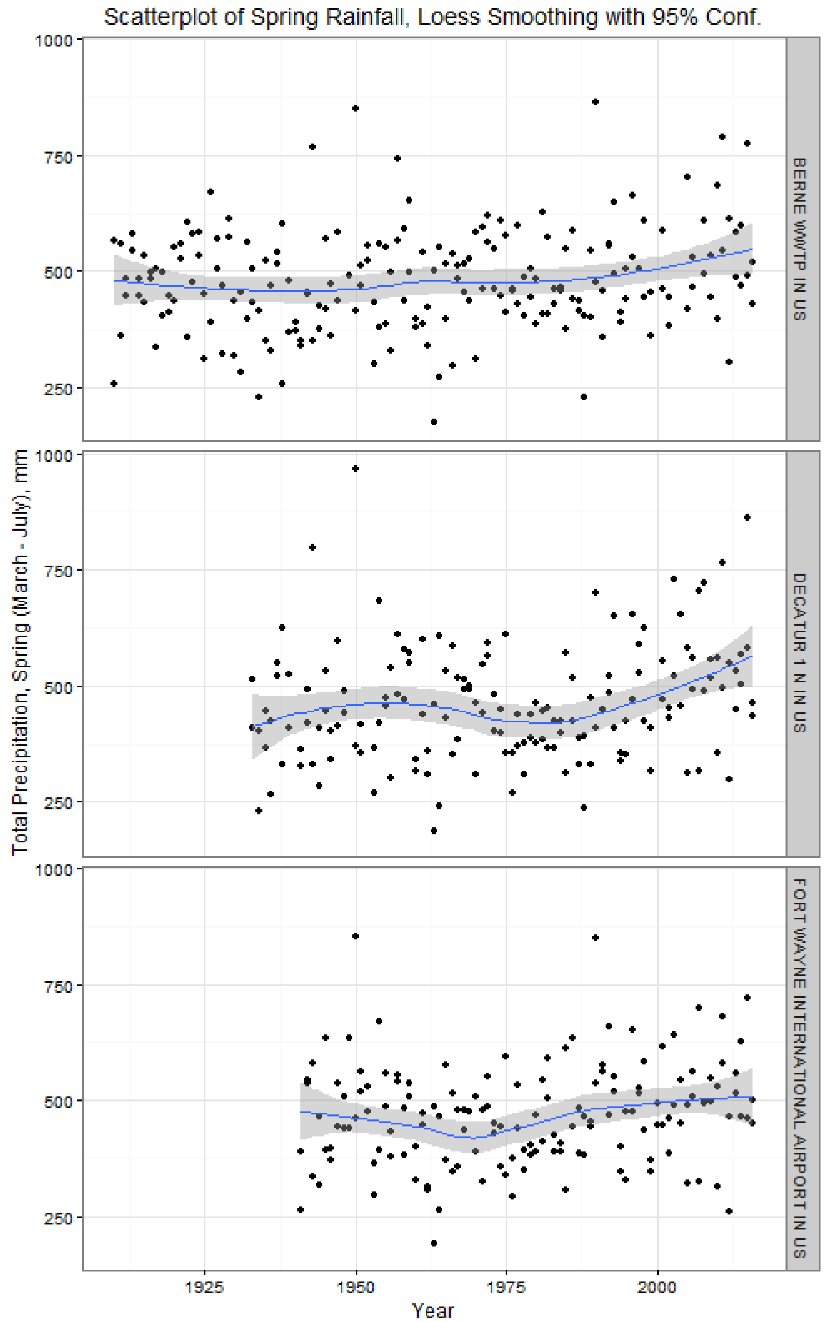

Figure 3-11. Total spring precipitation, excluding years with fewer than 355 data points, plotted by station and by year. Stations are located in north-east Indiana. The smoothing curve is bounded by a 95% confidence interval and uses a loess fitting method.

3.1.5 Fertilizer Application

Fertilizer in agricultural soils is an important (but not exclusive) determinant of nutrients carried from the landscape into waterbodies, and their sediments and banks. Fertilizer is applied to fields to increase yields by supplementing soil nutrients to meet crop needs. Crop needs vary by crop, strain, growing season, weather conditions, plant health, and soil types, among other factors. Nitrogen, phosphorous, and potassium (in that order) are the three main nutrients that are contained in inorganic fertilizers. Nutrients can also be supplied by other products such as organic manures, as well as from plants residues from prior crops, and biological nitrogen fixation in the roots of crops like alfalfa and soybeans. Practical nutrient requirements for certain crops should come from regionally specific guidelines, such as the Tri-State Fertilizer Recommendations (Vitosh et al., 1995) for Indiana, Ohio, and Michigan, along with soil test data. Under ideal growing conditions, crops take up 100 percent of nutrients available from fertilizer to meet their growth requirements. In reality, planting and growth conditions are always less than optimal, which may result in lower crop needs than anticipated when applying fertilizer. The more the actual crop needs deviate from their anticipated need, the greater the potential for a larger fraction of applied nutrients to go unused, and possibly to be mobilized and released from fields to groundwater or surface water rather than to be taken up into crop roots, stems, leaves, and seeds.

The available excess fertilizer that can be mobilized in dissolved or particle-bound forms from farm fields by run-off or tile drain discharge in any given year reflects the cumulative effect of prior years of fertilizer use and newly applied nutrients. 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 both the short and the long term. These aspects of fertilizer application have received much attention as practices that can be adjusted to minimize nutrient losses from cropland and into natural systems. Losses are also a function of climatic and soil/watershed variables that are, for the most part, not controllable by farmers. This attention to fertilizer parameters translated into efforts to optimize these dimensions for crop uptake and to minimize losses. The framework within which this optimization is incr Right amount, Right time, Right place, Right source

Amounts of applied fertilizer are not directly measured in either the U.S. or the Canadian census, nor do farmer surveys capture this information. Only fertilized acreage is recorded directly and on a county basis. The amount of fertilizer applied in a given geographic area has to be estimated based on expenses and sales (introduced in previous section). Here we present data available on application rates by state, fertilized acres by county and watershed, and nutrients applied by county and watershed in a set of studies for the U.S. as well as our own estimates for Canada.

Fertilizer Use and Price from USDA-ERS includes data from 1964 to 2010. The tables report fertilizer *use* by crop as phosphate (and nitrogen) per acre at state level. Data on fertilizer type is provided for the U.S. as a whole, not at the state level. Limited details on methods used are included in data table notes at the bottom of each spreadsheet in the Excel workbook available here: https://www.ers.usda.gov/data-products/fertilizer-use-and-price.aspx The methods for calculating crop-specific fertilizer application rates are not described in detail on documentation included with the data, but may be available from other publications.

For the three major crops, Figure 3-12 shows the percent of acreage receiving phosphate, and the per-acre application rate on each crop between 1964 and 2010. In the states of Indiana, Michigan, and Ohio, the percent of the acreage receiving phosphate has decreased between approximately the early to mid-1980s to the late 1990s for corn and soy, and stayed stable but variable into the 2000s. The decreasing trend continued to 2010 for wheat. The per-acre application rate for corn also shows a steady decrease since approximately 1980. For soy, the application rate has increased somewhat, and since about 2000 shows increased variability. For wheat, the application rate increased to about the mid-1990s and decreased since, also with more variability. It is interesting that while 80-100 percent of corn and wheat acres have always received phosphate fertilizer, less than half of the soy acres receive phosphate. On a per acre basis, the soy that has been fertilized, has been fertilized less; wheat and corn have received similar amounts.

However, among the three crops, the trends have led to a convergence of fertilizer amount per acre by the 2000s to about 30-70 pounds P_2O_5 per acre (13-31 lb. P/acre, or 15-34 kg P/ha) for all three crops (Michigan is generally on the lower end, Ohio and Indiana have higher application rates). The three states have similar patterns and absolute amounts, except for corn in Michigan, where much less is applied per acre of crop than in Indiana or Ohio. These data are available in Electronic Supplement folder ES-1 (subfolder Fert5). We did not identify sources of similar crop-specific statistics for Canada.

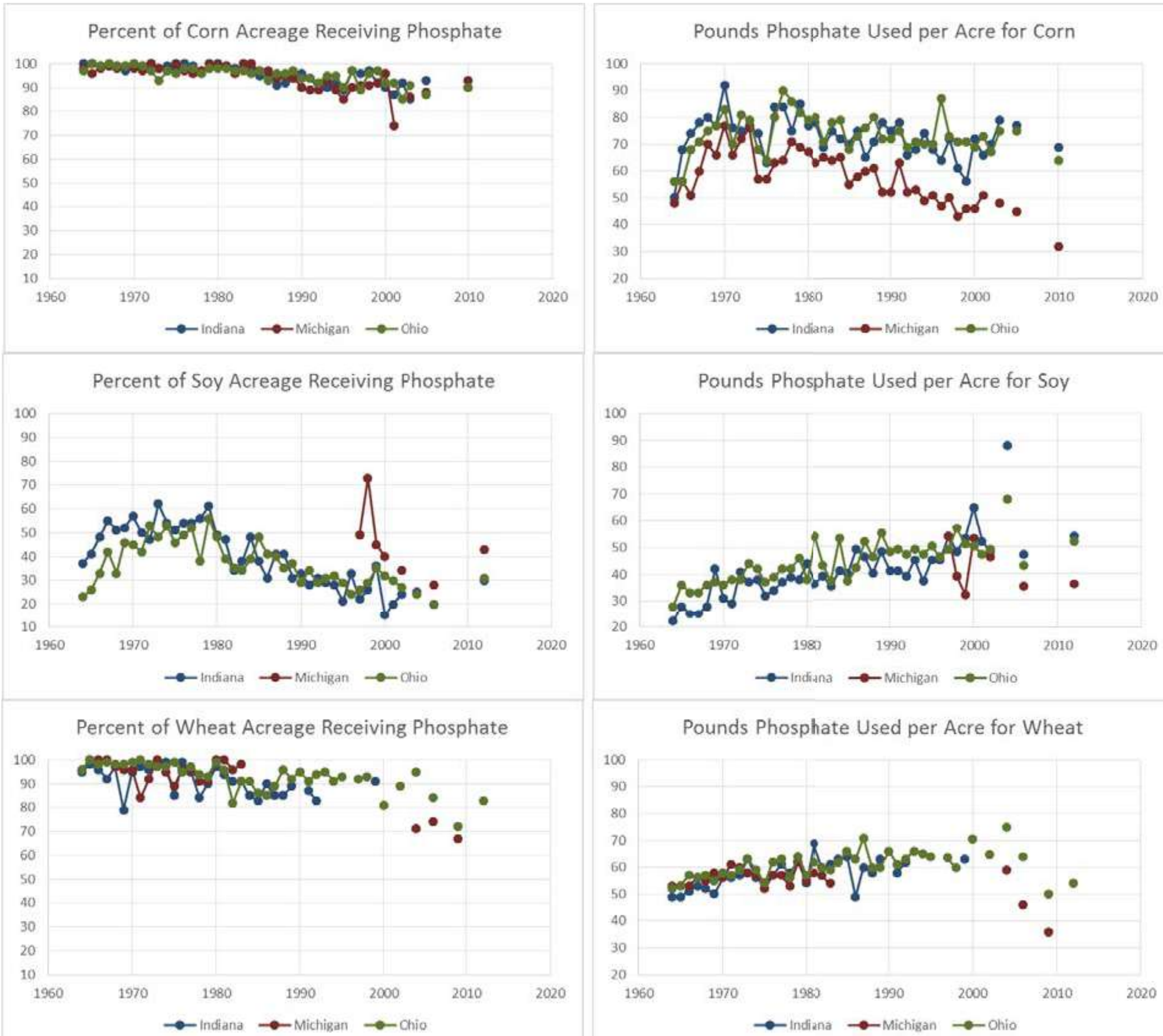

Figure 3-12. Application of phosphate to corn, soy, and wheat.

Fertilized acreage data are available from the USDA Agricultural Census via QuickStats, and from the Canadian Interpolated Census of Agriculture. Figure 3-13 shows the temporal evolution of fertilized area for each watershed in the WLEB. Fertilized area is generally consistent from year to year, to slightly declining through time. This is consistent with the overall data on cropland area in the region, which is quite stable through time (discussed below).

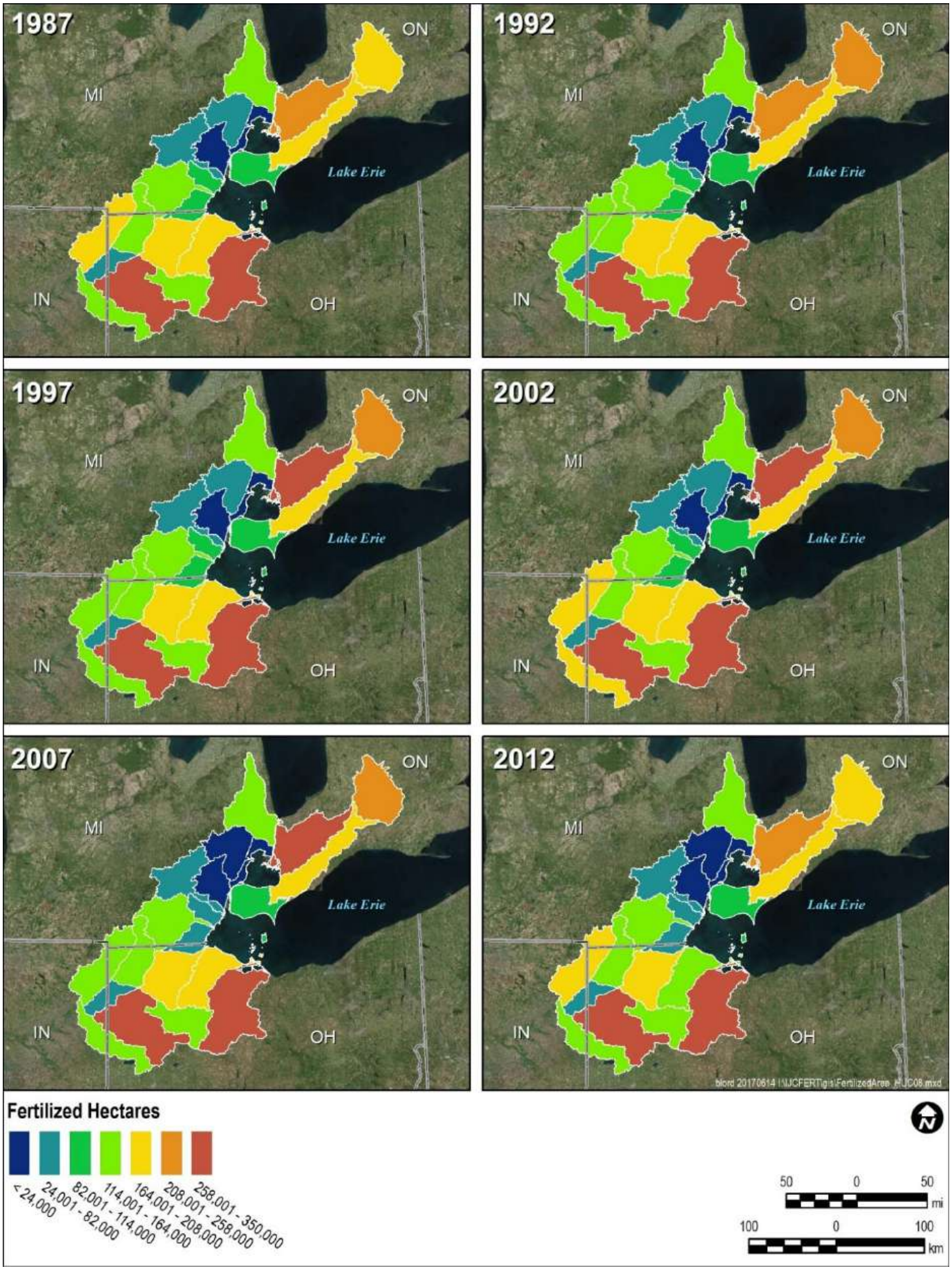

Figure 3-13. Evolution of fertilized hectares over time in each HUC-8 watershed for six consecutive census periods. Canadian data are one year earlier compared to the U.S.; dates on the maps indicate the year for the U.S. data. Supporting geodatabase files can be found in Electronic Supplement Folder ES-4.

Fertilizer application time-series in U.S. counties are available from five studies: Ruddy et al. (2006), Gronberg and Spahr (2012), Brakebill and Gronberg (2017), IPNI-NUGIS (2012 - U.S.) and IPNI-NUGIS (2013 - Canada). Ruddy et al., 2006 estimated fertilizer nutrient inputs for the years 1987-2001. Estimates of fertilizer nutrient application are based on state-level fertilizer sales (yearly data from AAPFCO) apportioned based on county-level fertilizer expenditures (5-yearly data from the USDA Agricultural Census), while also accounting for farm and non-farm fertilizer use. For non-census years expenditures were estimated by linearly interpolating between census years. The Gronberg et al. (2012) study is an extension of the Ruddy et al. (2006) study in order to correct some shortcomings of the farm and non-farm allocation of fertilizer sales, and covers the same time period as the original Ruddy et al. study. Brakebill and Gronberg extended the Gronberg analysis with new data to 2012. The USGS study results are available in Electronic Supplement folder ES-1 (subfolder Fert6), and are not discussed further here.

The IPNI-NUGIS (2012, 2013) studies cover the years 1987 to 2012 for the U.S. (counties) and 1954-2007 for Ontario (province). For the U.S., IPNI-NUGIS followed a more complex method of allocating sales to counties, based not only on farm expenditures but also on an interpolation method to allocate sales by distributors to counties. Farm and non-farm uses are also separately accounted for, similar to Ruddy et al. The IPNI-NUGIS method also estimates farm fertilizer expenditures for counties for which expenses are withheld in the census. For Canada, nutrient inputs are estimated for the province (discussed under

-NUGIS studies cover a longer time frame and have more complete spatial coverage, we used these results for presentation and discussion. IPNI-NUGIS results and study methods are provided in Electronic Supplement folder ES-1 (subfolder Fert7).

For the U.S., study results of phosphorus application were converted from county level to watershed level, based on the proportion of a county in each watershed; application rates were further scaled by normalizing for the farmland fractional area of the county. For Canada, study results for Ontario were scaled down from the province to the watershed level based on farm fertilizer expense data from the Canadian Interpolated Census of Agriculture. Both results are presented side by side, however data manipulations and details of the scaling approach differ, and comparison between the countries should be done with an understanding that uncertainties are different on the two sides of the border. Electronic Supplement folder ES-1 (subfolder Fert7) discusses the down-scaling method and shows the calculations and results. These results for Canada were combined with results for the U.S. to generate the plots and maps presented below.

Figure 3-14 shows the evolution of fertilizer phosphorus application as total mass and normalized to total cropland area in the WLEB watersheds of the U.S. and Canada. The temporal pattern varies regionally. Watersheds in Michigan receive much less total phosphorus application, which correlates with fewer fertilized acres. The trend in applied P has been consistently downward in Michigan watersheds. In Ohio/Indiana watersheds, total phosphorus applied is considerably higher than in Michigan, and temporal variation is also greater with no clear trend, although the last 2 years on record are the lowest. Canadian application rates in 2007 (last year with data) are similar to rates in Michigan.

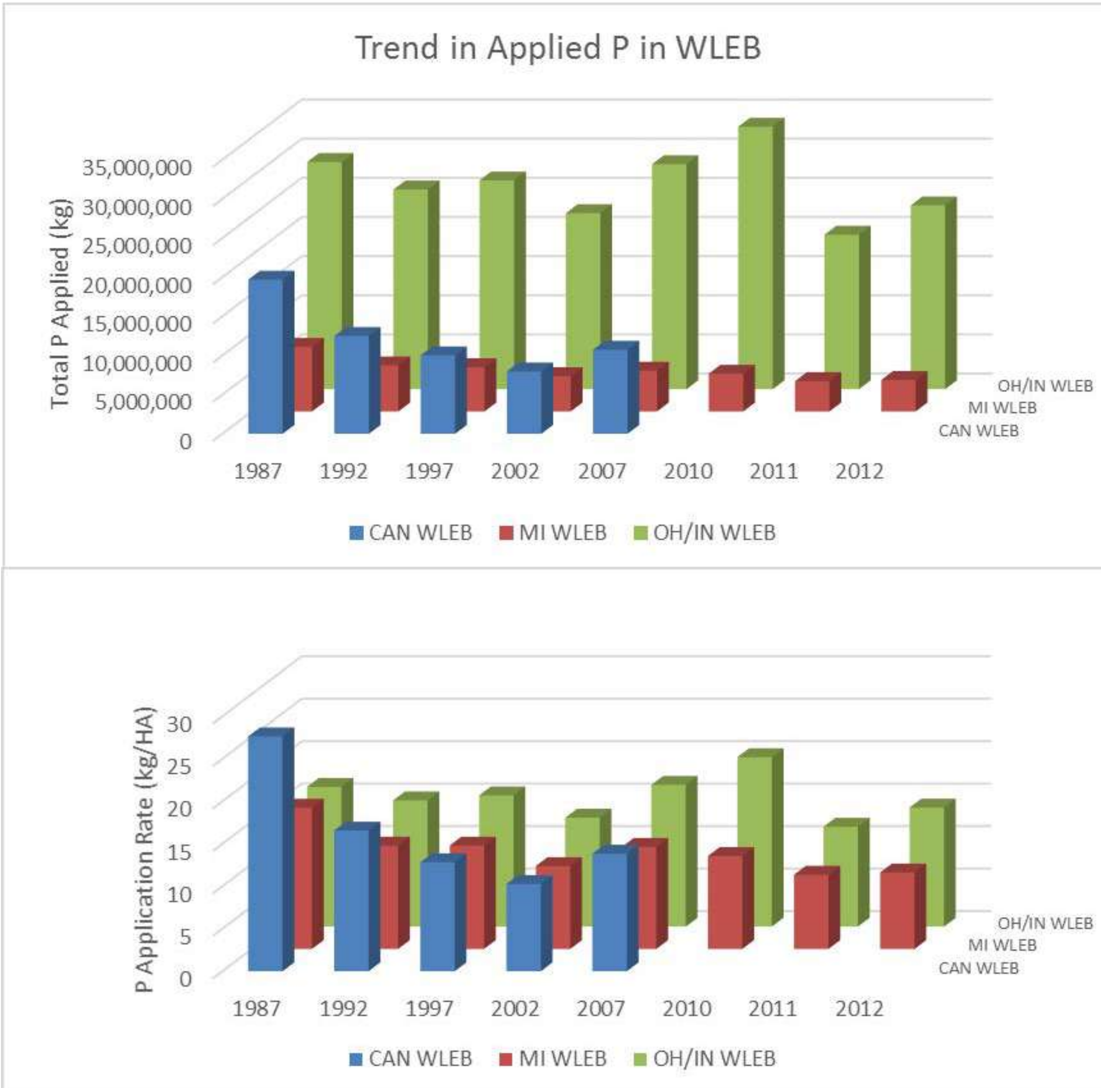

Figure 3-14. Temporal evolution of fertilizer-applied phosphorus in the WLEB watersheds. Michigan watersheds are entirely within the state, Ohio includes all other watersheds, including the Tiffin. Canadian expense data were available up to 2007, so values could not be calculated for the last 3 years. IPNI-NUGIS reported additional data for non-census years 2010 and 2011 for the U.S. from unspecified sources.

Figure 3-15 show the same data in map format. This map indicates that the watersheds with the highest applied phosphorus rate are the Sandusky, St. Joseph, and Cedar-Portage watersheds in the U.S. The Sandusky ranks highest in terms of both area and rate. In Ontario, application rates are in the middle of the U.S. range, however the Cedar ranks highest and exceeds rates in the U.S. in 2007. The Cedar watershed stands out among the Canadian and U.S. watersheds. As seen in Figure 3-16, while rates in the Thames and Sydenham have decreased steeply to 2002, with a modest increase to 2007, the decrease in the Cedar was more attenuated and reversed into a steep increase between 2002 and 2007. Currently, it is unknown if this trend continued to more recent times, due to unavailability of farmer fertilizer expense data.

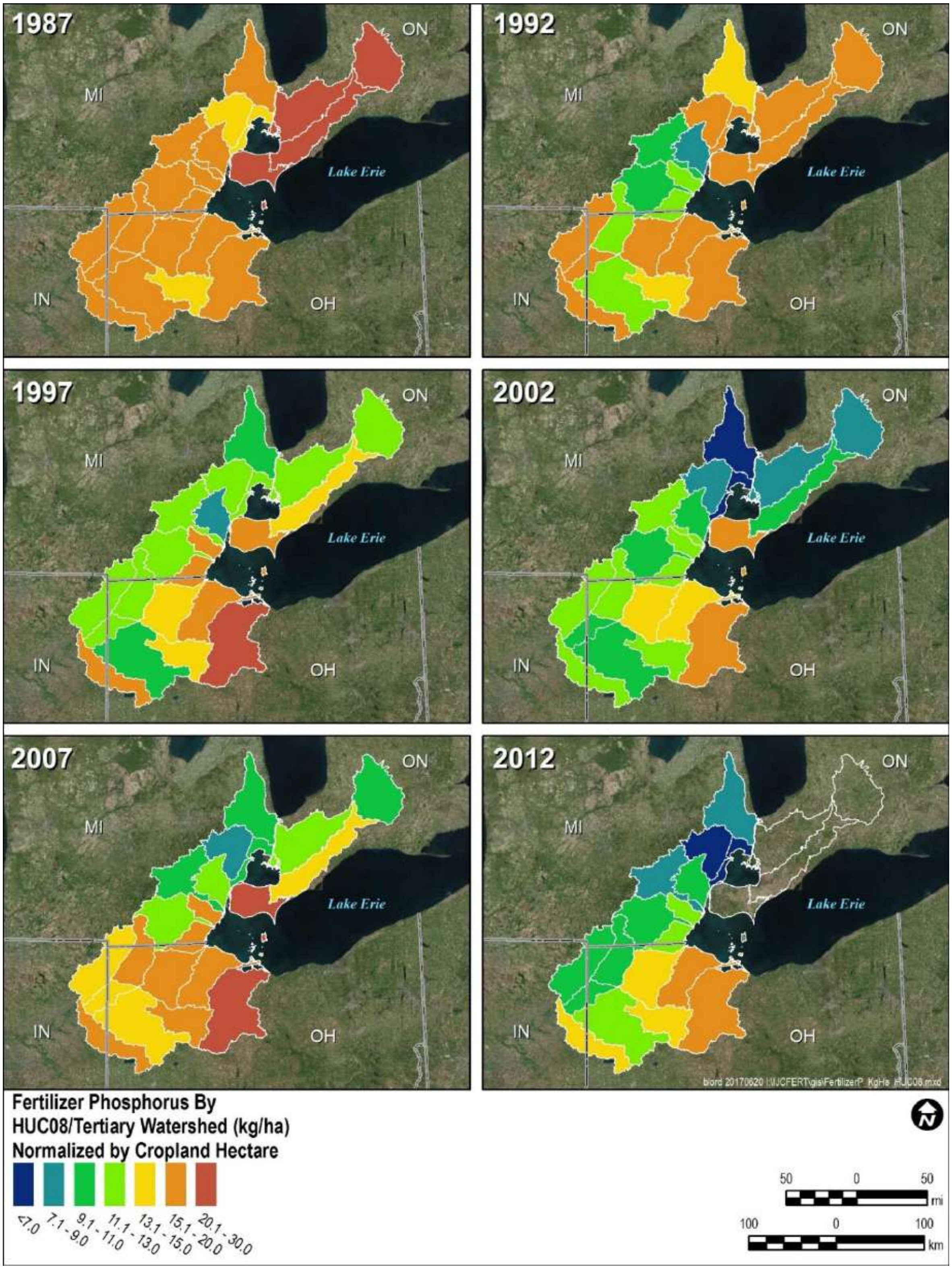

Figure 3-15. Evolution through time of normalized inorganic fertilizer application intensity for cropland by watershed for six consecutive census periods. Data for 2012 are not available for Ontario. Supporting geodatabase files can be found in Electronic Supplement Folder ES-4.

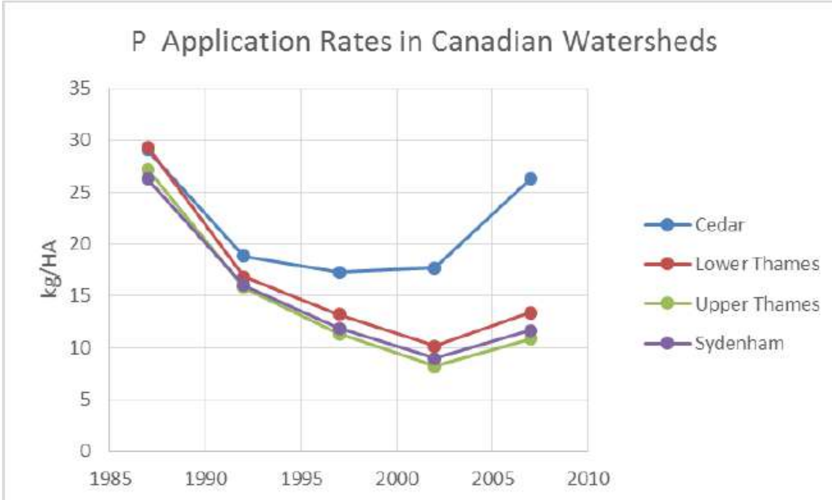

Figure 3-16. Evolution through time of normalized fertilizer application intensity for cropland in the Canadian portion of the WLEB.

Overall, in terms of amount at the watershed scale, application rates in 2012 averaged 11 kg/ha (10 lb./acre) across U.S. watersheds, with the maximum in the Sandusky watershed at 19 kg/ha (17 lb./acre). In Canada, rates in 2007 averaged 16 kg/ha (14 lb./acre), with the maximum in the Cedar watershed at 26 kg/ha (23 lb./acre). Crop-removal across the U.S. WLEB (based on IPNI-NUGIS, 2012) ranges from approximately 11 to 22 kg/ha (10 to 20 lb./acre). Thus, recent phosphorus application rates for inorganic fertilizer are similar to crop removal rates. The P values above in soil tend to be in the so- - for soil P for most crops (i.e., below buildup range and maintenance range), as defined in the Tri-State Fertilizer Recommendations (Vitosh et al., 1995) for corn, soy, wheat, and alfalfa. Note that multiple methods exist for measuring soil P; these recommendations are based on the Bray P1 test, which is used to estimate P availability for crops but not total P in the soil. This means that at these fertilization rates soil P levels can be expected to be depleted over time. Nevertheless, crop yields have been increasing over time in this region (Ray et al., 2012), indicating that there is a surplus of built-up soil phosphorus that has supported yields, in addition to other factors such as genetic improvements to seed corn varieties that increase yield, and higher precipitation during recent growing seasons. The soil P surplus continues to support crop removal rates that meet or exceed fertilization rates. Bruulsema et al. (2011) calculated a nutrient balance for the state of Michigan, Ohio, and the province of Ontario, and indicated that the sum of fertilizer and manure application approximately matched crop removal by 2008 (see also Han et al., 2012). Our results suggest a close match of crop removal with fertilizer alone (without manure), possibly because of the different geographic definition (entire states vs. select watersheds in these states). Data on soil test levels are consistent with this overall relationship. Figure 3-17 shows soil test results, available from IPNI-NUGIS (2016) at the state level. These data indicate the continued existence of a surplus (>50 ppm) in 24 to 37% of soil samples, as well as a downward trend of the proportion of soil test results in the highest categories of phosphorus concentration in soils of the Lake Erie region, including Ontario. These soil test trends are discussed in some detail by Bruulsema (2016).

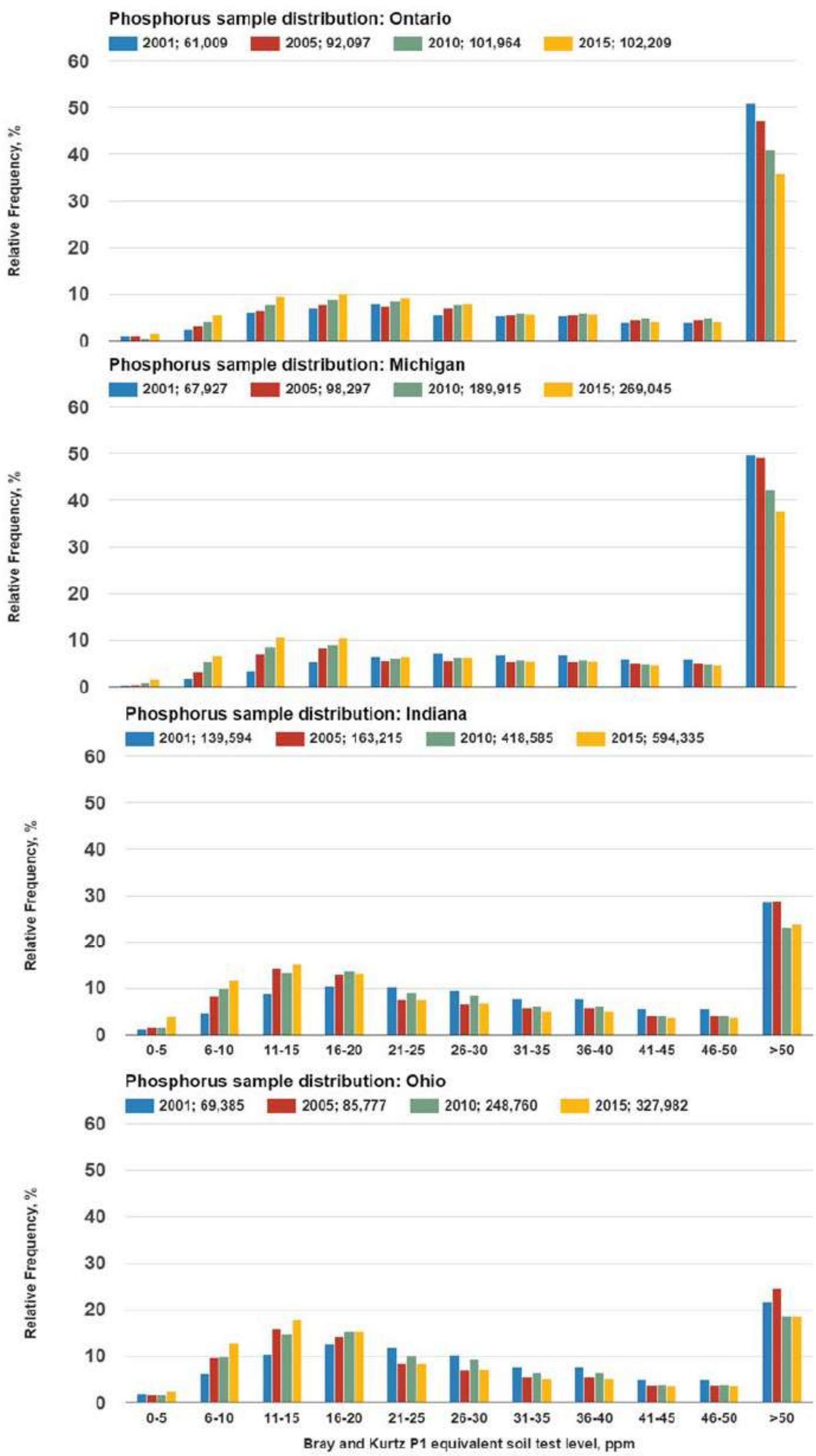

Figure 3-17 Change in soil test P levels between 2001 and 2015 in Ontario, Michigan, Indiana, and Ohio (data from IPNI-NUGIS, 2016; values in legend after year are total numbers of samples).

The above regional balances and trends still allow for geographic variation and the existence of soils that are fertilized at rates that exceed (or are below) crop needs. Across Indiana WLEB counties, fertilizer input ranges from 22 to 35 lb. P_2O_5/acre (the net balance of all inputs minus crop removal ranges from -11 to 9 lb. P_2O_5/acre), across Michigan WLEB counties fertilizer input ranges from 12-30 lb. P2O5/acre (net balance of -23 to 10 lb. P_2O_5/acre), and across Ohio WLEB counties fertilizer input ranges from 16-55 lb. P_2O_5/acre (net balance -23 to 60 lb. P_2O_5/acre). Maps in Figure 3-18 created with the interactive mapping tool of IPNI-NUGIS (IPNI-NUGIS, 2012) show the evolution of the balance between fertilizer and manure inputs relative to crop removal for P_2O_5. While in 1987 there was a surplus throughout the U.S. WLEB, by 2012 the balance is negative in most counties. However, positive balances remain in a large portion of the a moderately positive balance in the Maumee and Auglaize. Such local net surplus fertilizer applications have the potential to sustain phosphorus inputs into waterways, while net deficits paired with crop yield gains indicate an historical build-up of legacy P in farm fields. While these data reflect the phosphorus status of farm fields, the excess phosphorus applied in the past moves beyond the boundaries of farms. Legacy phosphorus resides in buffer zones, wetlands, stream and river banks, and sediments, where crop removal as a drawdown pathway does not exist. The presence of legacy P in these reservoirs will likely delay reduction of agricultural P loading to western Lake Erie based on farming practices alone, given the lag time for substantial reduction of this background source of P in the watershed.

In contrast to the amount of applied fertilizer, data on timing, placement and source of applied fertilizers are much less readily available, as this information is not systematically collected over the WLEB. Most of this data are collected via farmer surveys administered by various programs over various geographies. With the interest and promotion of the 4R program, however, the intensity with which such information is collected has steadily increased. The Conservation Effects Assessment Program of the USDA NRCS administers surveys that increasingly target quantitative information on each specific 4R principle, in their geographic area of interest; results of surveys have been published for the WLEB on the U.S. side (USDA NRCS, 2016). The 4R Nutrient Stewardship Certification Program also actively collects and manages data (Vollmer-Sanders et al., 2016), though we have not been able to determine if and in what form this information is available. Researchers at Ohio State University conducted and published the results of three farmer surveys, two in the Maumee basin (Wilson et al., 2013; Burnett et al., 2015) and one encompassing the WLEB on the U.S. side (Prokup et al., 2017). Also at OSU, LaBarge and Prochaska (2014) published a brief summary of results of a survey of agricultural retailers about soil testing and nutrient application practices in Ohio. Finally, in Canada, the Canadian Field Print Initiative by Pulse Canada has conducted two in-depth farmer surveys on 4R practices and reported on their results (Stratus 2016). These results are discussed in the sections below.

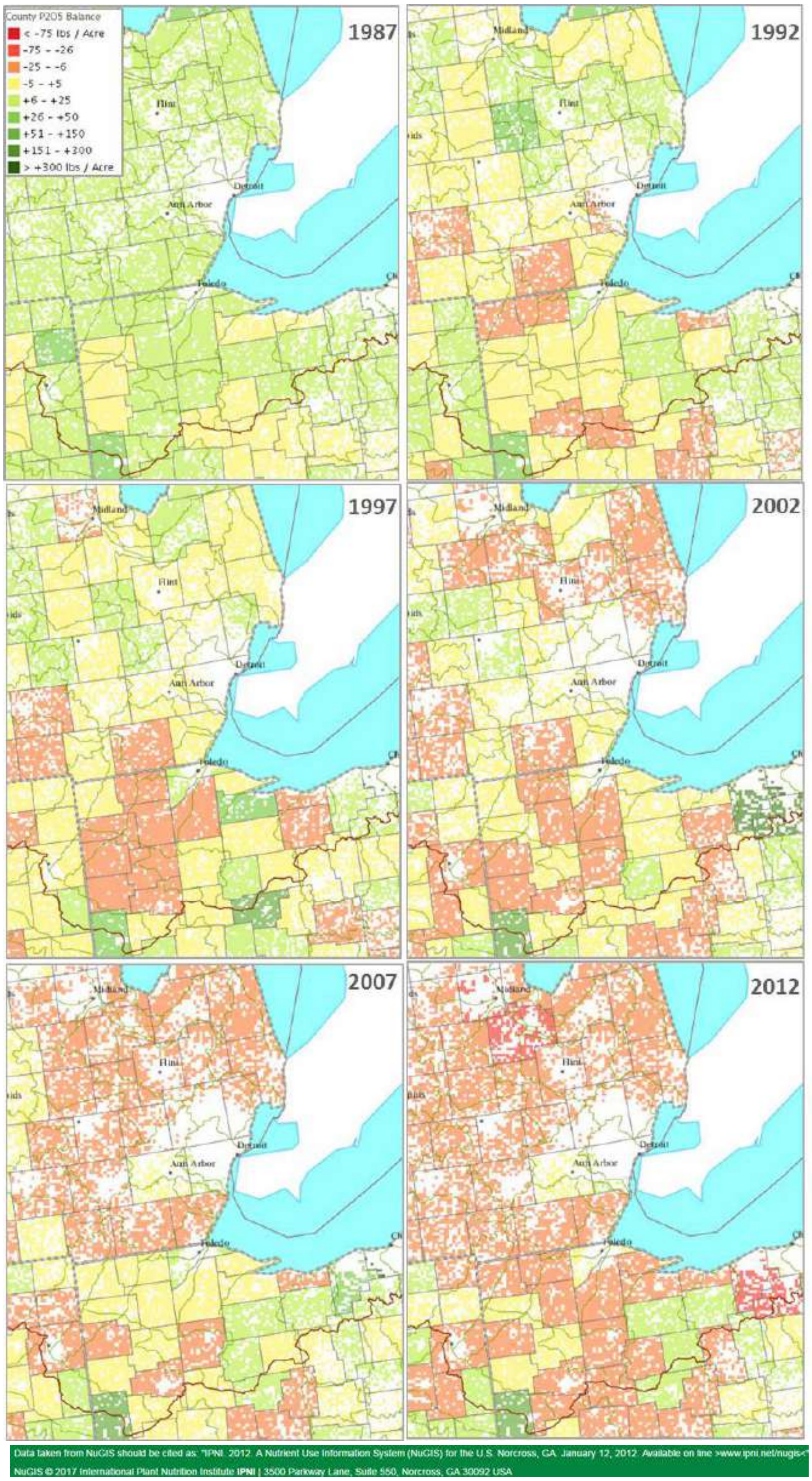

Figure 3-18. U.S. county estimates of a partial P_2O_5 balance (fertilizer + manure - crop uptake) over time created using the IPNI-NUGIS interactive mapping tool. County estimates are shown only in areas of agricultural land-use; white areas denote non-agricultural land-uses. Ontario data are not shown.

3.1.6 The 4Rs for Phosphorus Management: A Framework

The 4R system is a method of fertilizer application which follows four key principles (Bruulsema et al., 2009):

- Use the Right Source (i.e. product)
- Apply the Right Rate (i.e. matching expected crop needs, though recommendations may vary)
- Put fertilizer on at the Right Time (i.e. when it is most needed by crops and least likely to rain)
- Apply the product at the Right Place (i.e. soils that need it more, or closer to plant roots)

Each of these principles is associated with a variety of practices and tools that help to determine needs, make decisions and apply fertilizer. Figure 3-19 shows a selection of such practices and their association with the 4Rs.

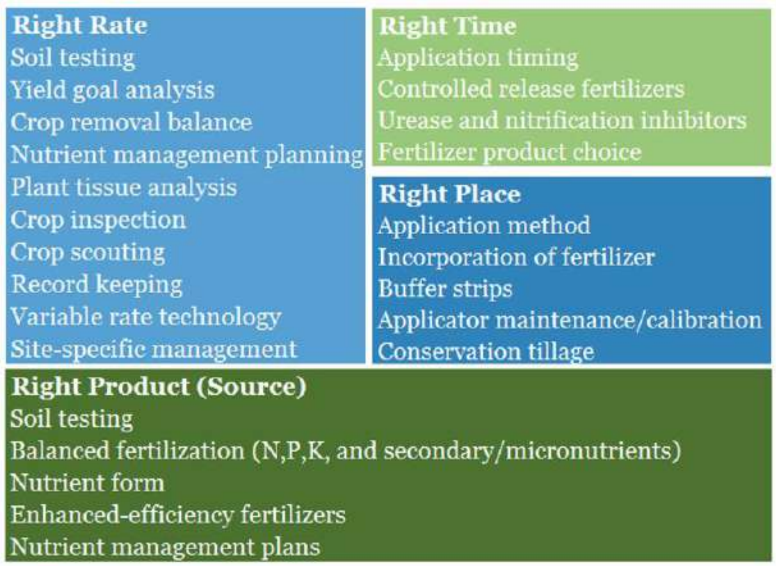

Figure 3-19. A block diagram of the 4R nutrient application principles and associated practices. *Permission for use of image will be requested prior to public release.*

This method of nutrient stewardship is applied to help minimize the impact of fertilizer application to the surrounding environment and improve the productivity of agriculture. When implemented correctly, the 4R principles str

rooting zone. This optimization of fertilizer application improves the per-acre yield of a given crop for each unit of nutrient applied and helps the producer weather fluctuations in the cost of inputs. The guidelines for the 4R principles are endorsed and supported by the International Plant Nutrition Institute, The Fertilizer Institute, (formerly The Canadian Fertilizer Institute), and the International Fertilizer Industry Association (http://www.nutrientstewardship.com).

3.1.6.a A Short Timeline of the 4Rs in the Region

After the 4R framework was proposed (Bruulsema 2009), specific implementation programs were started in various geographic areas. In 2014, the International Joint Commission published the following recommendation in their report on Lake Erie phosphorus:

> *The Governments of the United States, Canada, Ontario, Michigan, Indiana, Ohio, Pennsylvania, and New York should accelerate 4Rs (Right source, Right rate, Right time and Right place) outreach/extension programs, and phase in mandatory certification standards for agrology advisors, retailers and applicators to ensure fertilizer is applied based on the 4Rs (International Joint Commission 2014).*

In the U.S. side of the Western Lake Erie watershed (which covers parts of Indiana, Michigan, and Ohio), a voluntary program moved to provide a recognized standard for retailers of agricultural products in the participating states. This program was launched in March of 2014 and had its first certified nutrient providers by that October (Vollmer-Sanders et al., 2016). By April of 2016, 4R-certified providers were estimated to influence fertilizer application on 36% of farmland in the WLEB (Vollmer-Sanders et al., 2016). More information about this program can be found at 4RCertified.org.

The State of Ohio moved to regulate manure and fertilizer application with the passing of Senate Bill 1, which came into effect on July 3, 2015 (LaBarge 2015). Under this law, producers in the western basin may not apply fertilizer or manure when the ground is snow-covered or frozen, when the top two inches are saturated, or when there is a greater than 50% chance of precipitation based on the local weather forecast. The prohibitions do not apply if the product is injected into the ground, incorporated within 24 hours, or applied onto a growing crop.

The Government of Ontario, the Ontario Agri-Business Association, and Fertilizer Canada came together in 2015 to sign a 4R Nutrient Stewardship Memorandum of Cooperation (MOC). This formal commitment brought a combined investment of $300,000 over three years (Smith 2015). Its intent was to assist Ontario farmers with minimizing their impacts to the environment while maximizing crop yields. The Ontario Agri-Business Association also offers 4R certification within its Certified Crop Advisor Program.

3.1.6.b The 4R Metrics: A Description of Implementation Metrics and Assessment Methods

In the WLEB 4R program, there are three major sections and a total of 41 auditable criteria (Vollmer-Sanders et al., 2016) which nutrient service providers must be aware of. Those that do not make nutrient recommendations or applications may be in compliance when only fulfilling the requirements of sections 1 and 2, but all other providers must abide by all three sections. These sections are:

1. Initial training and ongoing education
2. Monitoring of 4R implementation
3. Nutrient recommendations and applications

Those service providers who join with the program participate in education and training along with record keeping. The implementation of the 4Rs is tracked at the HUC8 level; records include an annual summary of applied nutrients and the 4R practices observed. The WLEB program includes an auditing component which reviews these records to evaluate the progress of 4R adoption through time. As of February 2017, 38 nutrient service providers were certified by the 4R program and another 39 were committed to participate .

3.1.6.c Data and Trends of 4R Implementation

Although farmers are routinely surveyed by multiple agencies and research groups, it can be difficult to track the implementation of all the 4R principles in an area as large as the WLEB. The 4R program is still new, and research is in the very beginning phases (e.g., King et al., *in press*), however more can be expected to be known in the coming years. Studies and published results of 4R efficacy have not been identified covering the Ontario watershed region, although surveys of adoption of 4R practices have recently been completed for parts of Ontario.

In early 2012, a research group from the Ohio State University conducted a survey of farmers who lived within the Ohio section of the Maumee drainage basin (Wilson et al., 2013). Responses were received

including: only 15% of farmers never test their soil, 68% use a nutrient management plan at least part of the time, 71% generally avoid fall/winter application of manure or fertilizer, and 74% follow the NRCS guidelines for winter manure application at least part of the time. When asked to think about one of their own fields (with no filter strip), the survey found that farmers were most likely to apply their fertilizer in the spring (44%) and to broadcast it (46%).

LaBarge and Prochaska (2014) surveyed agricultural retailers in Ohio about current practices relating to the 4Rs. 74% of the surveyed acreage was soil tested according to recommended methods. 77% of phosphorus is applied in the fall and spring, 8% is applied in the winter and 41% in the spring. Some form of incorporation (broadcast with incorporation, banding, etc.) was used by 64% of farmers, with the rest using broadcasting with no incorporation.

Another survey was conducted by the same research group in the winter of 2016 (Prokup et al., 2017), with a focus on both the Maumee and Sandusky watersheds. This survey asked farmers specifically what their perceptions of the 4R principles were and what barriers they experienced in implementation. Winter cover (whether from wheat or a dedicated cover crop) was generally identified as a concern. During this survey, farmers again indicated that broadcasting was the most popular method of application (75%). In addition, most of these farmers were broadcasting and incorporating with tillage within 7 days (54% of respondents). Winter was the most popular time for application (31%) followed by fall (26%).

Table 3-2 summarizes the results of the three studies above. The studies span a time period from 2012 to 2016 (years of the surveys). While the metrics used are somewhat different from study to study, as is the spatial coverage, there is indication that adoption of some practices that support the 4Rs is increasing. The rate of soil testing is quite high, at about 75 to 86%. The use of broadcasting fertilizer without incorporation seems to be decreasing. On the other hand, winter application seems to have increased, with the opposite trend for spring application. There appears to be an increase in broadcasting of fertilizer on the soil surface followed by incorporation into the soil by some form of tillage, which was also observed by Bruulsema (2012), who states, arger planters and fewer stops to refill bins, there appears to be a trend to less band application and more broadcasting of P fertilizer.

Table 3-2. Summary of results from three surveys on 4R implementation in WLEB watersheds.

Metric	Wilson et al. (2013) Maumee in fields where run-off of greatest concern	LaBarge and Prochaska (2014) Ohio – Lake Erie (not Ohio River)	Prokup et al. (2017) Maumee and Sandusky
Soil test (Rate, Source)			
Every 2-4 years			86%
Never	15%		
As recommended or better		74%	
Uses nutrient management plan (sometimes + always)	68%		
Timing (fertilizer values for Wilson)			
Avoid fall/winter application (sometimes + always)	71%		
Fall and spring	67% (by sum)	77%	47% (by sum)
Spring	44%	41%	21%
Fall	23%	36% (by difference)	26%
Winter	3%	8%	31%
Follow NRCS guidelines for winter application at least part of the time	74%		
Placement			
Broadcast (w. or w./o. incorporation)		67%	75%
Broadcast and incorporation within 7 days		16%	54%
Broadcast and incorporation after more than 7 days		15%	
Some form of incorporation	24%	31%	
Broadcast with no incorporation	46%	36%	21%
Planter/Toolbar	26%	30%	
Furrow with seed or surf and subsurface banding			25%
Strip tillage		4%	

In addition to the above U.S. studies, the Western Lake Erie CEAP report (USDA NRCS, 2016) also summarizes survey results of conservation practice adoption in the U.S. WLEB (nearly identical in extent to the WLEB definition of this report on the U.S. side). With regard to 4R practices, it was found that

more c While most acres [63%] have some aspect of ideal nitrogen and phosphorus management, the majority [66%] of the acres in WLEB lack consistent use of the 4Rs on each

As part of the Canadian Field Print Initiative by Pulse Canada, Stratus performed two 4R surveys, one in 2014, and another in 2015 (Stratus, 2016). Currently, the 2015 survey is the most recent available. The surveys are password protected, and a password can be acquired by contacting Denis Tremorin at dtremorin@pulsecanada.com or (204) 925-3781. Both survey reports are included in Electronic Supplement folder ES-1 (subfolder Fert8).

The survey targeted corn and winter wheat growers with 200 acres or more in Eastern Canada (and barley, canola and soy growers with 100 acres or more in Western Canada) and asked growers directly about the timing, source, placement, rates and participation in the 4R program. The 2015 survey reached 297 corn growers and 203 winter wheat growers in Eastern Canada, representing about 3% and 5% of total planted acres. Results on each of the 4Rs are presented by crop and region. The survey results were partially evaluated for this report. Based on the key findings, corn (winter wheat) growers apply 59% (90%) of phosphorus by volume as monoammonium phosphate (MAP), 69% (76%) of the volume is applied at spring (fall) planting, 80% (77%) of which was side banded (seed placed) (this is a significant difference with the U.S., where broadcast application is more common), with an average rate between 40 and 45 (30 and 37) lb.

Gradually increasing use of monoammonium phosphate (MAP) and comparably declining use of diammonium phosphate (DAP) fertilizer was illustrated in the Ohio Lake Erie Phosphorus Task Force II

Final Report (2013, p. 15). The solubility and P content of both compounds are comparable, with DAP being slightly more soluble (90% versus 82% for MAP; Mullen et al., 2005). There is no clear indication of what impacts the shift in fertilizer form might be having on P loss from farm fields and corresponding impacts on water quality.

3.1.6.d Data and Trends of 4R Impact

While the effect of individual BMPs has been studied by many over time, research on the *efficacy of 4R practices as a program* (as opposed to individual BMP practices) in terms of export of phosphorus from fields has so far yielded few publications. Two CEAP studies on Western Lake Erie and Chesapeake Bay assessed the effect of conservation practices that included 4Rs (USDA NRCS, 2016; USDA NRCS, 2013). The approach used surveys that yielded information on actual practices over time informing a model framework (APEX and SWAT), rather than direct edge-of-field measurements (USDA NRCS 2013). Results of the Lake Erie report indicate that conservation practices (4R as well as other BMPs) together achieve significant reductions in phosphorus losses. The report suggests that 4R practices contribute in
at incorporates the 4Rs ... of nutrient application management theory must be utilized each year and on each crop in the rotation in order for the conservation benefits of the
ces are a necessary

pairing water erosion control practices with effective nutrient management practices so that the full suite of conservation practices work in concert to provide necessary environmental protection to preserve ecosystem services, (USDA NRCS, 2016).

Ford et al. (2014) presented results of an Ohio based study at the AGU Annual Meeting in Fall 2014. The study applied the Agricultural Policy Environmental Extender (APEX) in a tile-drained landscape in Central Ohio. Conservation practices that included the 4Rs were evaluated. (Results are not discussed in the available abstract.)

Kalcic et al. (2016) used information from a survey of several stakeholders (farmers, advisors, etc.) and other data sources to represent conservation practices in a SWAT model of the Maumee watershed and assess the relative impact of various conservation and 4R practices (timing and placement) on TP and DRP loads in the Maumee. Findings are similar to those of the CEAP report, in that 4R practices are found
erennial cover crops and vegetated filter strips were most effective for reducing seasonal total phosphorus (TP) loading. [...] Adoption of practices at levels considered feasible to stakeholders led to nearly reaching TP targets for western Lake Erie on average years; however, adoption of practices at a rate that goes beyond what is currently considered feasible will likely be required to reach the DRP target.
found that subsurface placement of fertilizer has a greater impact than timing considerations. Timing affected the seasonal distribution of DRP, but not the annual total phosphorus or DRP loss.

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%. 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 run-off and in subsurface drainage.

While the above studies suggest an important role for 4R practices, some studies have ambiguous results. Christianson and Harmel (2015a) in a meta-analysis for North America found that for nitrogen in drained

inconsistent with the current emphasis placed on application timing, in particular, as a water quality conclusions with regard to the impact of 4R principles (Christianson et al., 2016). Their results are also described in the project completion report to the 4R Research Fund (Christianson and Harmel, 2015b).

Three studies conducted in the Canadian WLEB are summarized by Kerr et al., 2016. Conclusions indicate that 4R practices have to be used in combination with other measures to achieve reduced P losses. In addition, these studies indicate that winter and early spring/snowmelt are important pathways of P-losses (Lam et al., 2016); that most of the loss of P occurs through tile drains with 19 67% of total annual DRP load exported by tile drains (Van Esbroeck et al., 2016); and that nutrient management (i.e. 4Rs) and wetland restoration have more significant impacts on nutrient reduction at the watershed outlet than do cover crops and buffer strips (Liu et al., 2016). Other studies have also shown limited water quality improvement or ecological benefit from some BMPs (Pearce and Yates, 2015; Holmes et al., 2016;)

3.1.6.e Future of the 4Rs

The 4R program is still new, and much research is still just in the very beginning phases and ongoing, so more can be expected to be known in the coming years. Among others, several grants have been awarded to fund assessments of the 4Rs principles by the 4Rs Research Fund (U.S.) (http://www.nutrientstewardship.com/4r-research-fund). According to the website, these include:

- Analysis of 4R Nutrient Stewardship implementation on drained land (King et al., *in press*)
- Meta-analysis of phosphorus fertilizer placement and tillage interactions for corn and soybeans in the U.S.
- Meta-analysis of enhanced efficiency fertilizers in corn systems in the Midwest
- Project to "Evaluate the 4R Concept and Certification Program in Western Lake Erie Basin"
- Project to study "Minimizing Phosphorus Loss with 4Rs and Cover Crops"

Mirroring the U.S. 4Rs Research Fund, the Canadian 4R Research Network is studying the 4Rs in Canada. f the University of Guelph is Principal Investigator Management of placement timing of phosphorus fertilizers to reduce P runoff losses in the Lake Erie Again, publications can be expected to be forthcoming in the future. More information is available in: http://stream1.newswire.ca/media/2016/12/01/20161201_C8274_PDF_EN_829713.pdf

3.2 Manure

Introduction

Livestock production is an important component of the agricultural economy in the U.S. and Canadian drainage areas to the WLEB. Cattle, swine, and poultry farming operations are the most dominant types in the region. In addition to producing valuable and important human food sources, livestock farms generate an increasingly controversial byproduct, manure, also known as organic fertilizer. When managed properly, manure can serve as a valuable resource to cash crop agriculture operations that typically surround livestock farms by providing both nutrients, to offset crop removal rates, and organic matter, to improve soil health. When improperly handled, however, manure can cause environmental problems and becomes a liability rather than a valuable resource. Supporting data files regarding manure can be found in Electronic Supplement folder ES-2.

3.2.1 Manure Generation and Application

3.2.1.a Livestock Populations

Total livestock populations have remained relatively stable over the past 30 years in areas draining to the WLEB (Figure 3-20). Two estimates of total livestock populations for the three most dominant types are provided for the U.S. WLEB drainage area, both of which are derived from USDA Census of Agriculture data. The first (U.S. WLEB-1 in Figure 21) was derived by multiplying county-level livestock population totals (end of census year population) by the fraction of the county in the WLEB watershed. No weighting was performed to account for farm, cropland, or pasture locations. The second (U.S. WLEB-2 in Figure 3-20

series for the two 6-digit Hydrologic Unit Code (HUC) boundaries corresponding to the St. Clair and WLEB watersheds; HUC-040900 and HUC-041000, respectively. The two U.S. WLEB estimation methods resulted in very similar total swine and cattle populations for the overlapping years (Figure 3-20). Total chicken population estimates were similar for 2002 and 2007 census years, but deviated in 2012 (Figure 3-20). Agriculture and Agri-Food Canada (AAFC) in collaboration with Statistics Canada's Agriculture Division developed watershed scale GIS datasets of livestock populations through the 2011 census year (Agriculture and Agri-Food Canada, 2013). Sub-subwatershed estimates of total swine, cattle,

Figure 3-20. While swine and poultry showed gradual increases over the 30-year period, total cattle population showed a gradual decrease, resulting in an overall relatively stable number of animal units for the Canadian WLEB drainage area.

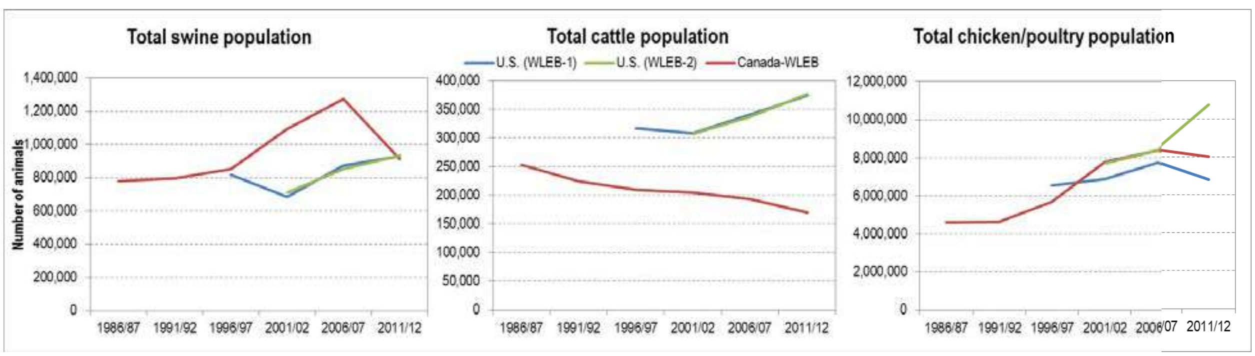

Figure 3-20. Total livestock population estimates for U.S. and Canadian portions of the WLEB drainage area from 1986/1987 to 2011/2012 (sources: USDA and AAFC).

3.2.1.b Manure Production

Like the total livestock populations, manure generation has remained relatively stable over the past 30 years in areas draining to the WLEB (Figure 3-21). For the U.S. WLEB drainage area, The Institute of Plant Nutrition (IPNI) Nutrient Use GIS (NuGIS) project provides county-level and HUC-8 watershed estimates of manure P_2O_5 excreted and recovered for the entire U.S. for Census of Agriculture years (i.e., 1987, 1992, 1997, 2002, 2007, and 2012) (IPNI, 2012). This dataset, derived from USDA Census of Agriculture livestock population estimates and standard manure production estimates for different livestock types, was the most complete (temporally and spatially) manure P production dataset obtained for the U.S. We used this dataset to derive the time series shown in Figure 3-21 by summing the tons of P_2O_5 excreted for all HEC and WLEB HUC-8 watersheds and converting to tons of P. In addition to estimating watershed scale livestock populations, the AAFC GIS dataset described above also provided estimates of total livestock manure P generation by sub-subwatershed (AAFC, 2013). Sub-subwatershed estimates of total livestock manure P for the four Ontario basins in the study area were summed and Figure 3-21. A panel of six maps depicting estimated total manure P production by HUC-8 and tertiary watersheds for the 1986/1987 through 2011/2012 census of agriculture years is shown in Figure 3-22. These maps were normalized by dividing by the total cropland area for the HUC-8 or tertiary watersheds for the corresponding year to produce the panel of six maps shown in Figure 3-23. Note that manure was not actually applied to all of that cropland; the approached was used to give a sense of the relative intensity of livestock operations and potential manure application in each watershed.

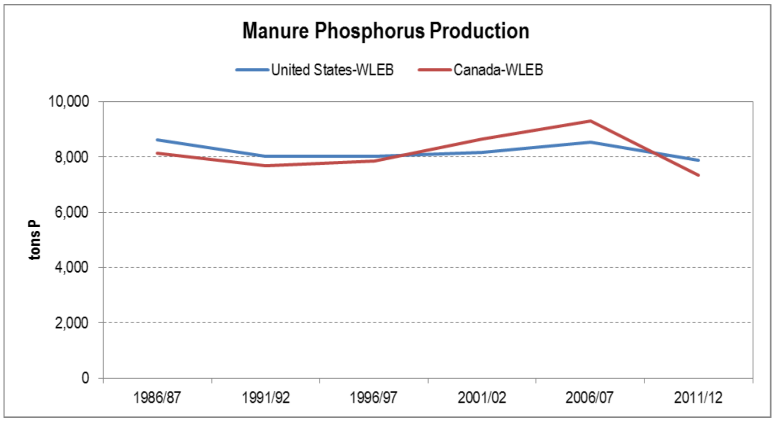

Figure 3-21: Manure phosphorus production estimates for U.S. and Canadian portions of the WLEB drainage area from 1986/1987 to 2011/2012 (sources: IPNI and AAFC).

A review of other studies quantifying manure production have also shown relatively steady to gradually increasing trends in generation of livestock manure in WLEB drainage areas in recent decades. Han et al. (2012) estimated no major changes in animal manure P generated between 1992 and 2007, and a steady decline from 1935 to 2007 for watersheds draining to Lake Erie. Powers et al. (2016) used the IPNI dataset described above and the work of Baker and Richards (2002) to derive annual manure P production estimates for the Maumee River basin for 1976-2010. Their final estimate of manure P production in the Maumee basin showed a gradual increasing trend from the early 1990s to 2010 (Powers et al., 2016). Although the Upper Thames (Ontario) drainage area is one of the highest ranked Canadian areas in terms of both livestock population density and manure production (Beaulieu et al., 2001; Hofmann, 2008; Hofmann, 2009), a study that estimated a 16% increase (1981 to 2006) in Canadian manure production found the majority of the sub-sub-drainage areas (SSDAs) with manure production increases per hectare were in Alberta (Hofmann, 2008). Monitoring data for the Upper Thames may show trends consistent with declining fertilizer and steady manure. Since 1986, the flow-weighted mean DRP has decreased with no trend in TP for the Upper Thames (North and South forks), while the opposite pattern exists in the Lower Thames, where TP is decreasing and DRP shows no trend (Maaskant, 2015).

In addition to the county-level datasets on livestock and manure production, several larger scale estimates of manure production were consulted for relative comparison of manure vs. inorganic fertilizer inputs of P for agronomic application. These estimates are summarized in Table 3-3 below.

Table 3-3. Estimations of manure contribution to total agricultural-related phosphorus inputs (i.e., manure plus inorganic fertilizer) from various sources for various time periods and geographic areas in the study area

Phosphorus Input: Manure vs. Inorganic Fertilizer			
Reference	Value	Description	Geographic Area
OEPA, 2010	27%	P handled annually for agronomic application	Lake Erie Basin (U.S.)
Davis, 2013	17%	P produced as % of crop need	WLEB (U.S.)
USDA NRCS, 2011	16%	P applied to agricultural land	Lake Erie Basin (U.S.)
USDA NRCS, 2016	12%	2012 conservation condition, P sources	WLEB (U.S.)

USDA NRCS, 2016	9%	2003-06 conservation condition, P sources	WLEB (U.S.)
IPNI, 2012	14%	1987-2012 census years	WLEB (U.S.)
Han, Bosch, and Allan, 2010	10%	1974-1992 census years	Lake Erie Basin (U.S.)
Han, Bosch, and Allan, 2010	9%	1974-1992 census years	WLEB (U.S.)
IPNI, 2013	36%	1987-2007 average	Ontario

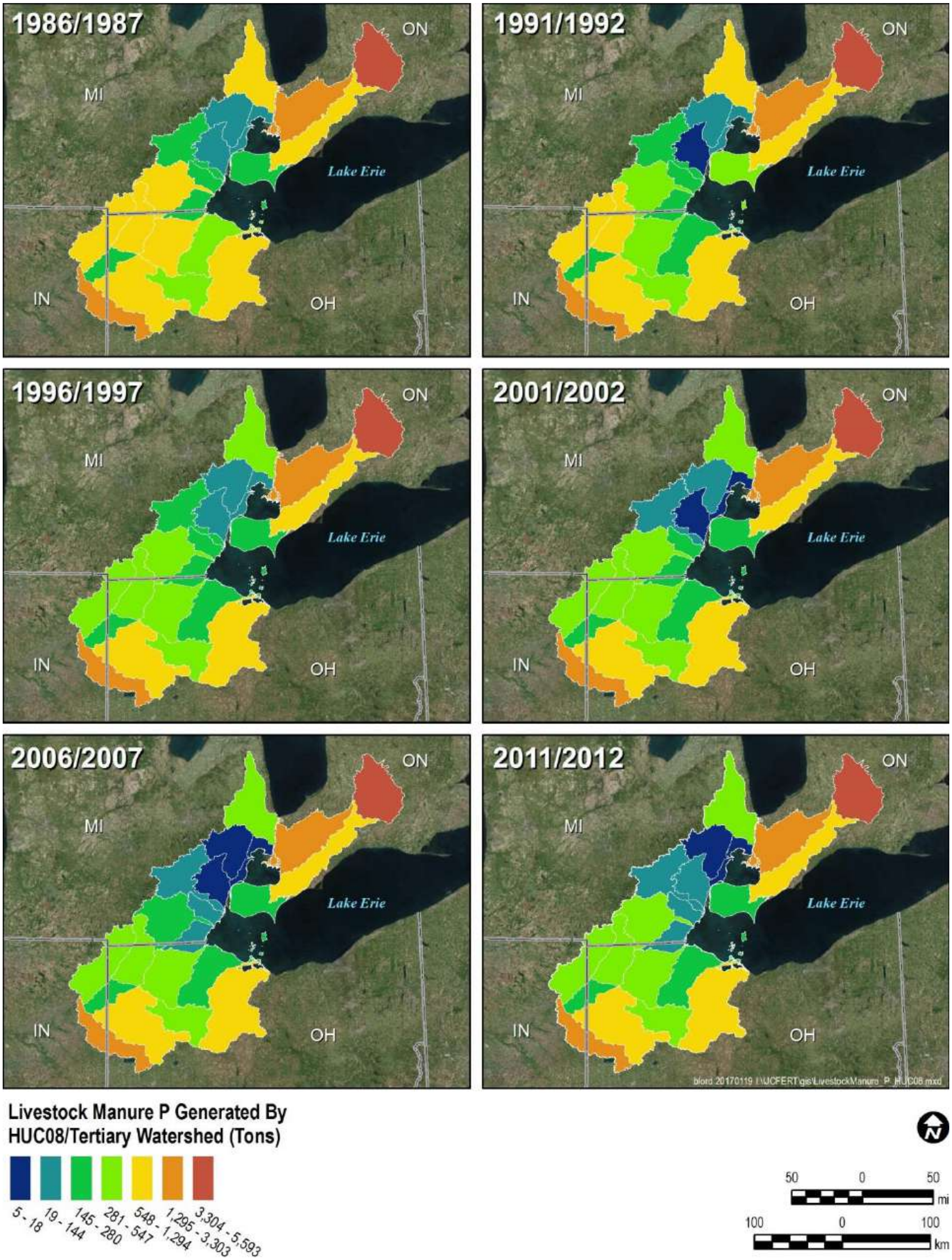

Figure 3-22. Estimations of livestock manure P generation for 1986-87 to 2011-12. Sources: IPNI (2012) and Agriculture and Agri-Food Canada (2013). Supporting geodatabase files can be found in Electronic Supplement Folder ES-4.

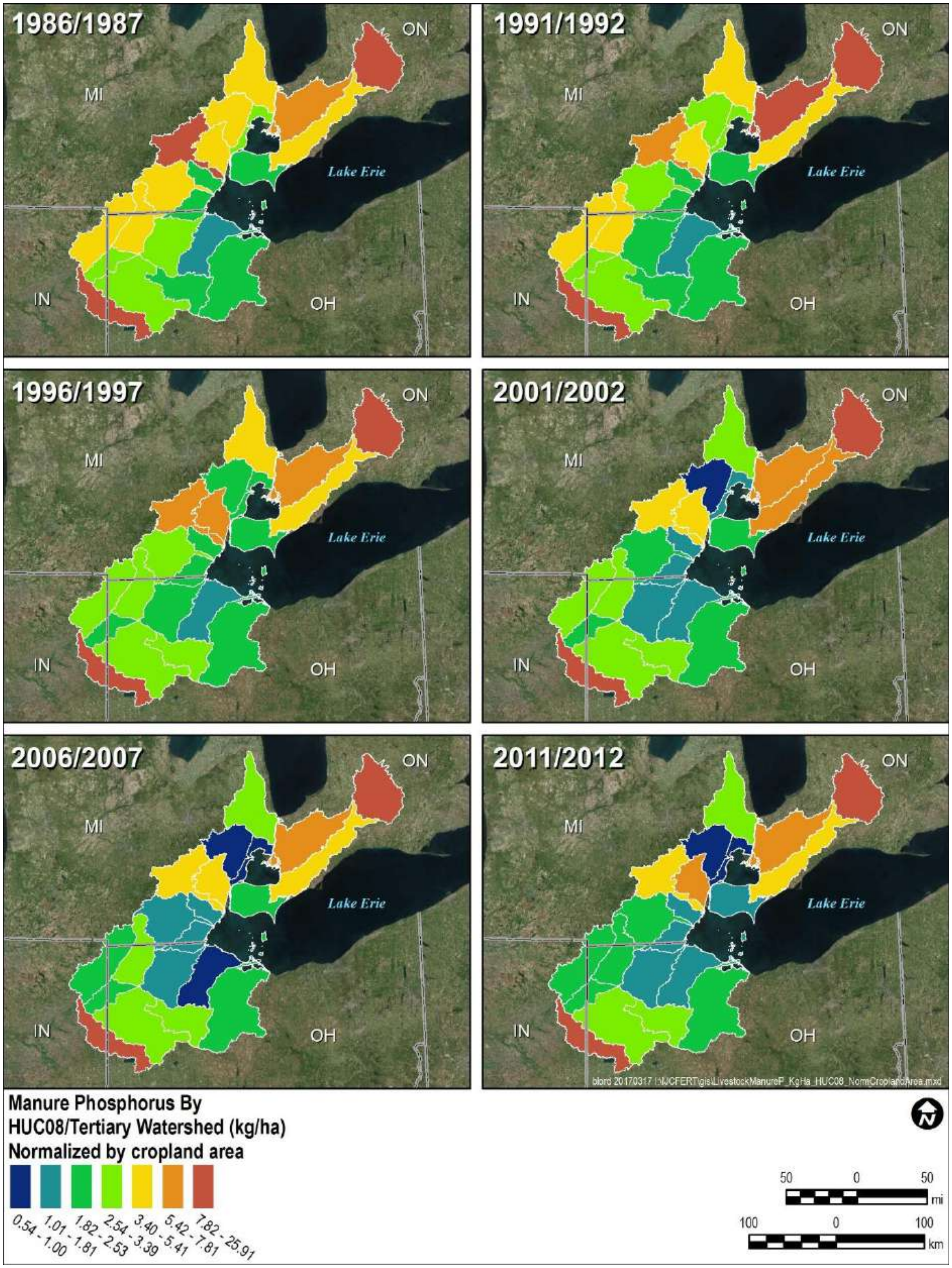

Figure 3-23. Estimations of livestock manure P generated, normalized by tertiary watershed cropland area, for 1986-87 to 2011-12. Supporting geodatabase files can be found in Electronic Supplement Folder ES-4.

3.2.1.c Farm Size, CAFOs, and Livestock Population Density

In both the U.S. and Canadian drainage areas to the WLEB, the proportion of livestock housed in relatively large farms has increased over the past 20-25 years for the most dominant livestock groups in the region; cattle, swine, and poultry (Figures 3-24 to 3-29). Swine farms in Ohio (entire state) saw the largest absolute change over the 25-year period, as the number of hogs/pigs in farms with over 1,000 head grew from 29% in 1987 to 93% in 2012. Trends observed at the county-level (for counties with >35% area draining to the WLEB) are consistent with state-level trends. The total number of cattle and swine farms has dropped while the number of farms in the largest category has increased. This trend in the number of farms is not consistent for poultry farms however. The number of poultry farms in the largest size categories has remained relatively unchanged to slightly decreasing, but the number of smaller farms has increased substantially.

In addition to computing the proportion of livestock population housed in the largest farms, an average livestock population density was derived by dividing the total population by the total number of farms for each type (Figure 3-29). This was done to better compare U.S. data with Canadian data, which does not split livestock populations or number of farms into ranges based on number of animals per farm (e.g., 1-49, 50-99, >500 animals, etc.). Results of this analysis are consistent with the previously described trends. In recent decades in both the U.S. and Canadian drainage areas to the WLEB the number of animals per farm has (1) sharply increased for swine, (2) gradually increased for cattle, and (3) gradually increased for poultry followed by a sharp decrease with the increase in small farms reporting chicken production (Figure 3-27 and 3-28). The average number of animals per farm for the most recently reported census year is depicted in Table 3-4.

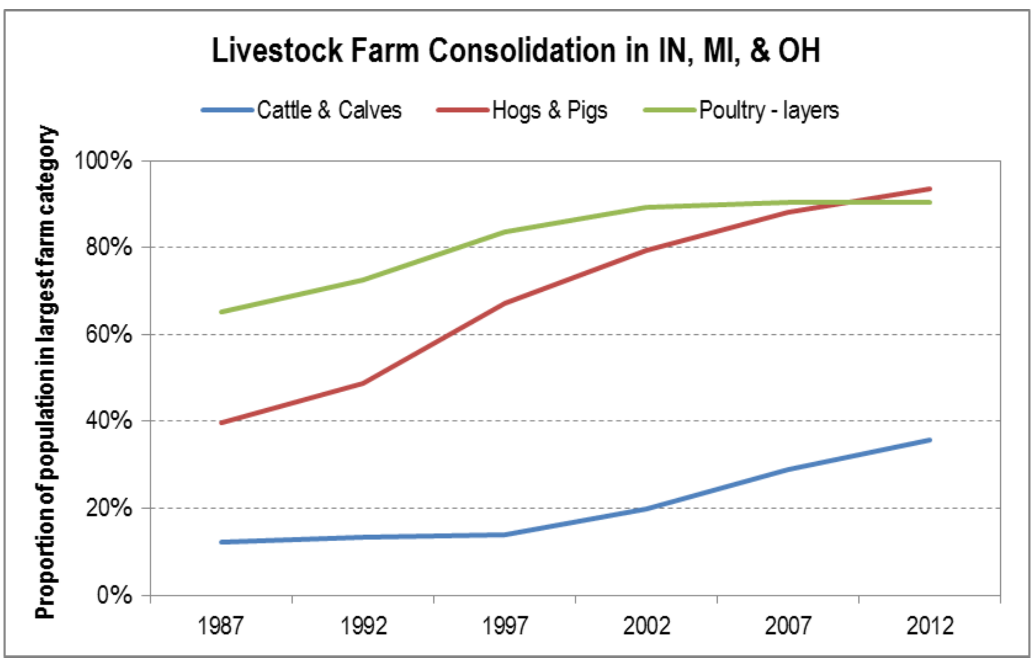

Figure 3-24. Proportion of total state (Indiana, Michigan, and Ohio combined) livestock populations represented in the largest category of farms reported in USDA Census tables (≥500 head for cattle, ≥1,000 head for hogs/pigs, and ≥100,000 head for egg-laying chickens).

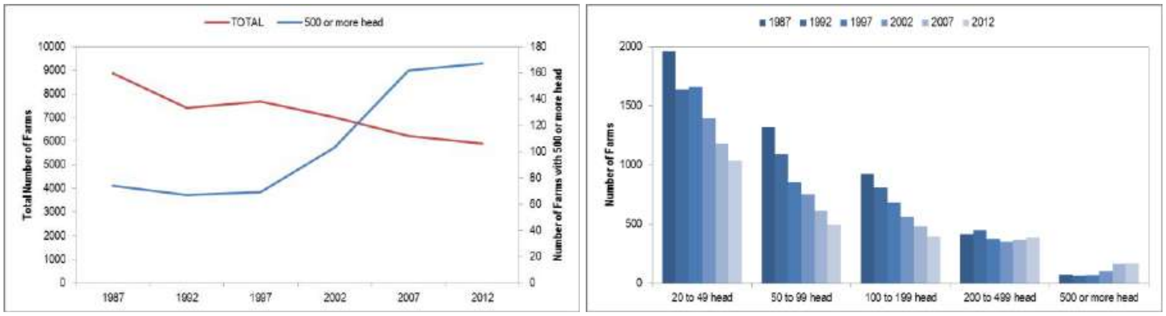

Figure 3-25. Cattle farms, all types, for counties with >35% areal overlap with the study area

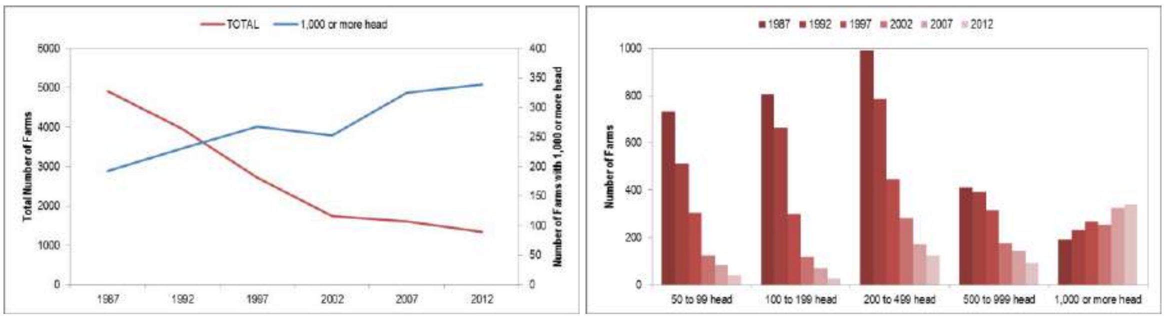

Figure 3-26. Hog and pig farms for counties with >35% areal overlap with the study area

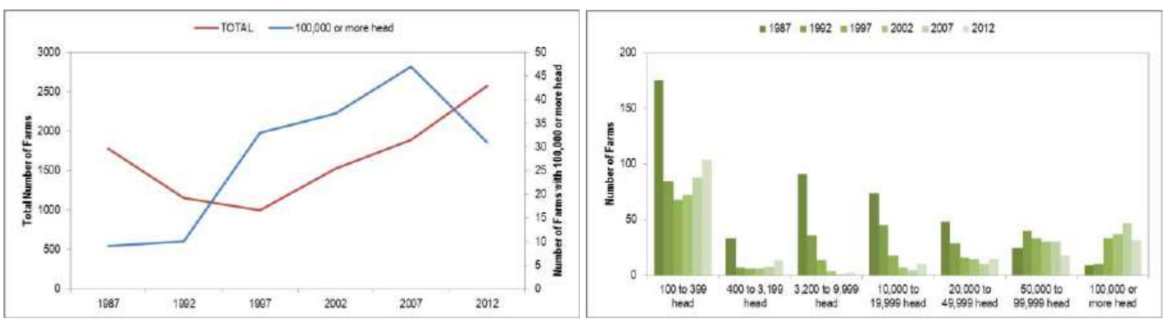

Figure 3-27. Layer farms (chickens) for counties with >35% areal overlap with the study area

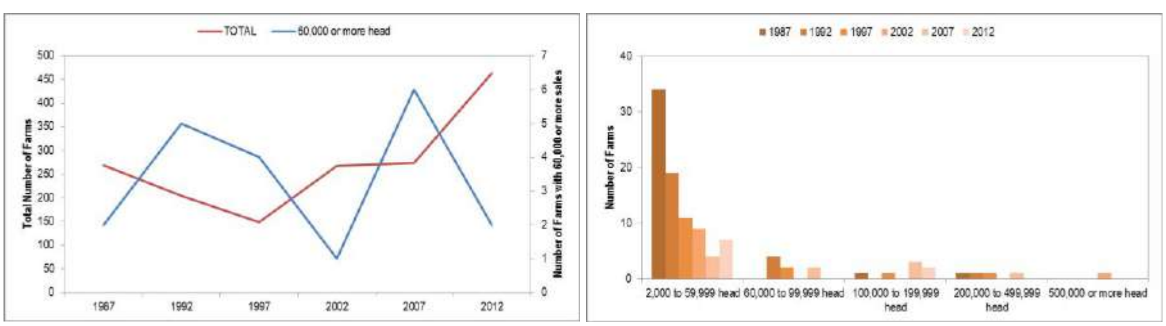

Figure 3-28. Broiler farms (chickens) for counties with >35% areal overlap with the study area (head are sales per year)

Table 3-4. Livestock population density estimates from the 2012 USDA Census of Agriculture and 2011 Canadian Census (AAFC, 2013) (number of animals per farm)

Category	IN+MI+OH	U.S.-WLEB	Canada-WLEB
All cattle and cows	57	71	98
Hogs and pigs	817	809	1946
All chickens	3183	4420	8377

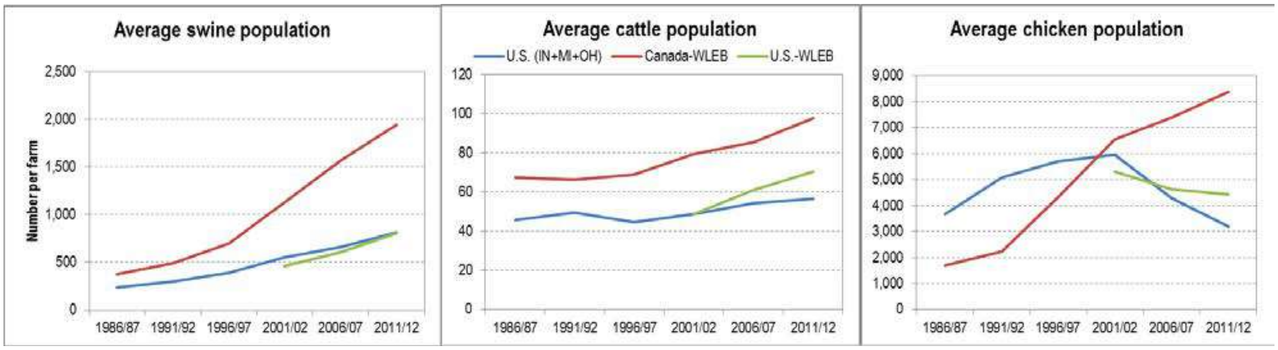

Figure 3-29. Livestock population density estimates for U.S. and Canadian portions of the WLEB drainage area from 1986/1987 to 2011/2012 (sources: USDA and AAFC).

Along with the increase in the number of large livestock operations has come the onset and growth of permitting of these operations by regulatory agencies in both the U.S. and Canada. In the U.S. drainage areas to the WLEB, animal feeding operations (AFOs), confined feeding operations (CFO), and/or concentrated animal feeding operations (CAFOs) are permitted by the Indiana Department of Environmental Management, Michigan Department of Environmental Quality, and Ohio Environmental Protection Agency or Ohio Department of Agriculture. In Ontario, OMAFRA and MOECC have jurisdiction over intensive livestock operations (ILOs) and oversight of nutrient management regulation via the Nutrient Management Act of 2002.

Although some data for permitted livestock operations were publicly available for the U.S., these datasets are limited to a point in time and therefore no temporal trends in the number of permitted operations from the onset of permitting could be created. Additionally, each state has unique rules and differing status of implementation of the federal NPDES CAFO permitting program implementation that complicates abilities to quantify and geospatially display CAFOs in the study area. As of the date on this report, both Indiana and Ohio plans for completing NPDES program revisions to address CAFO regulations remain under review (USEPA 2017). As depicted in Table 3-5, the estimated number of CAFOs in each state has increased from 2011 to 2016, but NPDES permitting of CAFOs varies considerably by state. A map depicting locations of permitted CAFOs in the U.S. is shown in Figure 3-30. Neither geospatial data (i.e., latitude and longitude) nor individual facility names and characteristics for permitted ILOs have been obtained for Canada, nor is there any indication that such data are publicly available.

Table 3-5. 2011-2016 NPDES CAFO regulations implementation status reports for the three states in the WLEB

State	Item	2011	2012	2013	2014	2015	2016
Indiana	Total # CAFOs	634	633	677	690	690	758
	# with NPDES permit	529	19	8	5	5	0
	% with NPDES permit	83%	3%	1%	1%	1%	0%
Michigan	Total # CAFOs	220	223	249	276	286	305
	# with NPDES permit	197	201	225	237	260	271
	% with NPDES permit	90%	90%	90%	86%	91%	89%
Ohio	Total # CAFOs	192	192	212	213	213	221
	# with NPDES permit	35	36	37	39	36	36
	% with NPDES permit	18%	19%	17%	18%	17%	16%

Source: US EPA (2017)

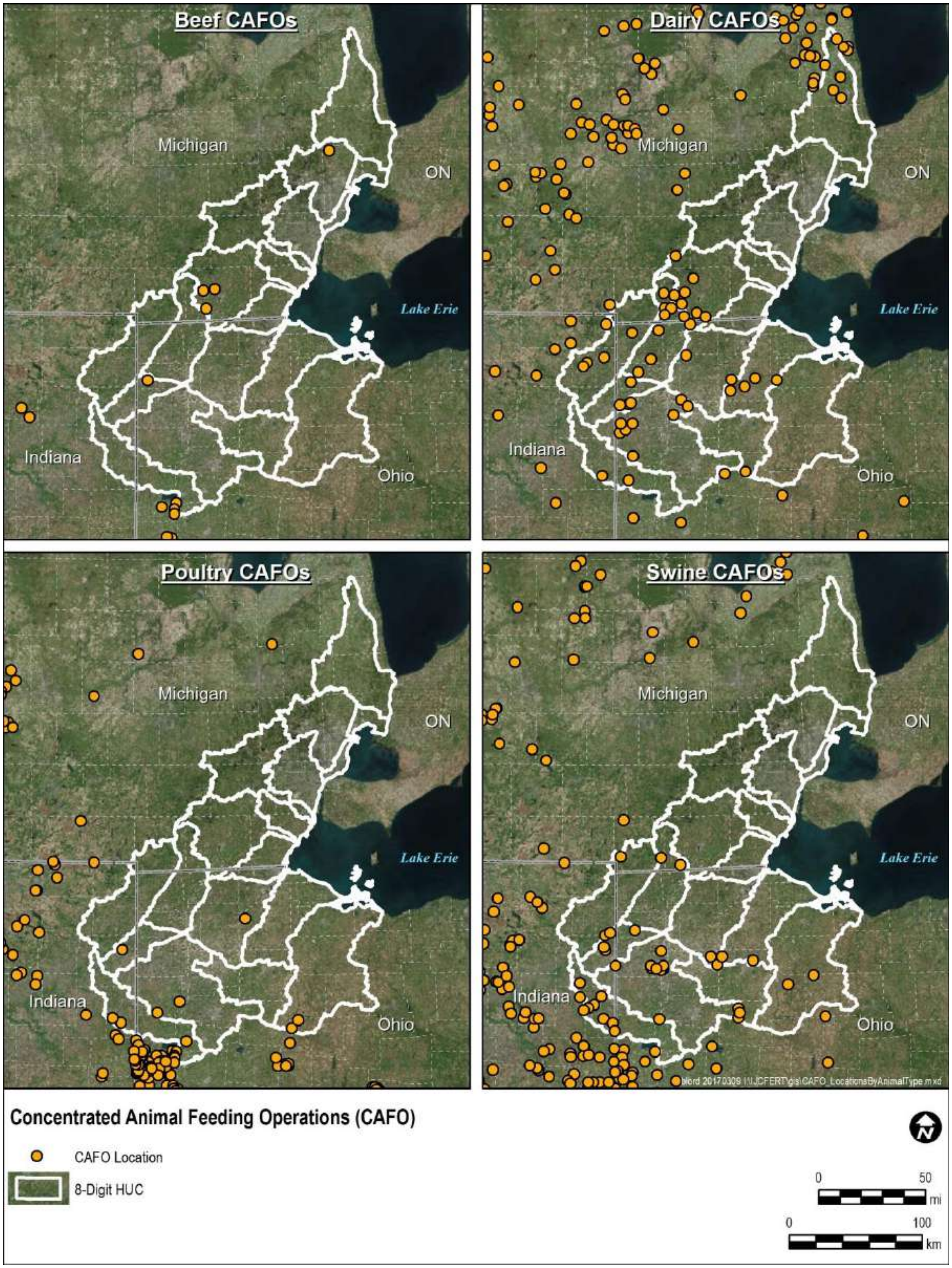

Figure 3-30: Locations of permitted CAFOs in the U.S. The number of permitted livestock operations was reduced from all state-available data to a limited number based on the USEPA thresholds for "large CAFOs" using information reported on the number of animals per facility or using state-reported information distinguishing CAFOs from CFOs or AFOs.

Although an attempt was made to estimate the proportion of total livestock manure production from CAFOs, several complexities prevented a precise quantification. First, distinguishing between permitted CAFOs, permitted non-CAFOs, and non-permitted CAFO-sized operations presents a challenge due to inconsistencies between states (i.e., if an operation meets the regulatory threshold for a large CAFO but it is not yet permitted, should it be considered a CAFO?). As indicated in Table 3-6, the majority of CAFOs in Ohio and all of the CAFOs in Indiana, as estimated by USEPA, do not have an NPDES permit and therefore attempting to quantify manure production for these facilities is difficult. Also, the number of animals reported for permitted operations is a static number based on the design capacity of the operation but the number of animals actually housed in the facility at a given time is likely less than full capacity.

Therefore, an analysis of livestock populations from a custom extraction of the USDA 2012 Census of Agriculture dataset was completed to inform the proportion of the animal populations in farms meeting the USEPA regulatory definition size thresholds of medium and large CAFOs. This gives a relative estimate of manure production from these relatively large operations and is similar to an approach used by Kellogg et al. (2000) that identified *potential* CAFOs from the Census of Agriculture information. As indicated in Table 3-6, over half the cattle, milk cow, and broiler chicken populations and the vast majority of hog and layer chicken populations are contained in operations meeting the USEPA regulatory definition size thresholds of medium and large CAFOs for the states of Indiana, Michigan, and Ohio. Note that although these are state totals and do not necessarily represent WLEB drainage areas, trends observed from other analyses where WLEB county-level values were not disclosed were consistent with state-level trends and values (e.g., Table 3-6), and therefore the following statements hold true for animal operations in the US WLEB drainage areas:

- The large majority of hog population and therefore hog manure production is from operations with over 750 animals.
- The large majority of layer chicken population and therefore layer chicken manure production is from operations with over 100,000 animals.
- The majority of broiler chicken population and therefore broiler manure production is from operations with over 37,500 animals.
- Roughly half the cattle population and therefore cattle manure production is from operations with over 300 animals.
- Roughly half the milk cow population and therefore milk cow manure production is from operations with over 200 animals.

Table 3-6. Proportion of 2012 Census of Agriculture livestock population in operations meeting the size thresholds of large and medium CAFOs according to USEPA regulatory definition. Note, these values do not necessarily represent the portion of livestock population in operations permitted by state regulatory agencies, as factors other than size thresholds apply.

Category	Weighted Total			Large				Medium			
	Combined	Large	Medium	Threshold	IN	MI	OH	Threshold	IN	MI	OH
Cattle on feed	55%	23%	32%	1,000	16%	36%	14%	300	27%	27%	37%
Milk cows	61%	40%	22%	700	49%	47%	25%	200	12%	27%	20%
Hogs	95%	78%	17%	2,500	84%	81%	66%	750	11%	13%	29%
Layer chickens	96%	90%	6%	0,000	93%	97%	85%	,000	3%	1%	10%
Broiler chickens	73%	48%	25%	125,000	50%	34%	49%	37,500	18%	55%	27%

Although the animal population data by size threshold presented in Table 3-6 were often disclosed from reporting on a county level, the number of farms meeting the size thresholds was not disclosed on a county level, and therefore allowed for a comparison of the number of farms meeting the regulatory thresholds for large CAFOs and the number of permitted CAFOs for counties in the WLEB. This exercise was completed in recognition of the importance to distinguish between large operations that meet the size thresholds for large CAFOs and those that are permitted by a regulatory agency and to gain further insight into the portion of total livestock manure production from permitted CAFOs. The results of this analysis suggest the number of permitted cattle, milk cow, and layer chicken CAFOs is generally consistent with the number of farms meeting the large CAFO size thresholds for counties in the WLEB. The number of permitted hog CAFOs, however, was generally much lower (i.e., overall approximately one-third or less) he

WLEB. For example, Van Wert County, Ohio had 14 operations with 2,500 or more hogs, but only 1 permitted hog facility. The cause for the discrepancy in hog CAFOs is unknown. One possibility may be

in the Census of Agriculture custom extraction information.

In conjunction with the results from the analysis presented in Table 3-6 the following semi-quantitative conclusions were derived from this comparison of permitted CAFOs and the number of farms meeting regulatory size thresholds. For counties in the WLEB:

- The large majority of the layer chicken population and therefore layer chicken manure production is from permitted CAFOs
- Less than half of the dairy cow population and therefore dairy cow manure production is from permitted CAFOs
- Less than one-quarter of the cattle population and therefore cattle manure production is from permitted CAFOs
- Less than half of the hog population and therefore hog manure production is from permitted CAFOs
    - The majority of hog manure production appears to be from a combination of permitted non-CAFO facilities (i.e., AFOs in MI, CFOs in IN) and relatively large (i.e., number of animals per farm comparable to large or medium CAFO thresholds) non-permitted facilities.

3.2.1.d Manure Application: Area

Several resources provided estimates of the area or percent of agricultural land receiving manure application at a county and/or tertiary watershed resolution. Agriculture and Agri-Food Canada in collaboration with Statistics Canada's Agriculture Division developed watershed scale GIS datasets of manure application (Agriculture and Agri-Food Canada, 2013). Table 3-7 shows the portion of cropland acres treated with manure relative to total cropland acres, averaged for the 2006 and 2011 census of agriculture years, for Canadian drainage areas to Lake Erie. U.S. county-level manure application area estimates were available from the USDA NASS Quick Stats database for census of agriculture years between 2002 and 2012. Table 3-8 shows the portion of cropland acres treated with manure relative to total cropland acres, averaged for the 2002 to 2012 census of agriculture years. The county-level values for 2012 were compared against county-level estimates of the proportion of surveyed farmers who applied manure (Wilson et al., 2013) in Figure 3-31. This comparison shows good agreement between the two datasets in terms of which counties practiced relatively low and high manure application (e.g. Mercer County, Ohio had both the highest ratio of manure application acres to total cropland acres and the highest portion of surveyed farmers that indicated practicing manure application), but the relative portion of individuals that indicated practicing manure application was roughly double the relative portion of manure application acres to total cropland acres (Figure 3-31).

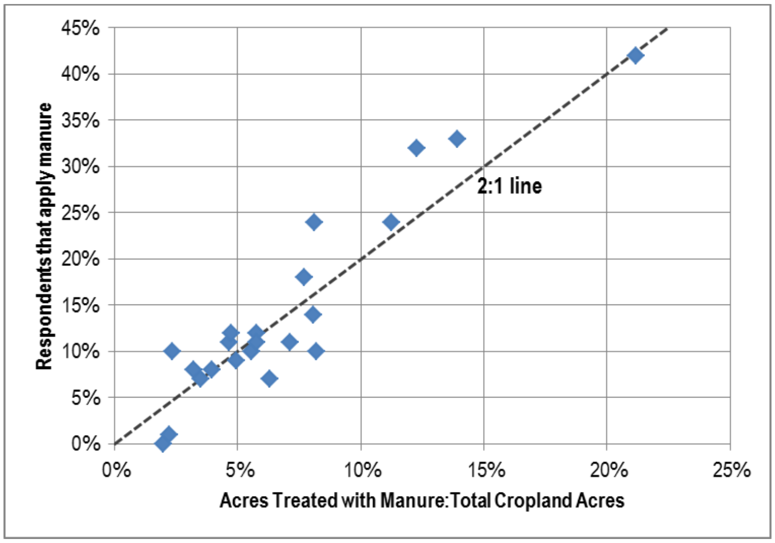

Figure 3-31. Relationship between percent of cropland acres treated with manure (estimated from 2012 Census of Agriculture) and percent of survey respondents that applied manure (Wilson et al., 2013). Each point represents a county in the U.S. portion of the study area.

A panel of six maps depicting estimated manure application areas by HUC-8 and tertiary watersheds for the 1986/1987 through 2011/2012 census of agriculture years is shown in Figure 3-32. Generating relatively higher spatial resolution maps of manure application areas is difficult due to several challenges. Although the practice of reporting of manure application areas is improving for permitted operations, there is no single geospatial dataset containing this information, and substantial effort is required to obtaining and process the information facility-by-facility. Researchers at the University of Michigan Water Center (UMWC) went through this process in a case study that compiled swine and dairy CAFO manure application maps for southeast Michigan areas of the WLEB (Long et al., 2017). The study produced valuable information including a breakdown of distance to manure application area (e.g., roughly 70% of CAFO-applied manure was within a 5-mile radius of the facilities), but it also highlighted additional challenges. The study was unable to fully account for all manure generated by the CAFOs because of a lack of information on manure transferred from CAFOs to other farming operations. If a Michigan CAFO sells manure, there is currently no mandatory tracking or reporting of how far away the manure goes and where it is applied, so movement of manure in and out of the watershed boundaries is not well understood (Long et al., 2017).

Another issue in attempting to create high-resolution manure application maps is the lack of geospatial information on non-permitted livestock operations, which, as demonstrated above, make up a large portion of the swine and cattle facilities in the study area. An effort by UMWC and OSU will attempt to identify these operations using remote sensing techniques, but that work was in early phases as of the date of this report (Rebecca Logsdon Muenich, UMWC personal communication). Efforts are also underway by researchers at the UMWC and the Ohio State University to compile and process manure application information for Ohio and Indiana CAFOs in the WLEB (Rebecca Logsdon Muenich, UMWC, personal communication).

The map in Figure 3-33 has a 5-mile buffer around the WLEB watershed and was created to emphasize CAFOs that have a relatively high likelihood of transporting manure into or out of the watershed boundaries for land application according to findings of the UMWC study. Additionally, poultry CAFOs have a greater potential to transport manure beyond 5 miles than the dairy and swine CAFOs of the UMWC because poultry litter is relatively less expensive to transport due to its lower moisture content.

Therefore, the high density of poultry CAFOs in the Mercer County/Grand Lake St. Marys area could be transferring manure into the western Lake Erie watershed.

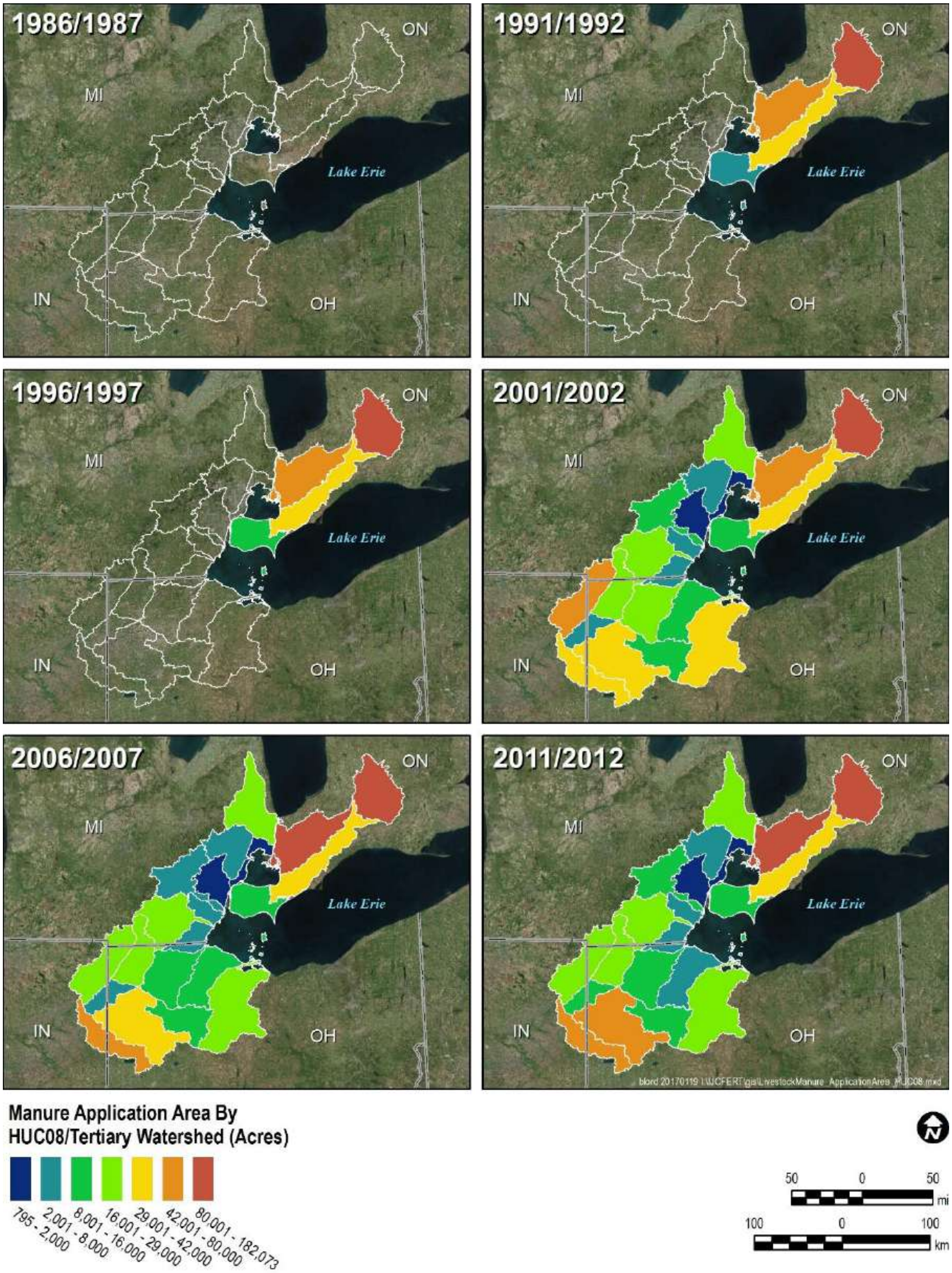

Figure 3-32. Estimations of livestock manure application area by watershed for 1986-87 to 2011-12. Supporting geodatabase files can be found in Electronic Supplement Folder ES-4.

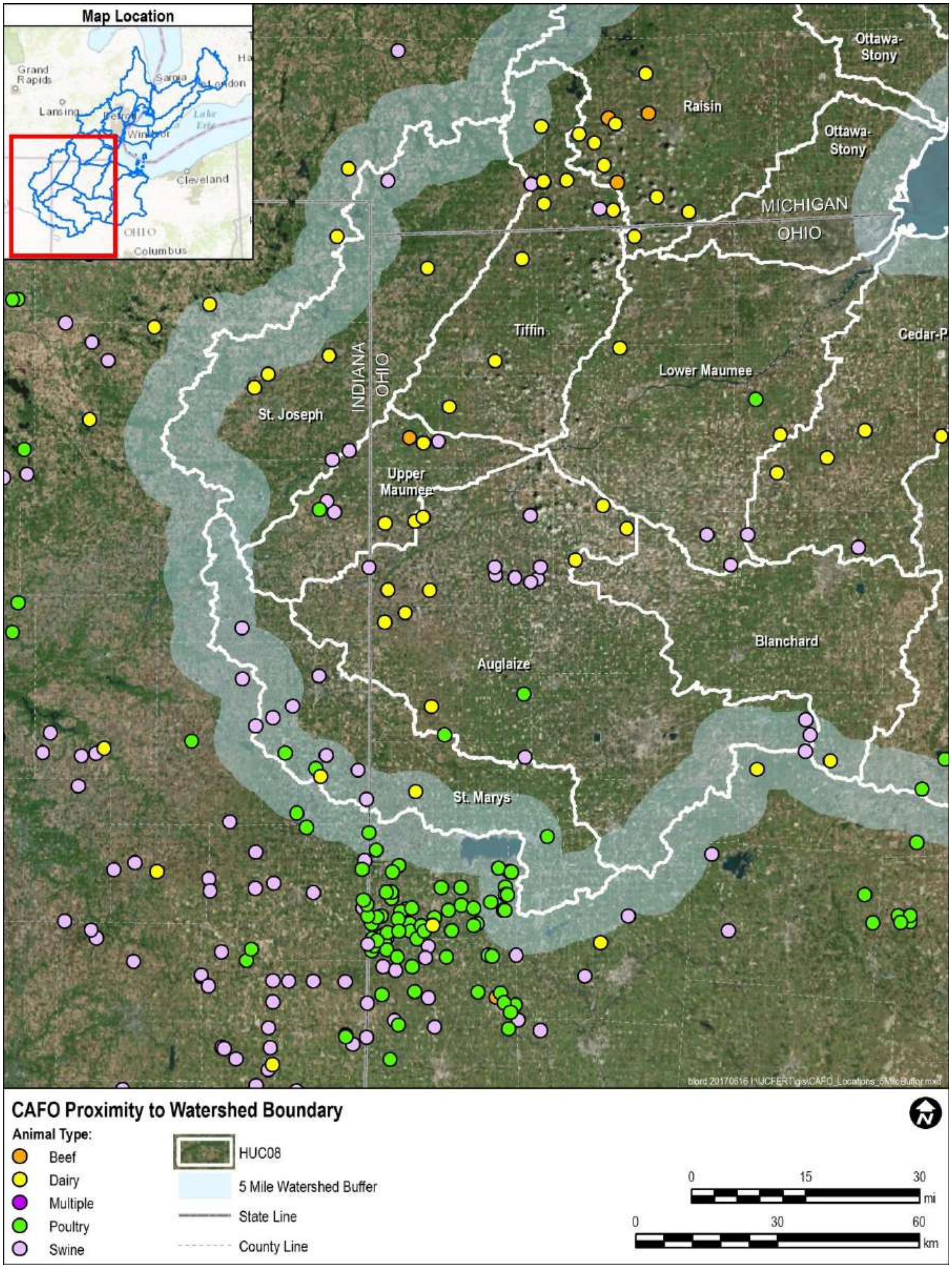

Figure 3-33. Illustrative map of CAFO locations near the watershed boundary, which is depicted with a 5-mile buffer on each side of the boundary to illustrate a zone where some amount of manure is relatively likely to be transferred into or out of the watershed from individual CAFOs prior to application.

3.2.1.e Manure Application: Method and Timing

Several data sources and journal articles were consulted to provide both quantitative estimates and qualitative observations on manure application practices in the study area with some insight into whether trends have changed over time. Sharpley et al. (2013) summarized management activities in the Lake Erie Basin that have led to increased dissolved P loads, including shifting fertilizer and manure management practices and the increase in extent of tile drainage. Michalak et al. (2013) and Sharpley et al. (2012) suggested the practice of fall and winter surface application of fertilizer and manure without incorporation has increased in the WLEB in recent years. There are significant differences in manure application practices between the U.S. and Canada.

Farmer survey results reported in Wilson et al. (2013) give some indication of manure application practices in the U.S. portion of the study area. The survey results indicated the majority of survey respondents that apply manure followed NRCS guidelines for winter manure application sometimes or always, but 25.6% of respondents indicated never following NRCS guidelines for winter manure application. The survey results also suggested that, for farmers who applied manure, fall application (55.3%) was the most frequent time of application and broadcast (62.5%) was the most common method of application (Wilson et al., 2013). The findings by researchers with Ohio State University also confirm the practice of winter and fall fertilizer and manure application is commonly practiced, but their results suggest surface application followed by incorporation with tillage is the most common application method, and that surface application with no incorporation is less common (Wilson 2013, Burnett 2015, Prokup 2017), which is contrary to the suggestions of Michalak et al. (2013) and Sharpley et al. (2012). Note that these survey results represent the proportion of respondents and therefore may not represent the proportion of acres treated by these manure application methods.

In Canada, both the AAFC (2013) GIS dataset and Farm Environmental Management Survey (FEMS) (AAFC, 2016) provided estimations of manure application practices. For 2006 and 2011, injection of liquid manure represented on average 36% and incorporation of solid or composted manure by tillage represented on average 30% of the total manure application for a total of 66% of manure incorporation (by area) in the Ontario drainage areas of the WLEB. The 34% of manure application area without incorporation was split equally between surface application of liquid manure and solid manure at 17% of the area each (AAFC 2013). The FEMS 2011 results indicated a lower adoption of injection of liquid manure at 12.8% for the Lake Erie Lowland ecoregion, but incorporation of surface-spread liquid manure by tillage was 56.7%, indicating a majority of liquid manure is incorporated (AAFC 2016). Results were similar for solid manure application, with 75.8% incorporation by tillage (AAFC, 2016). The FEMS 2011 results also provided insight into timing of manure application for the Lake Erie Lowland ecoregion. The most frequently reported seasons for solid manure application were fall (26.9%), spring (24.6%), and summer (17.6%) (AAFC 2016). The most frequently reported seasons for liquid manure were spring (32.1%), spring and fall (27.2%), and fall (20.4%) (AAFC 2016).

Table 3-7. Estimations of manure application as a portion of total cropland acres or as a portion of farmer survey respondents

Reference	Value	Description	Geographic Area
USDA NRCS, 2011	8%	Portion cropland acres receiving manure	HUC4: 0410
USDA NRCS, 2016	9%	Portion cropland acres receiving manure	WLEB (U.S.)
USDA Census of Agriculture data, 2012	5%	Portion cropland acres receiving manure	WLEB (U.S.)
Agriculture and Agri-Food Canada, 2013	16%	Portion cropland acres receiving manure	Lake Erie (Canada)
USDA Census of Agriculture data, 2012	18%	Portion of farms that used manure	WLEB (U.S.)
Wilson et al., 2013	23%	Portion of survey respondents that apply manure	Maumee Watershed (OH only)
Burnett et al., 2015	16%	Portion of survey respondents that apply manure	Maumee Watershed (OH, IN, MI)
Prokup et al., 2017	13%	Portion of survey respondents that apply manure	Maumee and Sandusky Watersheds

Table 3-8. Estimations of manure application practices as related to the 4Rs from OSU farmer survey responses tabulated for the Maumee River basin and Farm Environmental Management Survey (FEMS) 2011 responses tabulated for the Lake Erie Lowlands ecoregion

Report	Wilson et al., 2013	Burnett et al., 2015	Prokup et al., 2017	AAFC 2016
Freq.	77.2% did not apply manure [p27] (therefore 23% apply)	16% apply manure [p24,p36,p48]	12.5% apply manure past crop [p25]; 32.9% have [ever] used manure [p15]	6.1% of cropland receives solid manure; 5.7% of cropland receives liquid manure
Method	62.5% broadcast 33.75% incorporate [p29]	Did not distinguish fertilizer vs manure	Surface 85%[p26]	76% of solid manure worked in; 13% of liquid manure injected; 57% of liquid manure worked in
Time	Fall, then Spring pre-plant, then Winter [p29]	Did not distinguish fertilizer vs manure	Fall 38%, Winter 41%, Spring pre-pant 26% [p26]	Solid manure: Spring and/or Fall 59% Liquid manure: Spring and/or Fall 80%
BMP	69.7% No manure lagoon [p26]	Did not distinguish fertilizer vs manure	No information	No information
BMP	35.5% always, 25.6% never follow NRCS guides for winter application [p26]	Did not distinguish fertilizer vs manure	No information	No information

3.2.2 Delivery of Phosphorus from Applied Manure: A Review of Current Literature

Best practices for manure management and application to reduce the risk of runoff and nutrient loss are well-understood and are captured in both regulatory mandates and non-regulatory guidelines for Ontario and the three US states in the study area. This knowledge has been incorporated into tools and software that are used to both help producers improve manure and nutrient management practices and to quantify phosphorus loss risk. Researchers at USDA ARS developed a tool for quantifying P losses in agricultural runoff from manure and fertilizer and validated the tool using data from over 20 published edge-of-field studies (Vadas et al., 2009).
been used to estimate risk of phosphorus runoff from agricultural land including areas affected by manure application (Van Bochove et al., 2011, Clearwater et al., 2016). Additionally, work is ongoing to further advance our understanding of nutrient losses from manure application that can be used to build upon existing knowledge and continually improve manure management guidance, tools, and models. Researchers with USDA ARS currently are conducting edge-of-field monitoring that will quantify the P runoff potential on paired field(s) of treatment with manure-P/inorganic fertilizer-P, but results from these efforts are not yet available (Kevin King, personal communication, 2017). Similarly, researchers in Ontario at the Harrow Research and Development Center (HRDC) have been conducting long-term edge-of-field monitoring and although some preliminary results have been reported (Zhang et al., 2017; Zhang et al., 2017b), a complete synthesis is not yet available.

The benefits of liquid manure injection and incorporation of surface-applied manure over surface application without incorporation in terms of minimizing nutrient loss have been sufficiently studied and are captured in manure application guidance resources. Veith et al. (2011) evaluated five methods of liquid dairy manure application and found surface broadcast with no incorporation to have substantially higher TP and dissolved phosphorus export rates than the four methods that either injected or incorporated the manure with tillage. The potential for phosphorus losses from land-applied manure as it relates to the form of manure are also well-understood. Several studies suggest a strong correlation between the water soluble P content of surface-applied manure and export of dissolved P in surface runoff, i.e. the greater the water soluble P content of the manure, the greater the export of dissolved P in runoff (Kleinman et al., 2002; Sharpley et al., 2002, Kleinman and Sharpley 2003; Franklin et al., 2006; Shigaki et al., 2006). Additionally, manures with high organic matter content may reduce surface runoff and erosion by increasing soil cover and infiltration capacity (Sharpley et al., 2002). Kleinman et al. (2005) surveyed a variety of common livestock manures and tabulated mean water-extractable phosphorus (WEP) contents.

Not only did the study demonstrate the high variability in manure WEP across different livestock types, but it also showed variability within a single livestock type depending on, for example, whether a dry or liquid manure storage system was used (Kleinman et al., 2005). In Canada, researchers recently used laboratory and field incubation studies to arrive at a recommended procedure for determining manure phosphorus source coefficients (PSC) that accounts for variation in manure types and soil properties (Wang et al., 2016). The study also recommended new PSC for liquid swine (lagoon or slurry), liquid dairy (lagoon or slurry), solid poultry, and solid beef cattle manure to be used in future quantification of phosphorus loss risk in Ontario (Wang et al., 2016).

Although these various tools and guidelines for manure management have been developed and are continually improved, and research has been and is being conducted to help address the topic, assessing the mobility of manure at a large watershed scale is complicated. 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 U.S. or Canadian drainage areas to the WLEB. Due to the multitude of

-of-in runoff (Figure 3-34). One of the major unknowns identified by UMWC researchers in the case study described above was the lack of information on CAFO manure application method and timing that is critical to generating better estimates of manure mobility (Long et al., 2017). Because it is not currently possible to distinguish P sources from each other at the point of delivery to Lake Erie from tributaries, fertilizer sales data, reported rates of application to the land surface, and total manure generation based on livestock numbers within watershed boundaries are used as proxies. One area of high and steady manure generation, but declining fertilizer application is the Upper Thames River watershed. Water quality trends from this basin show decreasing DRP concentration trends and steady TP (Maaskant, 2015). This pattern would be consistent with a stronger influence on DRP from fertilizer than manure, although changing tillage practices and tile drainage patterns may complicate this interpretation.

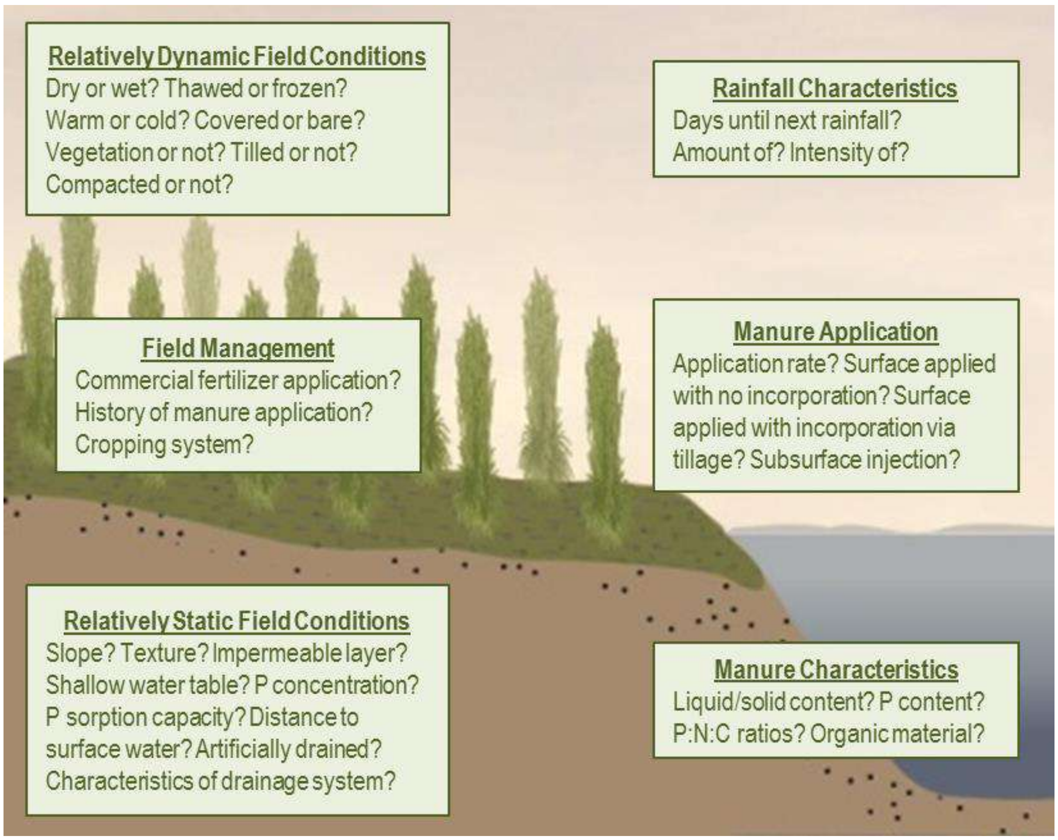

Figure 3-34. Illustration of key questions that will affect how much of the applied manure is lost in runoff.

Laboratory and field experiments (e.g., Chaffin et al., 2011; Davis et al., 2015) indicate that nutrient ratios (e.g., N:P) may be important in initiation, growth, toxin production, and shifts in species dominance for blooms of cyanobacteria in Lake Erie. Ratios in different fertilizer and manure sources are variable and may play a role in the large variation of ratios observed in particulate and dissolved nutrient ratios in different tributaries, different parts of Lake Erie, and different seasons (Prater et al, 2017; particulate N:P range of 3.7 to 122.9). For example, N:P ratios are highly variable in manure; typical values are 6.3 in swine manure (lagoon), 2.8 in dairy cow manure (lagoon), and 2.3 in poultry litter (Lory, 1999). Inorganic fertilizers are intentionally blended with different ratios of N:P, for example MAP = 0.5 and DAP = 0.9 (Rehm et al., 2002). Nitrogen can be volatilized from waste in the form of ammonia or lost as N_2 or N_2O by denitrification and other processes, resulting in net decreases in N:P ratio along travel paths from animal to field to lake. The importance of these variations in sources and transformations to algal blooms is an area of active research.

3.3 Greenhouses

Greenhouse production in Canada is primarily centered in two industries: vegetable production and floriculture. In Ontario, the greenhouse flower industry can broadly be considered to consist of bedding plants, cut flowers, and flowering potted plants (OMAFRA 2016d). Where vegetables are considered, the major industry products are peppers, tomatoes, cucumbers, and lettuce with tomatoes being the dominant vegetable greenhouse crop in Canada (Agriculture and Agri-Food Canada 2017a).

3.3.1 Greenhouse Production: Locations and Trends

3.3.1.a Canada

Greenhouse vegetables have, in recent years, been a growing industry in Ontario. From 1979, the total reported production of greenhouse grown tomatoes, cucumbers, and peppers has increased from approximately 23,000 tonnes to over 520,000 tonnes (Figure 3-35).

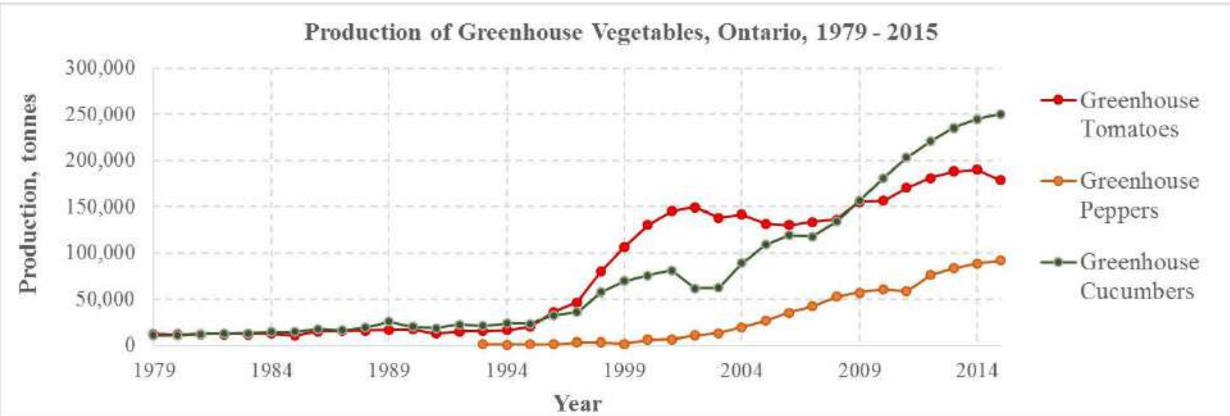

Figure-3-35. Production in tonnes of Ontario Greenhouse Vegetables from 1979 to 2015. Data sources are **(OMAFRA 2016c)**, **(OMAFRA 2016b)**, and **(OMAFRA 2016a)**.

Although production of these vegetable products has been increasing, the number of farms has decreased with 2,876 census farms in Ontario involved in greenhouse, nursery, or floriculture production in 2001 and only 2,372 census farms in 2011 (OMAFRA 2012c). In Southern Ontario specifically, production is centered in the counties of Essex, Haldimand-Norfolk, Hamilton, and Niagara as they account for 790 of the 1,036 farms recorded during 2011 (OMAFRA 2012a). From the number of farms and total greenhouse area, the average greenhouse industry farm in Southern Ontario manages 10,350 square meters of land under plastic or glass. This number is found to be much higher in Essex County where there are 207 farms covering over 6.2 million square meters of land (Figure 3-36).

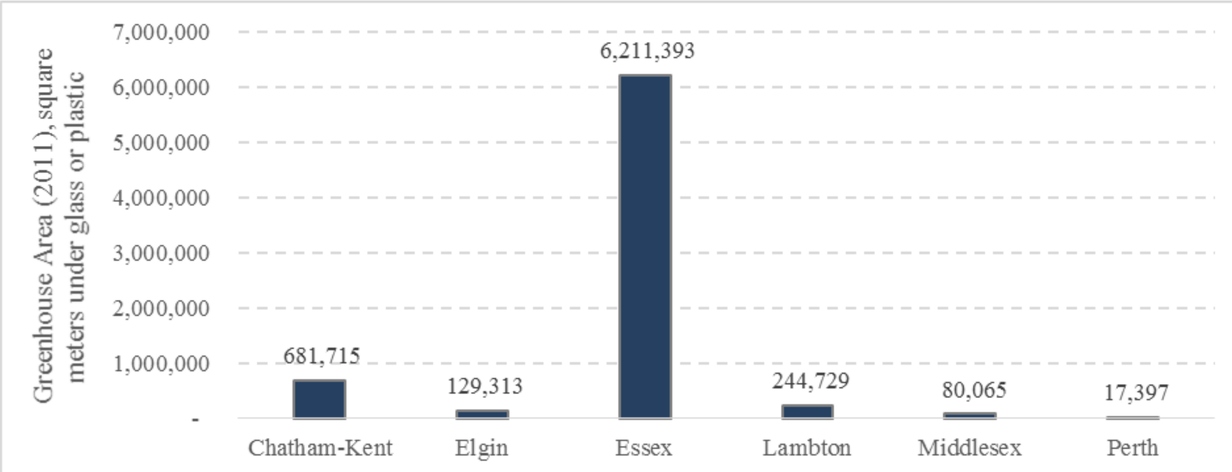

Figure 3-36. Total greenhouse area by county in Southern and Western Ontario [7] and **(OMAFRA 2012b)**. Given counties are those considered to exert an impact on the Western Basin of Lake Erie.

While the productivity of the vegetable greenhouse industry has risen, sectors of the greenhouse floriculture industry have experienced contraction. From 2009 to 2014, the total area of production for greenhouse flowers in Ontario shrank from 4.2 million square meters to 3.5 million square meters (Agriculture and Agri-Food Canada 2017b; Agriculture and Agri-Food Canada 2017c). One specialty which has been particularly hard hit is the cut rose industry. Ontario produced over 34 million tea and sweetheart rose stems in 2002, but by 2008, production had dropped to a little over 8 million stems per year (OMAFRA 2016d). As of 2012, only a single cut rose grower remains in Ontario. Gerberas and tulips now dominate the cut flower market (Agriculture and Agri-Food Canada 2017c). While popular, cut flowers are only the second largest category of greenhouse flowers and plants. Ornamental bedding plants comprise the largest sector of greenhouse flowers and plants when total number of plants are considered (Figure 3-37).

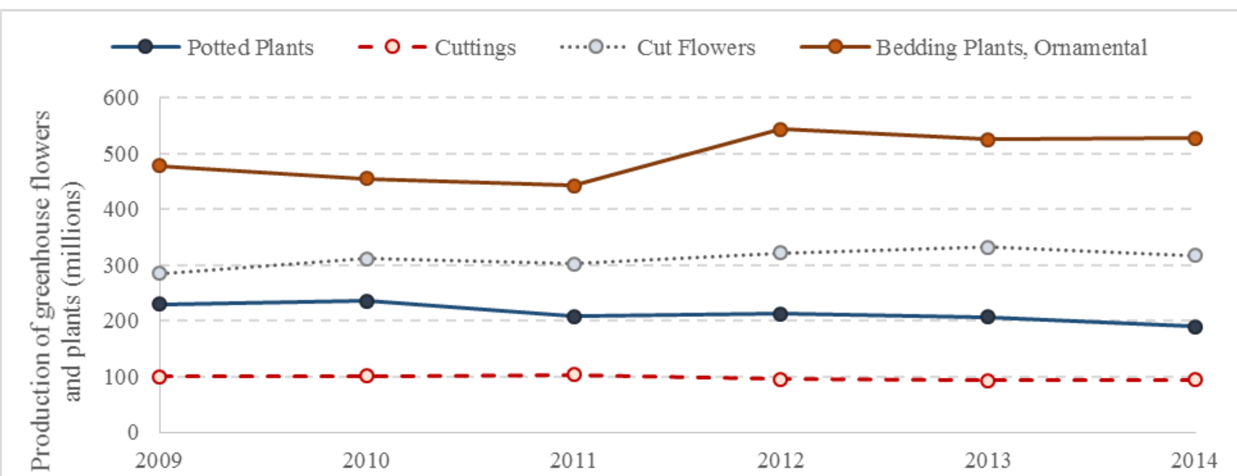

Figure 3-37. Production of greenhouse flowers and plants by category. Data sourced from (Agriculture and Agri-Food Canada 2017b; Agriculture and Agri-Food Canada 2017c).

During the 2011 Census of Agriculture, Statistics Canada tracked the total area of greenhouse space in use for both floriculture and greenhouse vegetable production by census subdivision (Figure 3-38). Reported values in the southern Ontario region ranged from 0 sq. meters to 3,725,665 sq. meters (373 ha.) per

subdivision (Statistics Canada 2011)
south-east Essex County, Ontario near the Leamington area. Together, these two census subdivisions contained over 610 hectares of greenhouse space.

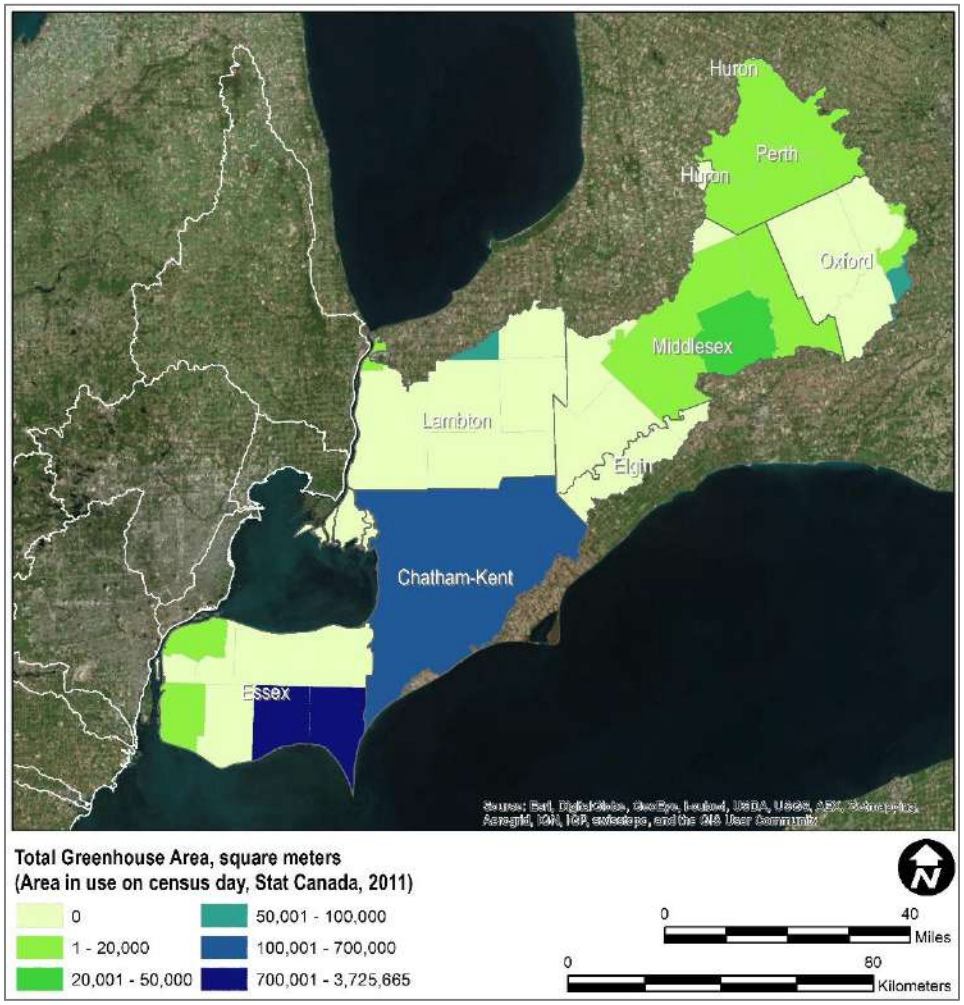

Figure 3-38. Square meters of greenhouse space in use on the day of the 2011 Statistics Canada Census of Agriculture. Data plotted by census subdivision. Blank values in the data were assumed to be zeros in order to obtain complete coverage of the study area. Supporting geodatabase files can be found in Electronic Supplement Folder ES-3.

3.3.1.b United States

Greenhouse vegetable production in the Midwest United States is growing as producers move to take advantage of decreased transit times to population centers, abundant water resources, and affordable utilities. In 2015, Fulton County, Ohio gained a large greenhouse tomato production center for these and other reasons when the Canadian company NatureFresh[5] Farms (originally of Leamington, Ontario) announced a plan to build up to 180 acres (728,434 m^2) of greenhouse facilities. With three phases scheduled for completion by the end of 2016, the facility will have a total of 45.9 acres (185,750 m^2) of greenhouse facility in place (*The Produce News,* 2016). This facility alone will be more than 20 times larger than the total greenhouse area in tomato production as of 2012 (Figure 3-39). As of 2014,

[5] Use of specific company names does not imply endorsement.

additional areas of 961 m^2, 44,379 m^2, and 4,832 m^2 were found to be growing cucumbers and peppers in Indiana, Michigan, and Ohio, respectively (USDA-National Agricultural Statistics Service, 2017).

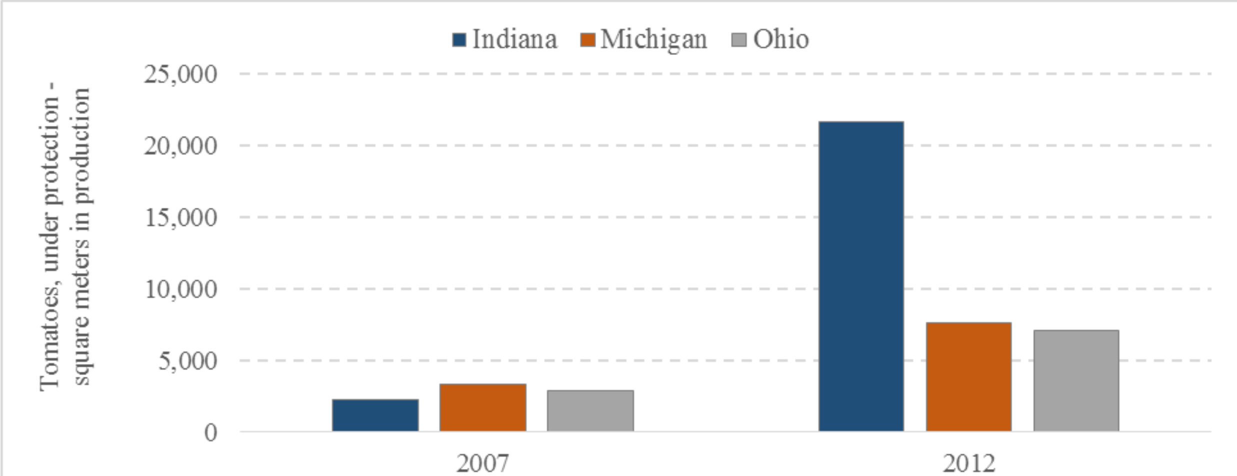

Figure 3-39. Square meters of tomatoes grown under protection in the states of Indiana, Michigan, and Ohio for the years 2007 and 2012. Data as reported by data item "Tomatoes, under protection – sq. ft. in production" from source (USDA-National Agricultural Statistics Service, 2017).

3.3.2 Management of Greenhouse Vegetables and Flowers

3.3.2.a Flowers

Greenhouse grown flowers can be grown in both soil and soil-less media. Irrigation methods may vary depending on the type of product grown and can come from the surface or via sub-irrigation. Tulips, a dominant cut flower type in Ontario greenhouses, can be grown hydroponically with a crate system. Total quantity of water required varies by type of crop grown (cut, potted, etc.) and plant variety (tulips, gerberas, etc.). However, industry literature recommends growers size their irrigation equipment to handle no less than 1 L/m^2/hour (Ministry of Agriculture, Food and Rural Affairs: Ontario, 2014). Growers must also handle pest and disease problems much like growers of edible crops.

3.3.2.b Vegetables

Like flowers, greenhouse vegetables can be grown with or without soil. Growing vegetables without the use of soil is accomplished with a variety of media such as rock wool or coconut fiber. Producers with large greenhouses tend to make use of hydroponic systems (Peet and Welles, 2005). As the plants grow, their roots expand through the media. Nutrients and water are supplied through small tubes placed directly into the growing media, this process is called drip irrigation. Tomato pollination can be carried out by purchasing bumblebees for deployment within the greenhouses (Blake 2017). Artificial lighting is generally employed to extend the growing season and the tray which contain the growing media are elevated above ground level to assist with harvest and other management actions (Figure 3-40).

Figure 3-40. Tomato plants grown hydroponically on rockwool. Photo obtained from Wikipedia Commons under a license for free distribution.

Tomatoes, cucumbers, and peppers require different management regimens to supply the growing plants with the proper amount of water and nutrients. By growing a single type of plant per greenhouse unit, growers can simplify their irrigation, management, and pest control schedules. Single-greenhouses can still experience management shifts, however, as the plants have different needs at each stage of their

of growth media and can require changes in nutrient or water supply as they grow.

3.3.3 Impact of Greenhouses on Local Water Quality

Estimates provided for flower-producing and vegetable-producing greenhouses are reported as volume provided directly to the plant. These estimates should not be understood as direct runoff or direct pollution to surface and sub-surface water bodies. Excess water, which contains nutrients, is termed leachate and is typically collected as a resource in hydroponic systems. It is not disposed of until the greenhouse determines it contains constituents which it considers undesirable for plant growth. At the time of its disposal, greenhouse wastewater typically contains nutrients which are expected to be in concentrations smaller than estimated here.

3.3.3.a Flowers

With competition from overseas growers, floriculture operations can be reasonably expected to maintain private records of their specific fertilization and irrigation routines in order to pursue a competitive edge. An additional complicating factor is that each floral type might require different amounts of fertilizer and irrigation to grow most efficiently. Considering this, broad generalizations were made when estimating possible plant applications of water and nutrients. All floriculture greenhouses were assumed to use an annual irrigation amount of 1,630 L per m^2 of greenhouse space (20 L/m^2 per day for 163 days per year in 50% of the total greenhouse space, (Bilderback et al., no date)). Nutrients were assumed to be applied via fertigation (combined fertilization + irrigation) at a rate of 200 ppm N and 66 ppm P (Bilderback et al., no date), resulting in each floriculture greenhouse receiving 0.33 kg/m^2 of nitrogen annually and 0.11 kg/m^2 of P annually. Note that these numbers transfer up to about 3,260 kg/ha of nitrogen and 1,076 kg/ha of phosphorus which is extremely high when compared to a commodity crops like corn and soy.

3.3.3.b Vegetables

Based on literature availability and the status of tomatoes as one of the most popular crops for greenhouse vegetable growers in Canada, the assumption was made to use fertilization and irrigation requirements for tomato crops for all greenhouse areas. Tomato plants were recognized to grow in three stages, each requiring differing amounts of irrigation and nutrients (Table 3-9).

Table 3-9. Tomato growth stages and the associated irrigation consumption and fertilizer amounts used in the estimates (Dodson, Bachmann, and Williams 2002)

Tomato Growth Stage	Description	Fertigation, L/plant/day	N-ppm	P-ppm	K-ppm
1	From transplant to the first fruit set	0.89	90	45	195
2	From first fruit set to the point where plants are ~6' tall, called "topping"	1.2	125	45	195
3	From "topping" to the end of crop life	1.77	165	45	310

Each stage was assumed to occupy equal days within a year and production was assumed to take place 360 days per year (which assumes plants are replaced as they become unproductive). Based on photographs of modern tomato greenhouses, 50% of the internal space was assumed to be available for plant beds. Numbers are scaled to report use per square meter of total reported greenhouse space (which can include walkways and other non-producing areas). In addition, each plant was assumed to require 0.32 m^2 (3.5 ft^2) of grow space (Hochmuth 2012). This resulted in each vegetable greenhouse using an estimated 723.75 L/m^2 of irrigation water, 0.098 kg-nitrogen/m^2, and 0.033 kg-phosphorus/m^2 per year These numbers translate to about 980 kg-N per ha and 330 kg-P per ha. One other literature source from France (Le Bot, Jeannequin, and Fabre 2001) indicates that 2,000 kg-N per ha are supplied to their rockwool-grown greenhouse tomatoes and about 50% is taken up.

3.3.3.c Local Water Quality Surveys

In 2007, staff from the Ontario Ministry of the Environment conducted water sampling in the Lebo Drain, Hillman Creek, and Sturgeon Creek drainage areas (Ontario Ministry of the Environment 2011). This report identified these drainage areas as having significant numbers of greenhouse operations. While staff did not report excess field runoff during the sampling period, they did observe discharges from some greenhouses. During this study, the Hillman Creek area was not found to have any significant nutrient impairment issues (Figure 3-41). Sturgeon Creek was found to exhibit evidence of heavy impact from nutrient loading with maximum total phosphorus values in excess of 15 mg/l. Lebo Drain was also found to exhibit high total phosphorus readings with nearly all the total phosphorus in phosphate form. Neither the Sturgeon Creek area nor the Lebo Drain areas were found to have any industrial sources which could account for the elevated phosphorus loading.

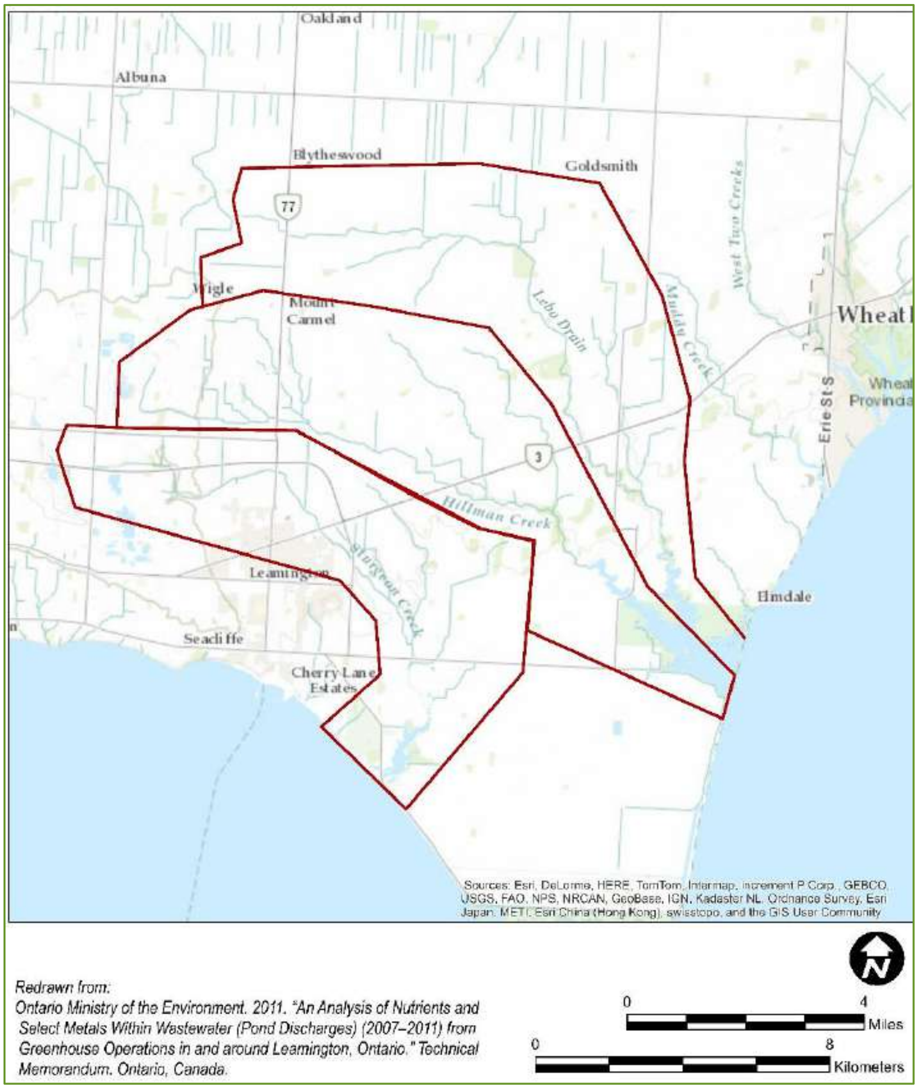

Figure 3-41. Study areas considered in the 2007 sampling event of drains and streams in the Leamington, ON area. Figure redrawn from Ontario Ministry of the Environment, 2011.

In 2010, staff from the Ontario Ministry of the Environment returned to the area and conducted sampling of greenhouse ponds (fertigation water impoundments) and outfalls to ditches and creeks around the Kingsville and Leamington municipalities (Ontario Ministry of the Environment, 2011). For total phosphorus, 100% of the source samples were determined to exceed the Canadian Water Quality Guidelines of 0.03 mg/l. The average total phosphorus concentration from the greenhouse ponds and outfalls during the 2010 sampling study was 42.2 mg/l. The study concluded that significantly higher concentrations of total phosphorus (along with other macronutrients) were found in the sampled greenhouse ponds as compared to control ponds and urban runoff/landfill runoff ponds.

Water quality monitoring activities have continued since 2010 and the Essex Region Conservation Authority (ERCA) recently installed new ISCO automated samplers at locations on Sturgeon Creek and Lane Drain, and has plans to install a third sampler at a location along Mill Creek (Katie Stammler, ERCA, personal communication, 2017). Preliminary data (collected from 2012-2015) indicate that average concentrations of total phosphorus in the Esseltine, Albert Gunning, and Lane Drains exceed the water quality guideline by over 150 times. Researchers at ERCA continue to build their datasets on phosphorus in the watersheds of interest; additional work will be completed to properly measure flow and allow for the calculation of loads. Researchers are also working to create an enhanced Digital Elevation Model to enrich their study of each of the watersheds of interest.

Until calculated loads from these tributaries are available, the relative contributions of greenhouse nutrients to the Lake Erie budget, in comparison with other point and nonpoint sources, cannot be determined. Despite this, it is reasonable to assume that even the high concentrations reported in these small tributaries are likely to have only local rather than regional impacts, given the magnitude of loads and flows from the Maumee River and Detroit River. Prevailing winds and common current directions are likely to carry most Leamington-area nutrients into the central basin of Lake Erie soon after discharge, further reducing the likelihood of substantial impacts on the western basin.

3.4 Other Nutrient-Containing Products

This section reports data on agricultural nutrient-containing products other than inorganic fertilizers and manure. Products considered included herbicides, pesticides, fungicides, liming material, and other soil amendments and conditioners. No sources of regional-scale information on the use of potting soil and peat were identified, although these products are used extensively in nurseries and may be locally important to nutrient cycling and water quality. The assessment includes consideration of relative quantities of each product class applied and the importance to particular crops, where data are available, as well as their contributions to nutrient loadings to the receiving environment, or an assessment of research gaps regarding their contributions. Data from the USDA QuickStats database have been downloaded covering non-fertilizer chemical use; literature was also reviewed pertaining to the fertilizer value of herbicides and their use with specific crops and crop varieties (e.g., Roundup-Ready corn). U.S. information on a variety of products is available from the Agricultural Chemical Use Program: https://www.nass.usda.gov/Surveys/Guide_to_NASS_Surveys/Chemical_Use/ A similar source for Canadian data was not identified. Additional U.S. data and analysis are available in Nehring et al. (2014).

3.4.1 Herbicides and Pesticides as a Source of Nutrients

In addition to obvious sources of phosphorus to the watershed, some of the most common crop protectants (plant herbicides and insecticides) contain nitrogen and phosphorus molecules. These products may be applied to vast acreages of corn and soybean crops on an annual basis and, in many cases, are subject to the same off-site transport processes as nitrogen and phosphorus fertilizers.

3.4.1.a Use of Herbicides and Insecticides in the U.S. WLEB

The NASS Quick Stats 2.0 database was queried for all chemical usage in Michigan, Indiana, and Ohio from 1990 to 2016. Returned values included fungicide, herbicide, and insecticide. For corn, the top five herbicides were determined to be atrazine, metolachlor, acetochlor, dicamba, and glyphosate (Figure 3-42). One of these five herbicides contain phosphorus, however they all, with the exception of dicamba, contain nitrogen. Atrazine was clearly the predominate form of applied herbicide over all three states considered for most years between 1990 and 2015.

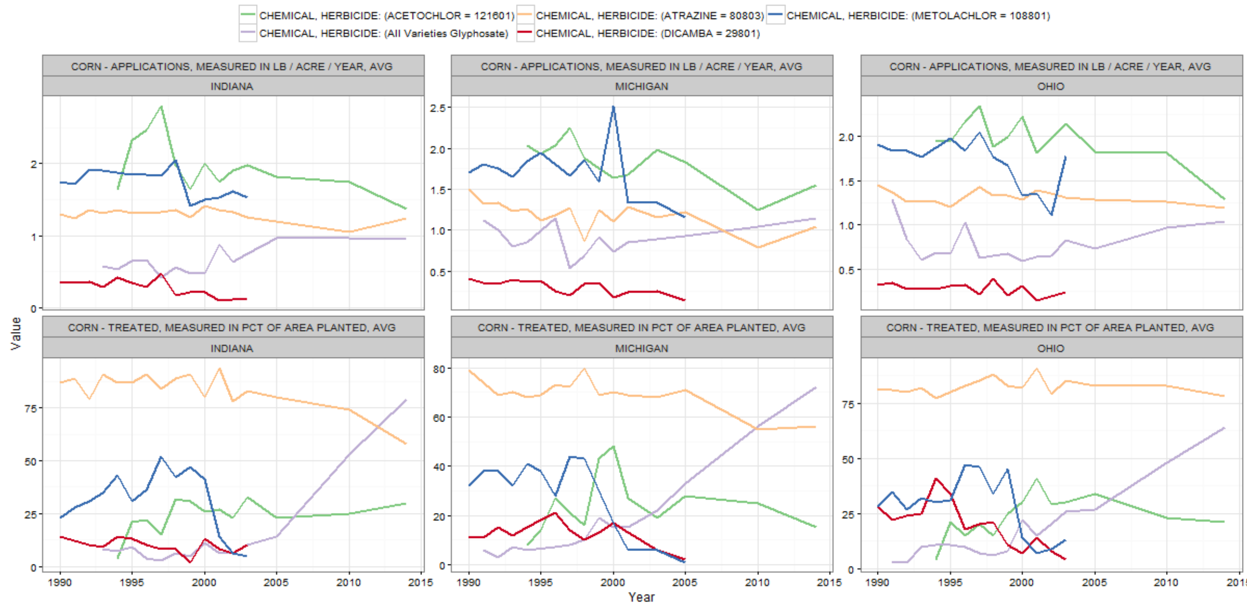

Figure 3-42. Corn herbicide use in the states of Indiana, Michigan, and Ohio from 1990 to 2016, both application amount (lbs/acre/year) and area treated (percent of acreage planted) are reported (NASS Quick Stats 2.0 database).

Glyphosate was sometimes reported by salt type after the year 2002. These forms included glyphosate isopropylamine salt, glyphosate diammonium salt, glyphosate potassium salt, and glyphosate dimethylammonium salt. To facilitate comparison with the other types of herbicide, the application area for glyphosate was considered to be the sum of the percent treated over all reported types and the application rate was considered to be the mean over all reported types (Figure 3-43). By state, this value generally did not exceed 100%. However, for soybeans in the state of Indiana in 2012, the sum of all areas treated by any glyphosate product was 103%. This value was assumed to be 100% in the following plots and calculations. Excluding glyphosate, the next three herbicide products that were most commonly applied to soybeans were chlorimuron-ethyl, metribuzin, and imazethapyr. Of the types considered, glyphosate was the only herbicide found to contain phosphorus; all of the considered types contained nitrogen.

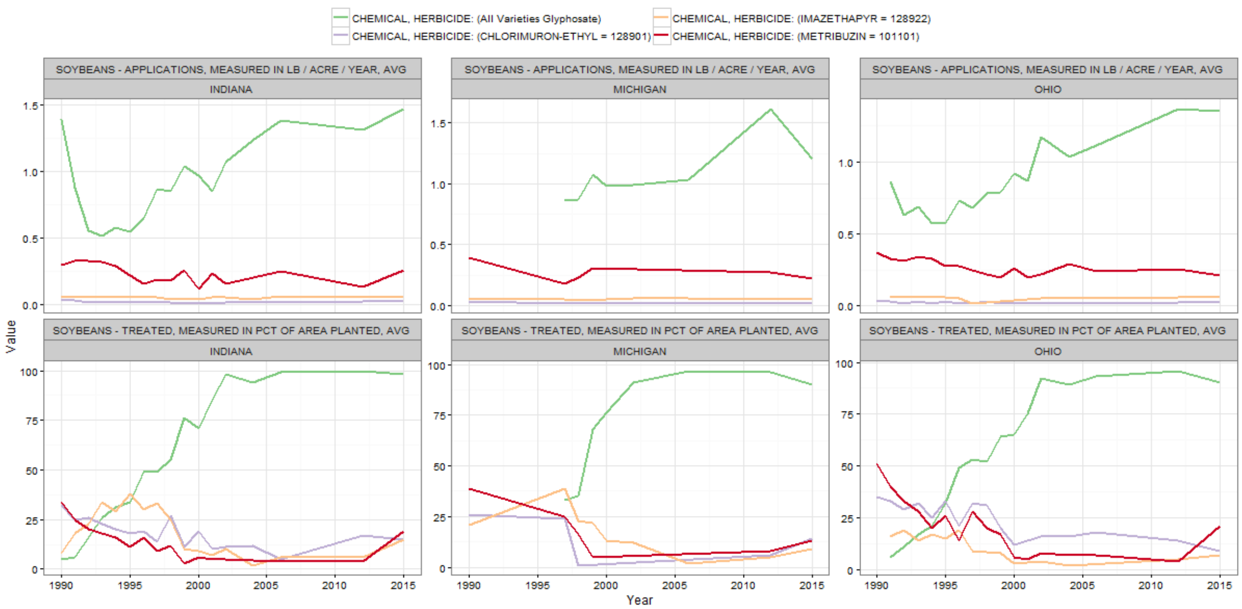

Figure 3-43 Soybean herbicide use in the states of Indiana, Michigan, and Ohio from 1990 to 2016, both application amount (lbs/acre/year) and area treated (percent of acreage planted) are reported.

From the NASS Quick Stats results, 13 insecticides used with corn and 5 insecticides used with soybeans were analyzed. Two formulations were found to contain phosphorus chlorpyrifos and terbufos. Very little data were reported for either formulation for soybeans, so analysis was restricted to corn. Neither chemical was found to be applied to greater than 15% of the area planted (Figure 3-44). Application rates for both products were consistently below 2 lbs/acre/year.

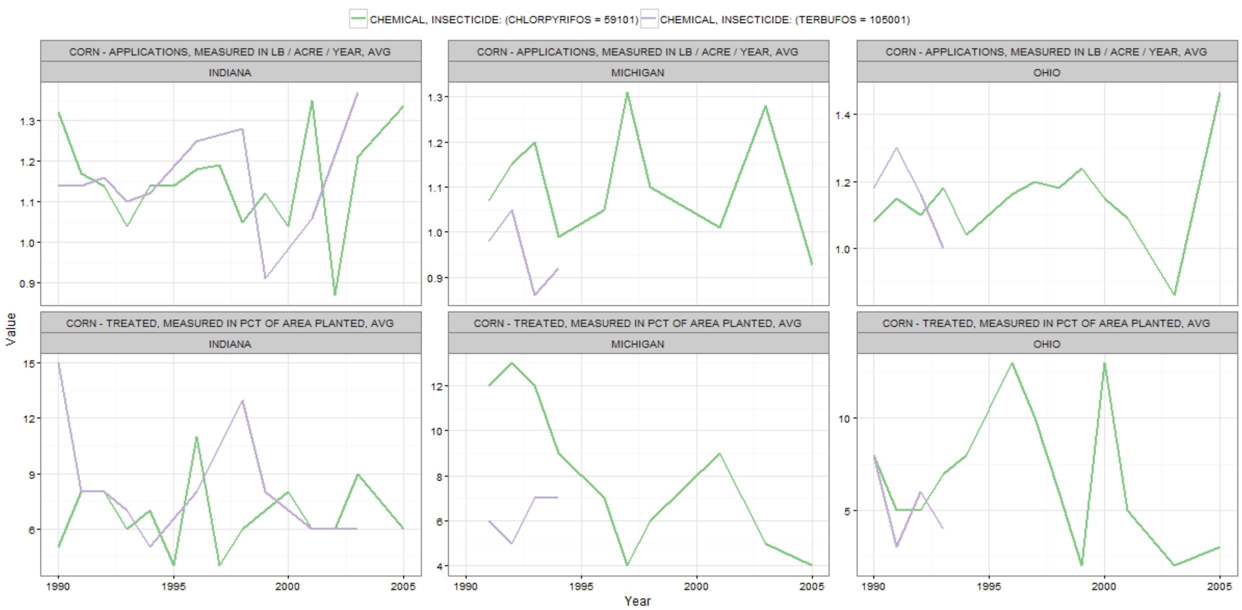

Figure 3-44. Corn insecticide use in the states of Indiana, Michigan, and Ohio from 1990 to 2016; both application amount (lbs/acre/year) and area treated (percent of acreage planted) are reported.

3.4.1.b Contribution to Nutrient Loading

For each major crop type, the most commonly applied herbicide and insecticide products were analyzed to determine their contribution to either nitrogen or phosphorus loading at the state scale. No insecticide product was considered for soybeans, and no Ontario data were obtained or analyzed, although application rates are expected to be similar in Canada.

Atrazine – Corn, Herbicide

Atrazine has a chemical formula of $C_8H_{14}ClN_5$ and a molecular weight of 215.68 g/mol (Pubchem, 2017a). Given the molar mass of nitrogen, atrazine can be considered to be 32.4% nitrogen. In the most recent year for which data are available (2014), NASS reports the percent of planted area treated and the applications in lbs/acre/year on a statewide basis (Table 3-10).

Table 3-10. Data from NASS Quick Stats regarding the application of atrazine in the Great Lakes states of Indiana, Michigan, and Ohio for the year 2014.

	Indiana	Michigan	Ohio
CORN - APPLICATIONS, MEASURED IN LB/ ACRE / YEAR, AVG	1.232	1.049	1.191
CORN - TREATED, MEASURED IN PCT OF AREA PLANTED, AVG	58	56	78
CORN - PLANTED ACRES, 2014, NASS CDL	181,573	353,088	1,295,305
Acres of corn, treated	105,312	197,729	1,010,338
Total tons of product applied	65	104	602
Phosphorus applied (0% phosphorus), tons	-	-	-
Nitrogen applied (32.4% nitrogen), tons	21	34	195

Glyphosate – Corn, Herbicide

Because glyphosate is the most common type of corn-applied herbicide during the evaluated period which also contains phosphorus, it was reviewed for corn as well as soybeans. Glyphosate is an organophosphorus compound known as a phosphonate. Glyphosate has a chemical formula of $C_3H_8NO_5P$ and a molecular weight of 169.07 g/mol (Pubchem, 2017c). Given the molar mass of nitrogen and phosphorus, glyphosate can be considered to be 18.3% phosphorus and 8.2% nitrogen. In the most recent year for which data are available (2014), NASS reports the percent of planted area treated and the applications in lbs/acre/year on a statewide basis (Table 3-11).

Table 3-11. Data from NASS Quick Stats regarding the application of glyphosate in the Great Lakes states of Indiana, Michigan, and Ohio for the year 2014

	Indiana	Michigan	Ohio
CORN - APPLICATIONS, LB/ ACRE / YR, AVG	0.95175	1.144	1.033
CORN - TREATED, PCT OF AREA PLANTED, AVG	79	72	64
CORN - PLANTED ACRES, 2014, NASS CDL	181,573	353,088	1,295,305
Acres of corn, treated	143,443	254,223	828,995
Total tons of product applied	68	145	428
Phosphorus applied (18.3% phosphorus), tons	12	27	78
Nitrogen applied (8.2% nitrogen), tons	6	12	35

Glyphosate – Soybean, Herbicide

Glyphosate applied to soybeans has the same properties as those listed above for corn. In the most recent year for which data are available (2015), NASS reports the percent of planted area treated and the applications in lbs/acre/year on a statewide basis (Table 3-12).

Table 3-12. Data from NASS Quick Stats regarding the application of glyphosate in the Great Lakes states of Indiana, Michigan, and Ohio for the year 2015.

	Indiana	Michigan	Ohio
SOYBEANS - APPLICATIONS, MEASURED IN LB / ACRE / YEAR, AVG	1.47	1.21	1.35
SOYBEANS - TREATED, MEASURED IN PCT OF AREA PLANTED, AVG	98	90	90
SOYBEANS - PLANTED ACRES, 2015, NASS CDL	236,037	509,827	1,902,561
Acres of soybeans, treated	231,316	458,844	1,712,305
Total tons of product applied	170	278	1,156
Phosphorus applied (18.3% phosphorus), tons	31	51	212
Nitrogen applied (8.2% nitrogen), tons	14	23	95

Chlorpyrifos – Corn, Insecticide

Chlorpyrifos has a chemical structure of $C_9H_{11}Cl_3NO_3PS$ and a molar weight of 350.58 g/mol (Pubchem, 2017b). Given the molar mass of nitrogen and phosphorus, chlorpyrifos can be considered to be 8.8%

phosphorus and 3.9% nitrogen. In the most recent year for which data are available (2005), NASS reports the percent of planted area treated and the applications in lbs/acre/year on a statewide basis (Table 3-13).

Table 3-13. Data from NASS Quick Stats regarding the application of chlorpyrifos in the Great Lakes states of Indiana, Michigan, and Ohio for the year 2005.

	Indiana	Michigan	Ohio
CORN - APPLICATIONS, MEASURED IN LB/ ACRE / YEAR, AVG	1.34	0.93	1.47
CORN - TREATED, MEASURED IN PCT OF AREA PLANTED, AVG	6	4	3
CORN - PLANTED ACRES, 2007, NASS CDL	181,307	410,714	1,320,406
Acres of corn, treated	10,878	16,429	39,612
Total tons of product applied	7	8	29
Phosphorus applied (8.8% phosphorus), tons	1	1	3
Nitrogen applied (3.9% nitrogen), tons	0.3	0.3	1.1

3.4.1.c Nutrient Availability

While glyphosate would intuitively be expected to act as a toxin to microbial communities (as a pesticide), research has shown that it is capable of positively influencing the growth of soil microbes and cyanobacteria (Saxton et al.,
on environmental microbiota, Saxton et al. (2011) collected water from Lake Erie in three sampling locations (in and outside of Sandusky Bay, and within Maumee Bay), and amended two samples from two of these locations with glyphosate. These samples were meant to represent water columns where *Microcystis* (Maumee Bay) and *Planktothrix* (Sandusky Bay) cyanobacteria dominated bloom assemblages. Research findings indicated that glyphosate enhanced the growth of *Planktothrix* cyanobacteria, but inhibited the growth of *Microcystis*. The researchers concluded that both glyphosate and AMPA (its breakdown product) are usable by some parts of the microbial community as nutrients.

3.4.1.d Prevalence in the Study Area

Ryberg and Gilliom (2015) included the Maumee River at Waterville USGS station (04193500) in their review of pesticide loading at 38 sites nationwide using data collected from 1992 to 2010. While glyphosate was not included in this analysis, atrazine was found to have in-stream trends which were consistent with steady to mildly decreasing use in crop fields. However, DEA (a decomposition product of atrazine) displayed more increasing than decreasing trends.

Battaglin et al. (2014) analyzed 3,732 environmental samples from 38 states and the District of Columbia to determine glyphosate and AMPA detections. Sites in Indiana, Michigan, and Ohio were included and tested for chemical presence in streams, groundwater, large rivers, soil water, ditches, and lakes/ponds. Out of all the samples available nationwide, 52.5% of the samples from streams had glyphosate detections and 71.6% had AMPA detections. Similar percentages were recorded for large rivers. Groundwater and pond/lake detection percentages were generally lower while ditches, precipitation, and soil/sediment samples had no less than 70% of samples with detectable glyphosate or AMPA.

The USGS tests for dissolved glyphosate in the Maumee River at the Waterville station. Samples are available regularly after November of 2010, with a gap in coverage between 2012 and 2013. Concentrations generally peak in the range of 1.5 to 2.3 ug/L around June/July each year (Figure 3-45).

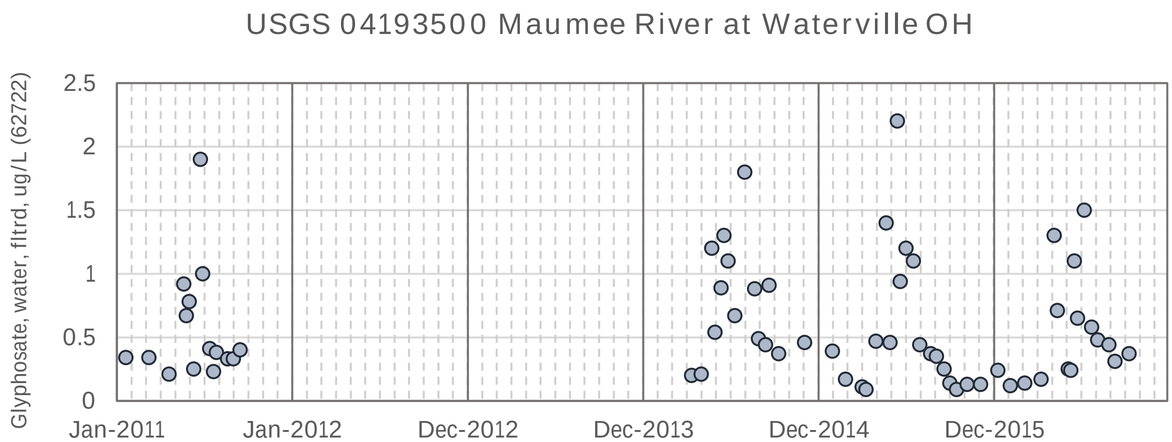

Figure 3-45. Glyphosate concentrations in the Maumee River at Waterville from January of 2011 to December of 2016. Concentration is given in ug/L.

3.4.2 Soil Conditioners as Nutrient Sources

While application data were not identified concerning the rates and coverage of other soil conditioners, a few product lines were reviewed to provide context for this category. Mention of specific companies, product lines, or brand names is for identification purposes only, and does not imply endorsement. Soil conditioner products generally make the claim that they provide one or more of the following benefits (Hickman and Whitney, no date):

- higher yields,
- improved soil structure,
- more water availability, or
- improved root growth.

Agriculture Solutions in Ontario, Canada, sells a product called *TrueBlend* , which contains humic acid, carbohydrates, and bio-stimulants for the purpose of breaking down crop residue. The product label calls for an application rate of 6-8L of diluted solution per acre and it contains 0.70% total nitrogen, 0.10% P_2O_5 phosphorus, and 3.10% potash.

In the United States, The Andersons sells several humic solution soil amendments. Their *UltraMate®* and *K-Mate™* lines both provide soluble potash (ranging from 3% to 14%), but no nitrogen or phosphorus. Application rates for their liquid product range from 1 to 3 gallons per acre, and they recommend that the product be applied with UAN to jumpstart microbial degradation of corn residue. Application rates for their dry products range from 1 to 3 pounds per acre. Their products *HumicDG™* and *BlackGypsumDG™* both contain humic substances, but no nitrogen or phosphorus.

3.4.3 Gypsum and Agricultural Lime Influence Nutrient Mobility

Gypsum is a readily available soluble source of calcium and sulfur, both of which are essential plant nutrients. One popular source for gypsum in the United States is flue gas desulfurization (FGD), a process necessitated by the Clean Air Act Amendments of 1990 which restricted sulfur dioxide emissions from power plants operated with coal combustion (Chen and Dick, 2011). Gypsum from this source is 18.5% sulfur and contains 970 ppm nitrogen and <1 ppm phosphorus, while mined gypsum from sources including mining operations in the WLEB, can contain as much as 30 ppm phosphorus (Chen and Dick, 2011). Pure gypsum contains only calcium, sulfur, oxygen, and hydrogen. The appropriate application rate for this product can be determined based on crop sulfur needs. Using this method, the recommended rate of gypsum application on a corn grain field or soybean field is 160 lbs/acre (Chen and Dick, 2011). At 1 ppm (mg/kg) phosphorus, this would represent an application rate of only ~73 mg of phosphorus per acre.

Several conservation organizations in the Western Lake Erie Basin are considering the possible use of gypsum amendments as a method of phosphorus trapping in farm field soils. Rates to accomplish this task are generally much higher than those recommended strictly for sulfur replacement for crop needs. Watts and Torbert (2016) found that a rate of 4.4 Mg/ha (~2 tons/acre) of FGD gypsum was optimal for reducing dissolved phosphorus losses from a pasture treated with poultry manure. King et al. (2016) tested two successive applications of 2.24 Mg/ha (1 ton/acre) FGD gypsum to a field in Ohio which had high soil test phosphorus levels. While concentrations of phosphorus in surface and tile water decreased after the first application, it was not until after the second application that significant reductions were seen in phosphorus loading.

The application of lime to adjust soil pH upward to optimize conditions for agricultural purposes can be necessitated by both natural and human-influenced phenomena. Soils developed from parent materials that are low in carbonate minerals are more likely to be acidic and to bind P to aluminum or iron, while those which formed from parent material high in calcitic and dolomitic minerals are less likely to experience acid conditions and more likely to bind P less strongly to calcium (Mullen et al., 2016). In addition to these natural drivers of soil pH, the application of nitrogen fertilizer that is high in ammonium generally causes soil to become more acidic (Mullen et al., 2016). Producers are encouraged to check their soil and buffer pH before applying lime to ensure that they are choosing the correct rate. While there are a few different options for chemical makeup, none of the most common varieties of lime used in agricultural applications contains phosphorus. However, the application of lime to a soil which has acidified can increase the availability of phosphorus in the soil profile to plants, but may also make it more available for leaching and transport to surface water.

3.4.4 Relative importance of non-fertilizer products and soil amendments

Although relatively large amounts of non-fertilizer products that contain P and N are applied to agricultural watersheds of the U.S. and Canada, the quantities of nutrients involved are not of the same order of magnitude as those contained in applied fertilizer and manure. For example, the total mass of P applied as glyphosate to all the corn (2014) and soybean (2015) cropland in the states of Indiana, Michigan, and Illinois (not just the WLEB watershed) is 411 U.S. tons or 372,853 kg (Tables 3-11 and 3-12). For comparison the total fertilizer and manure P applied to the U.S. and Canadian WLEB watershed in 2007 (Table 3-14) was 58,013,851 kg, or approximately 156 times as much P as was applied in the form of glyphosate to the entire states (= much larger area than the WLEB watershed). Sources of regional data for the application of soil conditioners, gypsum, and lime were not identified, but their overall influence on P migration is likely small in the WLEB watershed.

3.5 Summary of the State of Knowledge

The sections above have described available data from Canada and the U.S. for the western Lake Erie basin, including the Huron-Erie Corridor basin, on fertilizer and manure use and impacts, along with other related information. Although gaps in information and process understanding remain, a reasonable picture of the relative importance of these primary agricultural phosphorus sources for crops and, indirectly, algal blooms, is fairly clear. Some of the primary findings of this assessment are summarized below in bullet form, with additional discussion about recent attempts to identify agriculturally-linked factors that may have contributed to or driven the increase in Lake Erie algal bloom size and severity in the last 15 to 20 years. Table 3-14 summarizes information on applied P in inorganic form and manure P generated (approximately half is applied to fields; Bast et al., 2009) for the watershed, based on information shown in the lower left panels of Figures 3-15, 3-23, and 3-32. Note that lower total P and inorganic fertilizer P values for Canada are partially due to the smaller watershed area in Ontario versus the U.S. (Ontario watershed area = 29% of the U.S. watershed area or 22% of the total combined watershed).

Table 3-14. Summary of total elemental mass of inorganic fertilizer P applied to U.S. and Canadian agricultural land or generated (manure) in the study watersheds in 2007, the most recent year for which comparable data for both countries are available, based on GIS analysis described and shown in figures above.

	2007				
	Total P (kg)	**Manure P (kg)**	**Manure (% of Total P)**	**Fertilizer P (kg)**	**Fertilizer (% of Total P)**
US	41,687,180	7,735,580	19%	33,951,601	81%
Canada	16,326,671	8,443,129	52%	7,883,542	48%
Totals:	*58,013,851*	*16,178,709*	*28%*	*41,835,143*	*72%*

3.5.1 Summary of Key Findings

Summary of potential contribution of each fertilizer type:

- Inorganic fertilizer: typically about 70 to 80% of total P (fertilizer sold plus manure generated); lower percentage in Upper Thames (Ontario) due to greater manure generation and declining fertilizer application
- Manure: typically about 20 to 30% of total P (fertilizer sold plus manure generated); greater percentage in Upper Thames, but also a different crop mix there (more corn); declining DRP there suggests differential sensitivity to inorganic fertilizer versus manure
- Fertilizer used in greenhouse production: locally important (e.g., Leamington, Ontario area), but not regionally significant at present (small percentage of total loading; recent regulations passed in Canada regarding greenhouse discharge management)
- Non-fertilizer products that contain nutrients: not regionally significant, although actively being researched

Relative importance of fertilizer application details (4Rs) to eutrophic conditions in Lake Erie:

- Form: increasing usage of MAP (monoammonium phosphate) vs. DAP (diammonium phosphate) fertilizer has been reported, but significance to water quality is unclear
- Timing: recent regulation of winter and wet-weather application of manure in Ohio and other regulation actions could be important, but the impact has not been quantified
- Placement: mostly refers to soil depth; some benefit of incorporation/injection vs. broadcast on surface, but complicated by subsurface tile drain transport; impacts of less tillage are also complex, but include generally lower particulate P loading to waterways

- Rate: more emphasis on within-season application and movement away from single applications to cover multiple years, but complexities exist with respect to consideration of legacy P; nitrogen application is usually the primary concern for crop needs

Additional issues relevant to manifestations of eutrophication

- Importance of watershed phosphorus due to natural conditions: not examined in detail, but small localized sources of igneous apatite which could have been transported south by glacial activity exist in Ontario, notably at Kapuskasing about 450 km north of Georgian Bay (mine operated for several years and closed in 2013); sedimentary phosphate is actively mined primarily in Florida, North Carolina, and Idaho in the U.S.
- Legacy content of P in soils, river sediments, and lake sediments: area of active research (see 2016 and 2017 publications)
- Engineering modifications: hydrologic flow control using tile drain management devices and other approaches are being studied and implemented in some regions to slow P delivery and increase adsorption to soil

Priority information gaps

- Better quantification of agricultural sources of nutrients, particularly linking locations of manure generation with application, and documentation of the fate of manure that is generated but not applied for all animals (CAFOs and AFOs)
- Improved understanding of transport pathways, timing, and transformations after application, including sufficient detail to determine locations of legacy P and sufficient spatial and temporal resolution to tie water quality to fertilizer application and farm management practices (e.g., tile drainage and tillage)

3.5.2 Phosphorus Processes Operating on Longer Timescales

Until recently, research and agricultural management have focused on the dynamic part of the overall phosphorus cycle: inputs via agricultural application of P, and outputs via environmental loss pathways. Much less attention has been given to the pool of soil phosphorus that assimilates inputs and delivers outputs. This conceptual model of focusing on the movement of phosphorus in the system initially served well the objective to reduce phosphorus loads into Lake Erie. It also resulted in a convergence of agricultural inputs (fertilizers manure) and outputs (crops) as evidenced by an overall balance of these same inputs and outputs. However, observations of counterintuitive trends in phosphorus loads, particularly increases in DRP and the return of algal blooms in Lake Erie in the last two decades have

.

Notwithstanding the watershed-wide balance between agricultural inputs and outputs, locally there continue to be surpluses (more inputs) that further build up soil P, as well as deficits in parallel with increased crop yield. The latter implies that crop needs are supported only in part by the inputs, and in part by legacy P still in the farm soils. Both of these situations indicate that P is available beyond crop needs, supplying P into watershed pathways, from tiles, to ditches, to streams, to rivers.

Through implementation of erosion control strategies, TP loads to rivers have greatly decreased from 1975 to 1995 (Jarvie et al., 2013; Kleinman et al., 2015) and have been stable or slightly declining since then. Inputs of DRP to Lake Erie, however, have increased at the same time (Jarvie et al., 2013). Similarly, NAPI (Net Anthropogenic Phosphorus Input, a balance around the whole watershed that includes food, feed, and exports, and not just agricultural soil inputs and losses) has been decreasing over time, but the proportion that is exported by rivers has increased (Han et al., 2012).

What is driving these unexpected trends? Climate change and shifts in agricultural practices have been blamed .
converged, altering thresholds and boundary conditions that drive the P cycle. In each of these categories of potential drivers of problematic trends there are several candidate processes, all of which interact synergistically but with as yet unknown relative contributions.

3.5.2.a Legacy Phosphorus

Substantial amounts of legacy P have accumulated in agricultural soils (Han et al., 2012; Jarvie et al., 2013; King et al., 2017; Bast et al., 2009 [Figure 3-46]). One indication of the persistent availability of legacy 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 finite pool (King et al., 2017). Powers et al. (2016) estimated that the Maumee basin has accumulated over 200 kt of P beyond the inventory that existed in 1970; drawdown of this pool has been underway since the 1980s. Muenich et al. (2016) have modeled the Maumee River watershed and various conservation practice scenarios and determined that even if fertilizer application ceased entirely, it may take years to see decreases of the magnitude desired in phosphorus loads.

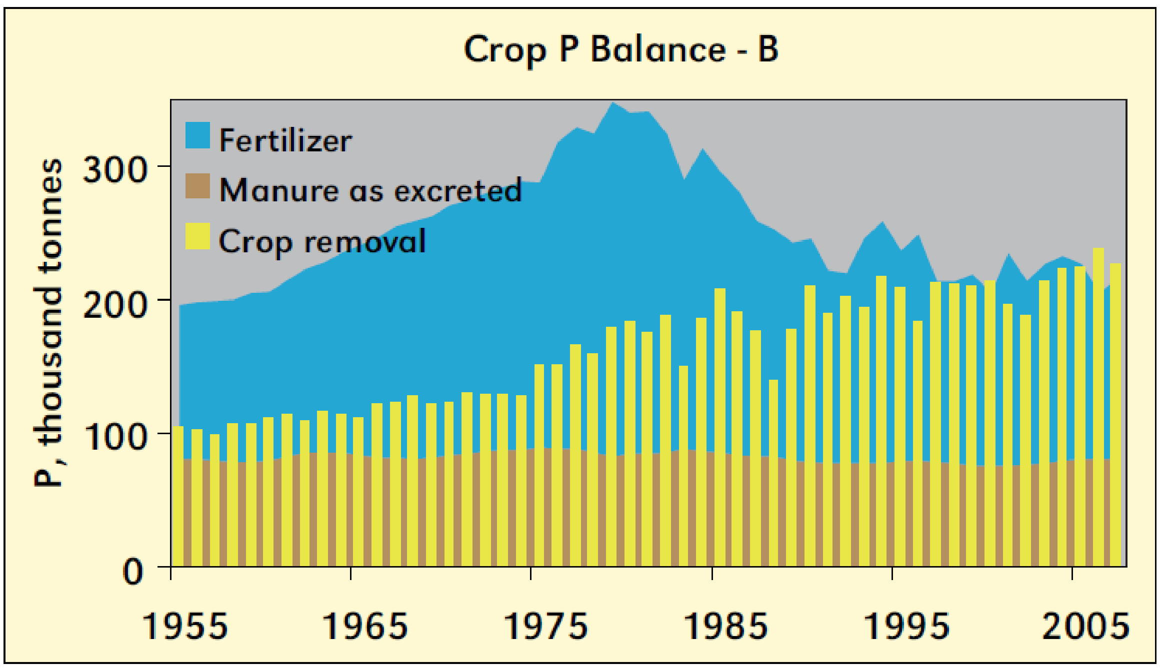

Figure 3-46. Summary of P balance over time for Ontario, Michigan, and Ohio (entire state/province, not watershed, and not including Indiana; from Bast et al., 2009). Note that only about half of manure P excreted is applied to crop fields. *Permission for use of image will be requested prior to public release.*

https://www.ipni.net/ppiweb/bcrops.nsf/$webindex/9C75DB1ABDF1B07B852575660082B2A7/$file/BC09-1p06.pdf

They also evaluated the effects of fertilizer reductions on crops, and found that with no 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. 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. Under these conditions, the time lag to water quality improvements and source reduction (i.e., drawdown of elevated soil P) is on the scale of a few years to 2-3 decades (Hamilton, 2012; Sharpley et al., 2013).

Phosphorus may also have accumulated to saturation in some non-agricultural compartments (buffer zones, filter strips, wetlands, riparian zones, ditches and ditch sediments). 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 (Figure 3-46). 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, which is also largely outside of current management and policy consideration.

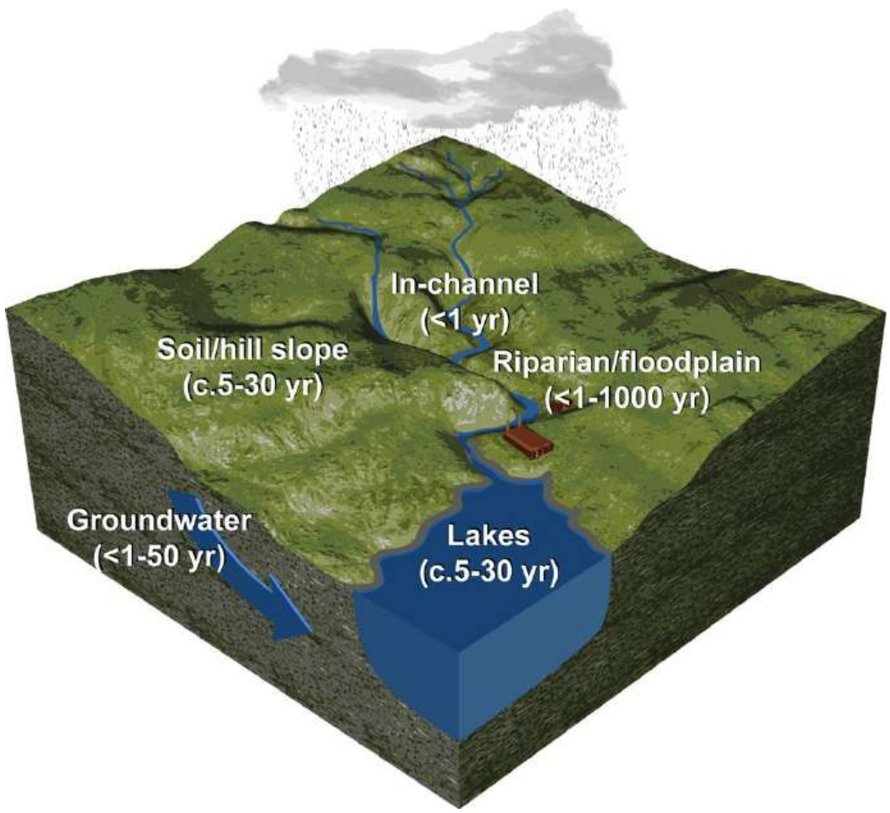

Figure 3-47. Typical time scales for phosphorus (P) retention and recycling in watershed and waterbody legacy P stores. These result in a continued chronic release of legacy P, impairing downstream water quality over time scales of years to decades, or even centuries (as shown in Jarvie et al., 2013b). *Permission for use of image will be requested prior to public release.*

3.5.2.b Climate Change Impacts

Climate change has resulted in more frequent and larger precipitation events in spring when fertilizer is more available in agricultural fields and Lake Erie HABs and hypoxia are most strongly influenced by higher inputs of P (Jarvie et al., 2013; Michalak et al., 2013; Kleinman et al., 2015). Jarvie et al. (2017) estimated that the contribution of runoff to SRP load increases in the Sandusky, Maumee and Raisin Rivers is about 35% (with about 65% accounted for by increased delivery via tile drainage). Scenarios modeled by Muenich et al. (2016) also indicate that climate and precipitation have an important influence on the time it takes to reach phosphorus load targets in the Maumee regardless of conservation practices.

Jarvie et al. (2011) showed that the ability of rivers to retain phosphorus is a function of flow regime, among other factors. These processes slow the further conveyance of phosphorus to Lake Erie. The study found that the Sandusky River retains 48% more of its annual phosphorus load than it would if P did not respond to in-stream interactions once it entered surface water from fields. At low flows, this percentage was 82 to 93%. Thus, the Sandusky River retains a significant proportion of its annual P load. Flow regime is greatly affected by climate, so the efficiency of internal P cycling can be expected to change as rivers respond to a changing climate, including the possibility of lower P retention. A modeling study by Chapra et al. (2017) concluded that cyanobacteria algal blooms are likely to increase in duration and number in U.S. freshwater systems due to climatic impacts on hydrology and associated nutrient delivery, as well as from water temperature increases that favor longer bloom durations and enhanced growth rates.

Research results on the impacts of climate change on crop yields are mixed between beneficial but small effects of increased CO2 availability, and adverse effects of changes in temperature and precipitation regimes (Long et al., 2006; Long and Ort, 2010). It is possible that gains in crop yields (genetic and CO2-related) could be halted or reversed. Crop yield is already stagnating in more southern areas in the U.S. (Ray et al., 2012). Crop yield changes in response to climate change would affect the phosphorus left behind after harvest (potentially more unused fertilizer if yields decline but application rates do not). To counteract the mobilization potential of predicted rainfall of greater frequency and/or intensity in the longer early growing season, 4R practices will need to be combined with structural (e.g., hydrological reconfiguration and water management in tiles) and other types of BMPs.

3.5.2.c Scale Differences between Human and Ecological P Fluxes

Agricultural trends have come to a rough balance between inputs and outputs, however, agricultural P fluxes are one to two orders of magnitude above the levels that cause problems ecologically. Powers et al. (2016) estimated that between 1975 and 2010 annual fertilizer P import and food/feed P export exceeded fluvial P export in the Maumee by 5- to 20-fold. Han et al. (2011) estimated that between 1974 and 1992 about 5-25% of Lake Erie watershed phosphorus inputs (U.S. side) was exported to Lake Erie. At the same time, crops account for more about 60% of phosphorus export from the watersheds (Baker and Richards, 2002). Han et al. (2012) estimate that for the U.S. side of the Lake Erie watershed about 25% of Net Anthropogenic Phosphorus Input was exported by the rivers Raisin, Maumee, Sandusky, Grand, Cuyahoga between the years 1974 and 2007. Another illuminating comparison is between the crop biomass and the algae biomass that is supported by P application. There were about 11,400 kt of corn, soy and wheat produced in the WLEB in 2012, and based on two estimates of algae concentrations (Boegman et al., 2008; and Kane et al., 2014), there may be up to 345 kt of algae in western Lake Erie during blooms, so algae production is about 0.6 to 3% of crop production (= grain, not total biomass). This means that a very small percentage of phosphorus lost from fields is enough to fuel a substantial part of large algal blooms. King et al. (2014a) calculated that P loss from tile drains in Ohio was typically around 1% of applied P in field experiments. Van Esbroeck et al. (2016) showed that total TP loss (0.37 kg/ha) from Ontario measurements was approximately evenly divided between tile drainage and surface runoff, so net measured P loss from applied P via both pathways was about 2%. Other field and weather conditions can result in higher losses, but total losses of less than 10% and often less than 5% of applied P are common, although some of this may come from legacy P rather than from P applied in the same year that it is lost.

3.5.2.d Shifts in Agricultural Practices

Reduced till and no-till agriculture, intended to reduce sediment and particulate P loss due to erosion, has 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 (short circuit) the elevated surface P to subsurface P transport pathways (tiles) (Smith et al., 2015). In combination with climate change, then, elevated surface P concentrations elevate the probability of increased P losses, especially in dissolved form (Kleinman et al., 2015). 4Rs and other conservation practices have the greatest potential here (Kleinman et al., 2015) to control the vertical distribution of phosphorus and its availability for transport.

As discussed previously, another agricultural trend has been that more land is more intensively tiled (Kleinman et al., 2015). Research by Smith et al. (2015) shows that the temporal response of tile drain DRP mirrors the quick response in surface waters and that tile drainage moves 25-80% of P losses from agricultural fields in the St. Joseph River watershed. Kane et al. (2014) showed that Maumee DRP inputs directly drive algae biomass growth in W Lake Erie, so the connection between tile drain SRP and Lake Erie algae growth may be quite direct. Adoption of 4R practices, especially right placement, can reduce available P to some extent, but additional conservation practices are needed (Kleinman et al., 2015).

Finally, emerging trends of greater concentration of animals into larger facilities can result in manure

needs of the individual farms and their neighboring farms. Unrecovered manure losses and excess fertilizer application near CAFOs and other large livestock aggregations can intensify local legacy P storage in soils and sediments (Long et al., 2017). In addition, livestock operations themselves are often concentrated in particular areas near meat processing and packing plants, off-site egg processing facilities, or commercial milk bottling plants and cheese factories to take advantage of lower shipping costs and specialized farm service providers.

4 Monitoring and Modeling Review

4.1 Monitoring

Several recent summaries of watershed and lake water quality monitoring in the Western Lake Erie Basin have been compiled, including a comprehensive table assembled by the GLWQA Annex 4 Objectives and Targets Task Team. Multiple results and recommendations related to monitoring are included in the 2015

attention to Detroit River inputs and additional monitoring of the Huron-Erie Corridor sources. Parallel and subsequent work by USGS and ECCC, building on their larger stream monitoring programs, as well as new research by the University of Michigan Water Center, has been responsive to that call. Organizations that have been active in maintaining, expanding, or assessing monitoring and data availability in this region include the Great Lakes Observing System (GLOS; see Lake Erie HABs portal and contributors: http://habs.glos.us/about/

Northeast-Midwest Institute, the Great Lakes Commission, USEPA, NOAA, drinking water utilities, ECCC, incial Water Quality Monitoring Network, Canadian conservation authorities, and multiple universities.

In this section, key monitoring programs are outlined for watershed and open water locations, along with a description of relevant remote sensing systems and products. Additionally, a few emerging, experimental, or time-limited monitoring and research programs are discussed. Accompanying these reviews, data gaps and limitations are mentioned and additional monitoring to fill these gaps is suggested. A section describing databases that store and disseminate this information is also included. A spreadsheet that outlines the temporal and spatial extent of monitoring programs, and the key parameters that are measured is included in the electronic appendices (Appendix X). Additionally a map showing key monitoring locations, programs, and frequencies is also presented (Figure 4-1).

4.1.1 Watershed Monitoring

Here key monitoring programs are described along with emerging datasets which will shed new insights in the Maumee River basin in the near future, along with gaps in watershed monitoring.

Key Monitoring Programs

In this section key watershed monitoring programs are outlined. These include national, state, provincial, and academic entities. Sampling locations are summarized in Figure 4-1, with an enlargement showing the lake monitoring stations in Figure 4-2.

National Center for Water Quality Research at Heidelberg University

Researchers at Heidelberg University have been involved in a variety of phosphorus load monitoring projects for over 40 years. Some projects have included: quantifying phosphorus runoff from crop lands, monitoring best management practices for crop lands, and determining the relative bioavailability of different forms of phosphorus entering the Great Lakes (Baker, 2011; Heidelberg, 2012).

They have also measured on a daily or sub-daily (autosampling at 3 times per day) timescale the loads of total phosphorus, dissolved reactive phosphorus, ammonia, and nitrate from major tributaries to Lake Erie since 1974 (Maumee, Sandusky and River Raisin watersheds). This represents one of the most comprehensive phosphorus loading data sets on the Great Lakes, or even in the entire U.S. Their data have shown that dissolved reactive phosphorus loads have been increasing from the Maumee River since the early 1990s, which is likely a factor in the increase in harmful algal blooms in the western basin of

Lake Erie (OEPA, 2010). Loading data and a summary of their research are available for download on their website:

https://www.heidelberg.edu/academics/research-and-centers/national-center-for-water-quality-research

U.S. Geological Survey, National Water Information System

USGS maintains a network of stream gage stations throughout the Great Lakes. At some of these they collect monthly base flow water grab samples, and approximately eight storm samples (up to 6 of these are analyzed; USGS, 2017). Nutrients and suspended sediments are among the parameters analyzed in these samples. USGS recently collaborated with ECCC on a study to jointly measure flow and loads of P and other constituents in a cross section of the Detroit River in 2014-2015 (no published results are available at this time).

U.S. Department of Agriculture, Agricultural Research Service

The Agricultural Research Service monitors several edge of field and tile drain sites throughout the Western Basin of Lake Erie. At these sites, auto samplers are utilized to composite 4 samples per day that are analyzed for several N and P species. Discharge from the field or tile drain and precipitation are also measured at the sites. With this information nutrient loads from the fields can be quantified.

These monitoring activities are split into two parts: a control field (maintaining the prevailing practice) and a field that implements a practice designed to reduce the effects of runoff pollution. This way the two can be compared and the benefits of the treatment practice can be quantified relative to the control. The other benefit of this approach is that the two sites are subject to the same weather conditions so it is more valid comparison (Williams et al., 2016).

The Agricultural Research Service also maintains a network of real time streaming monitoring stations in the St. Joseph River Watershed. These stations take measurements from the field scale up to the watershed scale. Some of the parameters include: meteorology, soil moisture, flow, and water quality parameters (USDA-ARS, 2017; Betanzo, 2015). It appears that nutrients are not regularly measured in this program.
The program website can be accessed here: http://amarillo.nserl.purdue.edu/ceap/index.php

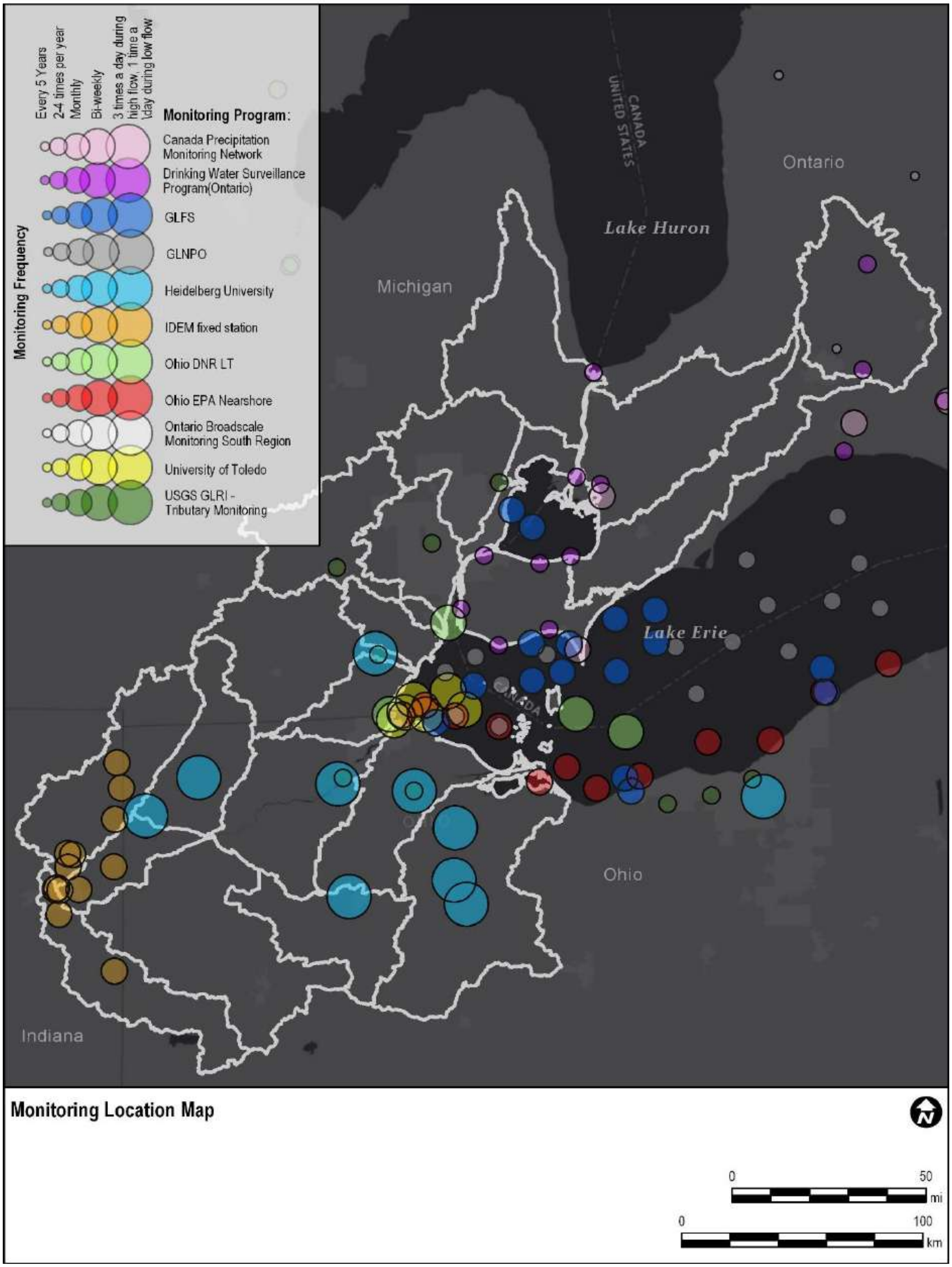

Figure 4-1. Key monitoring locations, programs, and frequencies (adapted from Grannemann, 2012). Supporting geodatabase files can be found in Electronic Supplement Folder ES-4.

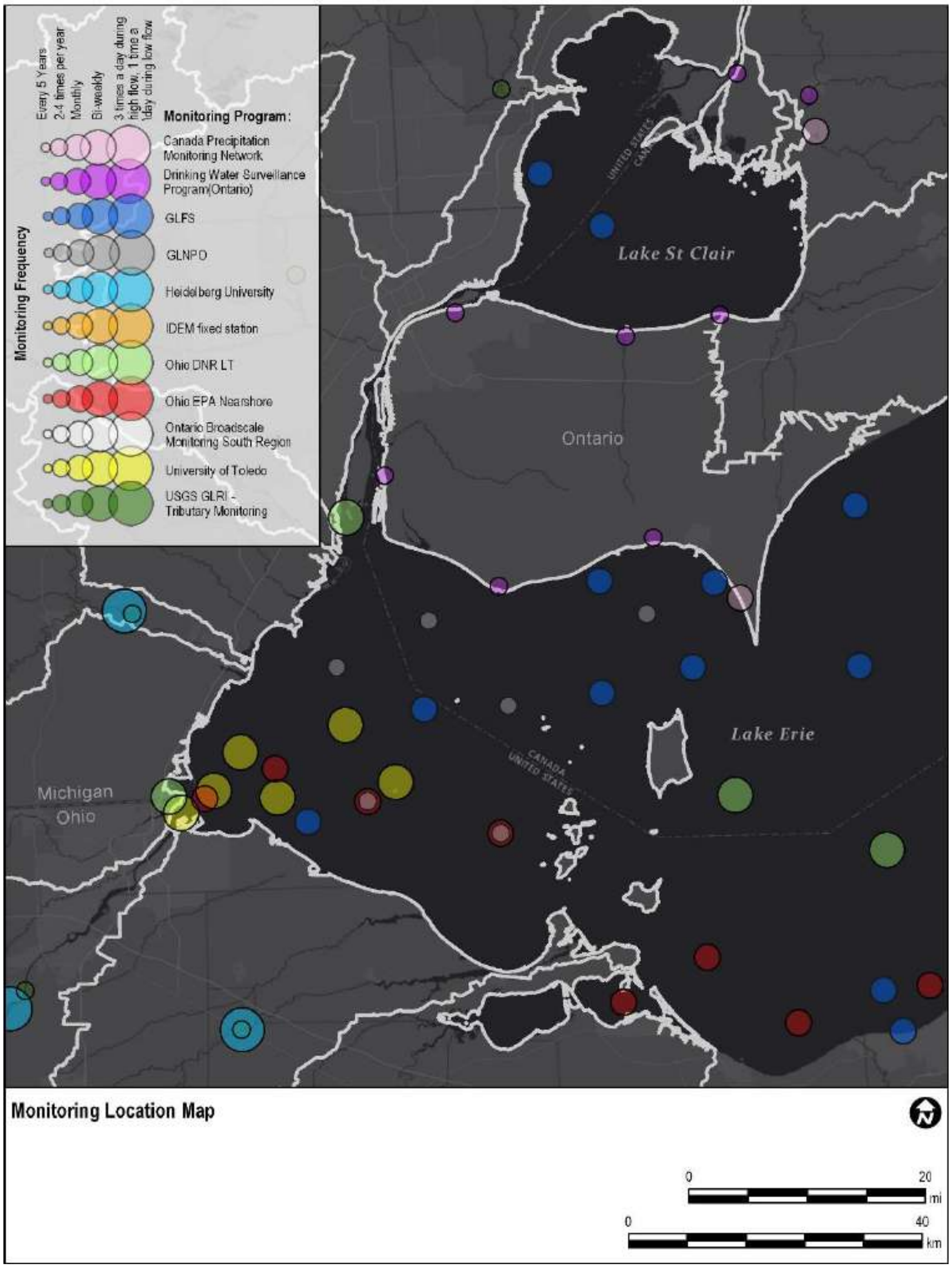

Figure 4-2. Enlarged map of western Lake Erie and Lake St. Clair to show in-lake monitoring stations.

Ohio EPA

Ohio EPA monitors the main stem of the Maumee River and several of its tributaries in 5 10+ year intervals as part of their *Statewide Biological and Water Quality Monitoring and Assessment* program (OPEA, 2017). Total and dissolved phosphorus are among the parameters measured (OEPA, 2012). A brief description of the monitoring at each tributary can be found here: http://www.epa.state.oh.us/dsw/tmdl/maumeeriver.aspx

Michigan Department of Environmental Quality

Michigan Department of Environmental Quality monitors the tributaries of the Huron-Erie Corridor on a 5 year rotating basis as part of *Michigan's Water Chemistry Monitoring Program.* Nutrients (including N and P species) are among the parameters measured (MDEQ, 2013). A summary of the state monitoring program can be found here:

http://www.michigan.gov/deq/0,4561,7-135-3313_3681_3686_3728-32361--,00.html

Province of Ontario - Ministry of the Environment and Climate Change (OMECC)

The Ontario Ministry of the Environment and Climate Change maintains a Provincial Water Quality Monitoring Network (PWQMN) for stream sampling in coordination with regional conservation authorities (e.g. Essex, http://erca.org/).

The PWQMN collects grab samples at stations throughout the province. Nutrients are among the parameters analyzed in this program (Ministry of the Environment and Climate Change, 2013). The Great Lakes Nearshore Monitoring program of the OMECC Environmental Monitoring and Reporting Branch (EMRB) undertakes multiple activities that are relevant to Lake Erie eutrophication. Among these are identifying sources of nutrients to the nearshore environment and tracking their fate and effects on aquatic life; and improving understanding of potential long term effects on the Great Lakes nearshore aquatic ecosystem resulting from climate change. MOECC programs also produce environmental compliance reports (point source discharge information), Great Lakes benthic invertebrate data, and sediment chemistry data for Great Lakes nearshore areas.

PWQMN data are available here:

https://www.ontario.ca/data/provincial-stream-water-quality-monitoring-network

A web map of the monitoring stations is here:

https://www.ontario.ca/environment-and-energy/map-provincial-stream-water-quality-monitoring-network

Data from all of the data monitoring programs in Ontario are here:

https://www.ontario.ca/search/data-catalogue?sort=asc

4.1.2 Emerging Datasets

Ohio EPA

Ohio EPA is beginning a new monitoring program. Their goal is to do intensive monthly grab and runoff event sampling in the Maumee River watershed to identify nutrient loading hotspots. This will help regulators to efficiently target the largest loads with watershed improvement programs (WTOL, 2017; OEPA, 2015). This sampling will fill a critical data gap in targeting management of land-based tributary loads. The plan for this sampling is available here:

http://epa.ohio.gov/Portals/35/documents/2015_Enhanced_WLEB_Trib_StudyPlan.pdf

Bowling Green State, Heidelberg, and Ohio State Universities

Kevin McCluney is leading a new project to examine the sources of phosphorus in the tributaries to Lake Erie with stable isotopes of phosphate. Heidelberg University and Ohio State University are also involved in the project. Blog post about this project: https://blogs.bgsu.edu/mccluneylab/2016/08/19/new-grant-for-studying-age-of-phosphorus-running-off-fields/

Paula Mouser and a group at Ohio State University are also involved in an organic phosphorus fingerprinting project. Some of the sources they are characterizing include urban and treated wastewater sources (Personal Communication, Michael Murray, NWF, May 2017).

Watershed Monitoring Data Gaps

Based on the monitoring program review, and the limitations of the current data sets, these watershed data gaps were identified:

1. Fertilizer use data (timing, amount, etc. for inorganic fertilizer and manure),
2. The condition of the soils (i.e., phosphorus content),
3. Small subwatersheds (HUC-8 or smaller) were not sampled consistently or at a high enough frequency and for sufficiently long duration to support management decisions (Betanzo, 2015),
4. Details of field and crop management practices (tile drainage, tillage practices, crop rotations, BMPs),
5. Climatological and hydrological information at higher resolution (flows, freeze/thaw, standing water, etc.).

These data are often collected, but not shared publicly, therefore values must be assumed in watershed models. The purpose of this data collection is to maximize crop yields, not to inform water quality managers. These data limitations could be overcome if these two objectives could be integrated.

Additionally if soil P test data could be linked with watershed models, and ultimately lake water quality models, and if watershed and lake monitoring were operationalized, real-time data collection and modeling could be used to inform P application rates and timing. This could potentially lead to an optimization of crop yields while still helping to meet water quality objectives.

In addition to not knowing the existing practices of the farms, the effectiveness of BMPs is often not known. 15 of the 1,890 active and historical water quality monitoring sites are located in small (50 square miles and smaller) They suggested that BMPs be implemented at a larger scale in these smaller watersheds, and that monitoring of both BMPs and the watershed be prioritized so the effectiveness of the BMPs can be quantified.

4.1.3 Open Water Monitoring

4.1.3.a Key Monitoring Programs

In this section key open water monitoring programs are outlined (Figure 4-2). These include national, state, provincial, and academic entities.

USEPA-GLNPO

The United States Environmental Protection Agency (USEPA) and their Great Lakes National Program Office (GLNPO) have a number of monitoring programs to assess the heath of the Great Lakes. These programs include the Great Lakes Integrated Atmospheric Deposition Network, Great Lakes Biology Monitoring Program, Great Lakes Fish Monitoring and Surveillance, Great Lakes Open Lakes Trend Monitoring Program, and Great Lakes Water Chemistry. Several parameters are routinely measured including: nutrient concentrations, water clarity, water temperature, dissolved oxygen levels. These are measured by the Water Chemistry Program in the spring and summer. Biological data, for example plankton, benthic organisms and chlorophyll a, are measured by the Biology Monitoring Program.

GLNPO monitors the phosphorus concentrations in Lake Erie. In the 1980s they observed a decrease in phosphorus concentrations in the lake due to controls put on point and nonpoint sources, but since the 1990s they have seen a steady increase in the phosphorus concentrations in the lake.

The program webpage: https://www.epa.gov/great-lakes-monitoring

The USEPA lab in Duluth (Mid-Continent Ecology Division) has collected continuous nearshore water quality data along shore-parallel transects using a towed instrument package (TRIAXUS 3D towed undulating vehicle) for several years in Lake Erie and other lakes. The USEPA coordinates the National Coastal Condition Assessment, which has included Lake Erie sampling stations in its program; reports are prepared approximately every five years, with the last one (report IV) released in 2012 (https://www.epa.gov/national-aquatic-resource-surveys/national-coastal-condition-reports). Illinois-Indiana Sea Grant and USEPA have collaborated on hypoxia monitoring in the central basin of Lake Erie in 2014 through 2017, including up to 25 monitoring stations (Collingsworth et al., 2017).

ECCC

Like the USEPA, Environment and Climate Change Canada (ECCC) also has a monitoring program, called

,

observe trends in the Great Lakes water quality, and to evaluate emerging issues. Several parameters are monitored at Lake Erie stations; a few that are relevant include: water temperature, water clarity, pH, nutrients, Chlorophyll a and other biological parameters. Approximately 55 stations are monitored on Lake Erie, with 10 of them being in the Western Basin. The monitoring is coordinated with the MOECC nearshore program.

The majority of the laboratory analyses are conducted by National Laboratory for Environmental Testing. The data are stored at the Canada Centre for Inland Waters in Burlington, Ontario, in the Storage and Retrieval (STAR) Database, and can be retrieved upon request.

The program webpage: http://www.ec.gc.ca/scitech/default.asp?lang=en&n=3F61CB56-1

NOAA

The National Oceanic and Atmospheric Administration (NOAA) and the Cooperative Institute for Limnology and Ecosystems Research (CILER), now known as the Cooperative Institute for Great Lakes Research (CIGLR), have developed monitoring and forecasting programs for harmful algal blooms in Lake Erie. NOAA has conducted weekly monitoring during the bloom season for microcystin concentrations (a toxin produced by cyanobacteria) and other parameters at four to eight offshore and nearshore stations to quantify community dynamics of algal blooms in western Lake Erie. Continuous monitoring instruments have been added to four of the offshore stations in recent years, and an instrument that is capable of making in situ toxin measurements was field tested by NOAA in Lake Erie in 2016. NOAA GLERL and CIGLR researchers are currently in Year 1 of a five-year research project to update the existing Lake Erie Operational Forecasting System (LEOFS) to include hypoxia simulation and nutrient-driven productivity.

The NOAA HABs data page is here: https://www.glerl.noaa.gov/res/HABs_and_Hypoxia/habsMon.html. The site also displays data for Lake St. Clair from Environment Canada and for Saginaw Bay in Lake Huron.

Ohio EPA

I . This was funded by the Great Lakes Restoration Initiative (GLRI). This project conducted monitoring over a 3-year period to evaluate environmental conditions of nearshore areas. This is now a permanent program called Monitoring of Lake Erie and the Maumee River Estuary measured at including: nutrients (P and N), chlorophyll, microcystin, and others. Samples are collected at 10 stations in the Western Basin and the Maumee River Estuary.

The 2015 monitoring plan is here:
http://www.epa.ohio.gov/Portals/35/lakeerie/2015_Erie_Study_Plan.pdf

Ohio EPA also funded installation in 2015 of continuous monitoring of source water quality at drinking water intakes in Lake Erie from Toledo to the Cleveland area, which supplemented existing monitoring. These data are available in near real-time via the GLOS HABs Data Portal for Lake Erie, along with data from several stations maintained by researchers:

http://habs.glos.us/map/

Michigan Department of Environmental Quality

The state of Michigan Department of Environmental Quality has monitored the water quality of the Detroit River since 1969. The monitoring is conducted to track water quality, loads, and trends over time (MDEQ, 2006). nutrients (P and N) loads from the Detroit River to Lake Erie for several years (Figure 4-3).

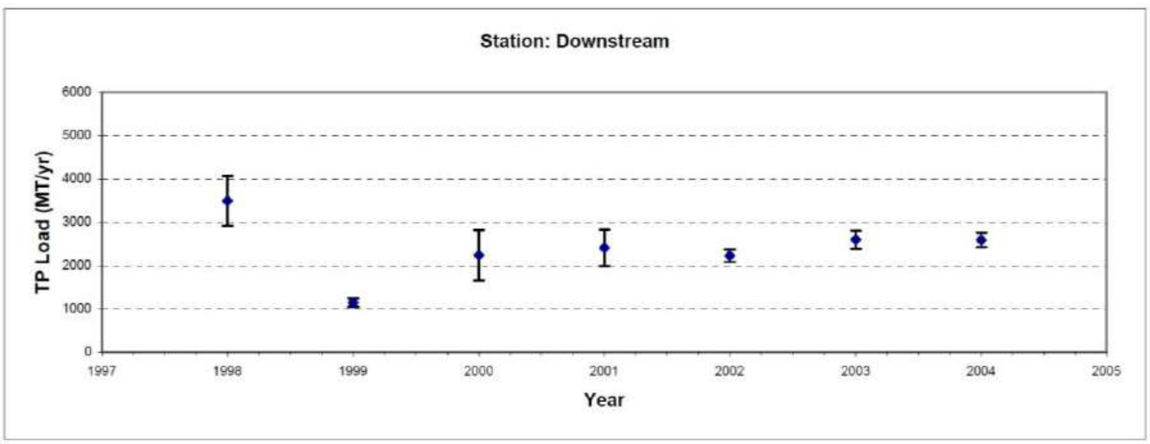

Figure 4-3. Phosphorus loads from the Detroit River to Lake Erie (figure from GLEC and LTI, 2006).

Lake Erie Center, University of Toledo

The University of Toledo has 8 nearshore-to-offshore transects sampled biweekly May September with fixed sample stations at 2, 5, 10, and 20+ m depth to assess nutrient pools of P, N, and C in the dominant biological (i.e., bacteria, phytoplankton, zooplankton, benthic algae, dreissenid mussels, dominant infaunal and epifaunal benthos) and physical compartments (i.e., water column, sediments) of Lake Erie.

Website: http://www.utoledo.edu/nsm/lec/

4.1.3.b Open Water Data Gaps

In the open waters of Lake Erie, reaction rates and fluxes are rarely measured. Examples of rates that could be measured to help make water quality models more accurate include: water column oxygen depletion, P mineralization, carbon oxidation, carbon hydrolysis, algal respiration. There are literature values for these rates that modelers use as guidance, but there are almost never recent site specific values to use. Examples of such fluxes would be sediment P deposition or P release rates. These sediment rates have been estimated by laboratory experiments, however more information is needed to accurately quantify the sediment P impact (Matisoff et al., 2016).

4.1.4 Remote Sensing

Here key remote sensing programs that cover Lake Erie and its watershed are described, emerging research is discussed, and remote sensing data gaps are defined.

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 ESA and NASA satellites, wind forecasts and current models from NOAA, and phosphorus loading and discharge data from Heidelberg University and the United States Geological Survey. Twice weekly, as cloud cover permits, it 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 (Figure 4-4).

Four main satellite instruments have been utilized for HAB monitoring and forecasting in the Western Basin of Lake Erie (Stumpf, 2014). These include:

1. MERIS launched in 2002 and failed in April 2012, operated by ESA
2. MODIS instrument on a two-satellite series launched in 1999 and 2002; filled in for MERIS after it failed in 2012; operated by NASA; imagery available from NOAA Great Lakes CoastWatch
3. Landsat 7/8 pair - Operational Land Imager (OLI) sensor has good resolution, but a poor return time of 8 days; operated by NASA and USGS; program began in 1972
4. OLCI on the Sentinel-3 satellites this is the replacement for MERIS, operated by ESA. The first satellite in the series was launched in February 2016. Two more instruments will be launched in 2017 and 2020 (ESA, 2017).

These satellites have a 1-2 day return period (except when otherwise noted). Parameters measured by these instruments include surface temperature, as well as sediment and chlorophyll concentrations, which can be useful for sediment plume and bloom tracking.

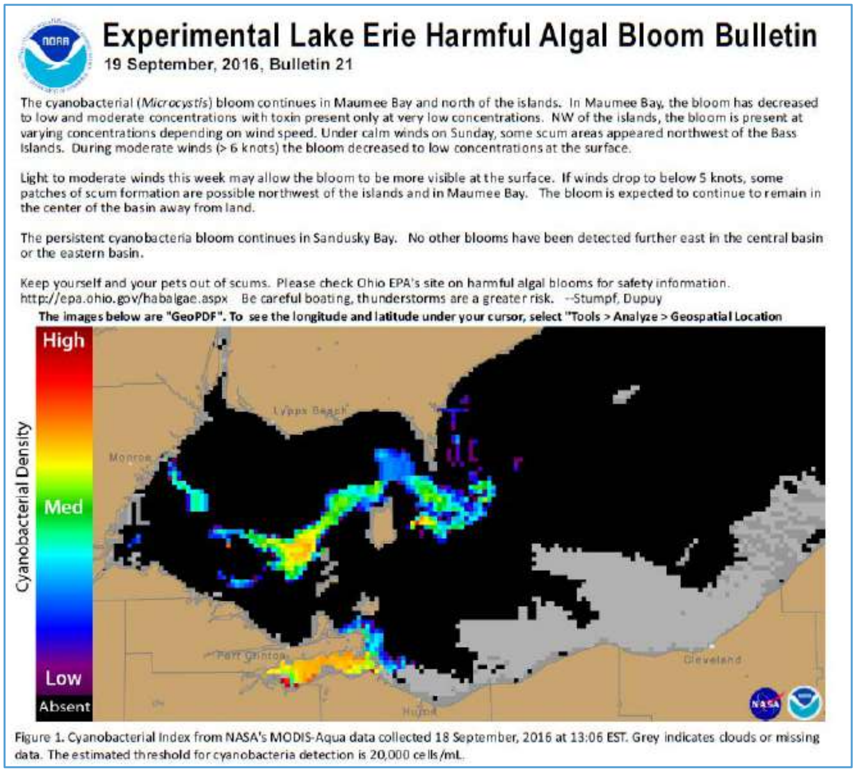

Figure 4-4. An example of part of **NOAA's** twice-weekly Lake Erie HAB Bulletin (from https://coastalscience.noaa.gov/).

4.1.4.a Emerging Research

In the spring of 2014, a series of two workshops were held to plan for the future of remote sensing in the Great Lakes (Shuchman et al., 2014). One of the main goal of the workshop was to advise NASA on the requirements of future remote sensing systems to address Great lakes issues. A few of the recommendations included:

1. Explore using unmanned aerial systems (UASs) and autonomous underwater vehicles (AUVs) to enhance data collection.
2. Develop data sharing and assets among regional researchers.
3. Provide a comprehensive list of where Great Lakes remote sensing data reside.

Kevin Czajkowski and his research group at the University of Toledo are using remote sensing to characterize field practices, and to map tile drain locations.

4.1.4.b Remote Sensing Data Gaps

These satellite instruments are limited to measurements on the surface. For example, if a harmful algal bloom is mixed into the water column at the time the satellite takes measurements, the true magnitude (total biomass) of the bloom would not be fully detected. 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 fitted with instruments that NASA developed for Mars missions. These are utilized for remote sensing of HABs on Lake Erie (Zona, 2014). These instruments 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. These instruments can produce a 3D representation of harmful algal blooms in the upper water column with transects across the bloom (NOAA, 2017; Churnside, 2015)

4.1.5 Key Databases

In addition to the monitoring programs described in this report, several of the datasets generated are stored and disseminated from a few key databases. Some of these are described here.

Great Lakes Environmental Database (GLENDA) from USEPA

Originally developed for the Lake Michigan Mass Balance study GLENDA provides data entry, storage, access, and analysis capabilities to Great Lakes data users (US EPA, 2016). Water quality data along with several other data sets including fish tissue and sediment chemistry information are stored here.

The website for this program is here: https://www.epa.gov/great-lakes-legacy-act/great-lakes-environmental-database-glenda

Great Lakes Observing System (GLOS)

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. Upcoming enhancements will add access to grab sample data, satellite imagery, hydrodynamic model results, and meteorological observations. HABs data page: http://habs.glos.us/map/

In addition to the HABs page, the Maumee River tracker webpage is under development by GLOS. The webpage began to be developed because the extent and severity of algal blooms in the Western Lake Erie Basin (WLEB) have been shown to be correlated with the amount of nutrients (nutrient load) entering the WLEB from the Maumee River Watershed through the Maumee River. Measurements of the concentration of nutrients in the Maumee River are collected by Heidelberg University and combined

tracking tool sums up nutrient loads day-to-
WLEB through the Maumee River, and charts the cumulative loads in the context of previous (2000-

chemistry on a regular schedule. During the critical spring and summer seasons of 2015, Heidelberg plans to publish analytical results and calculated daily loads on a weekly basis. The intensive schedule, along with development and implementation of this web page in partnership with the Great Lakes Observing System, is supported by the Great Lakes Restoration Initiative and the National Oceanic and Atmospheric

The GLOS website is here: https://www.glos.us/

Water Quality Portal (WQP)

In addition to the Great Lakes databases, national databases also hold information from the Great Lakes Basin. One place where data can be queried from three of these databases is the Water Quality Portal (WQP) maintained by the National Water Quality Monitoring Council (NWQMC). This website is linked to: USGS National Water Information System (NWIS) the EPA STOrage and RETrieval (STORET) Data
- Agricultural Research Database
System (STEWARDS). These databases hold water quality, biological, weather, and other data types.

The website for this program is here: https://www.waterqualitydata.us/

Canadian Open Data Portal

This data portal has many national Canadian datasets including water quality data that are collected in the Great Lakes. In addition several other national datasets are included in the database including biological and sediment data.

The website for this program is here: http://open.canada.ca/en/open-data

4.1.6 Linking Water Quality Monitoring with Fertilizer and Manure Application Information

Within the U.S. part of the western Lake Erie basin, there are multiple stations where concentrations of total phosphorus and specific phosphorus species are measured (Figure 4-5). These data can provide clues to the phosphorus-related questions raised by the distribution of phosphorus application in the watershed via manure and fertilizer, as indicated in Figures 3-15 and 3-23.

As an example, we reviewed USGS and Heidelberg University data from twenty stations in Ohio and Michigan for flow and phosphorus concentration (ortho-phosphorus, soluble reactive phosphorus, and total phosphorus). Only data for years 2011 through 2016 were selected, and multiple measurements during the same day were averaged together to create a daily mean. A watershed was delineated to each of the stations; examples are shown in Figure 4-5 (orange dots are sampling stations).

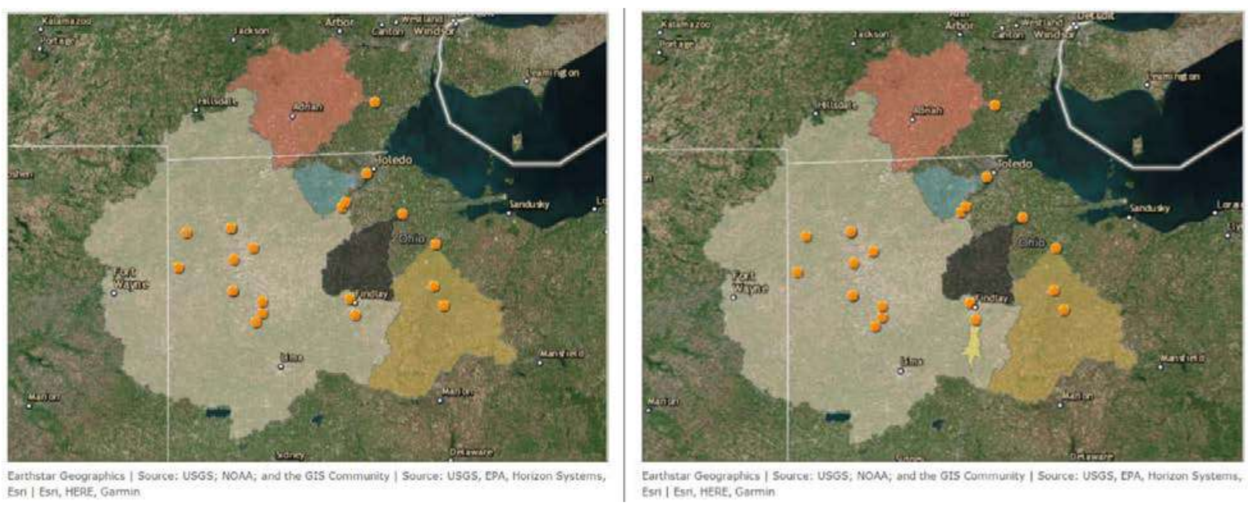

Figure 4-5 (Left) Drainage areas in the WLEB that are included within at least one of the stations (orange dots) from which data were analyzed. (Right) The advantage of having gages located within the watershed is that they can allow finer analysis within the larger HUC. Added to this figure (in yellow, center bottom) is the small drainage area for the station above Findlay, Ohio for Eagle Creek.

Each station was graphically analyzed four ways using boxplots, percent exceedances (trimmed to the 5th through 95th percentile for graphical purposes), flow regressed against concentration, and temporal

monitoring data. These analyses will increase in utility as the statistical handling of the data is sharpened.

4.1.6.a Findings

The spatial scope of this exercise was limited; only select figures to illustrate the approach and initial results are included here. These types of analyses should be regarded as a framework for designing future data explorations and additionally as guidance for design of future monitoring efforts.

Simple boxplots were first utilized to estimate a visual comparison of the range of values seen at each station (Figure 4-6). One interesting result was to find that the Maumee River near Waterville was consistently near the top of the list for both SRP and TP concentrations, while the Maumee River at Waterville was generally much closer to the bottom. These two stations are very near one another (see Figure 4-7), both stations are near the outlet of the Maumee River watershed, shown in light brown). The difference in the concentration boxplots is likely due to the vast difference in sample numbers for Maumee near Waterville (N = 102) and Maumee at Waterville (N = 6,265). Using the analysis protocol employed here, Maumee near Waterville never had more than 6 samples taken in any given month for any given constituent. In comparison, Maumee at Waterville regularly had 20 to 30 samples taken per month.

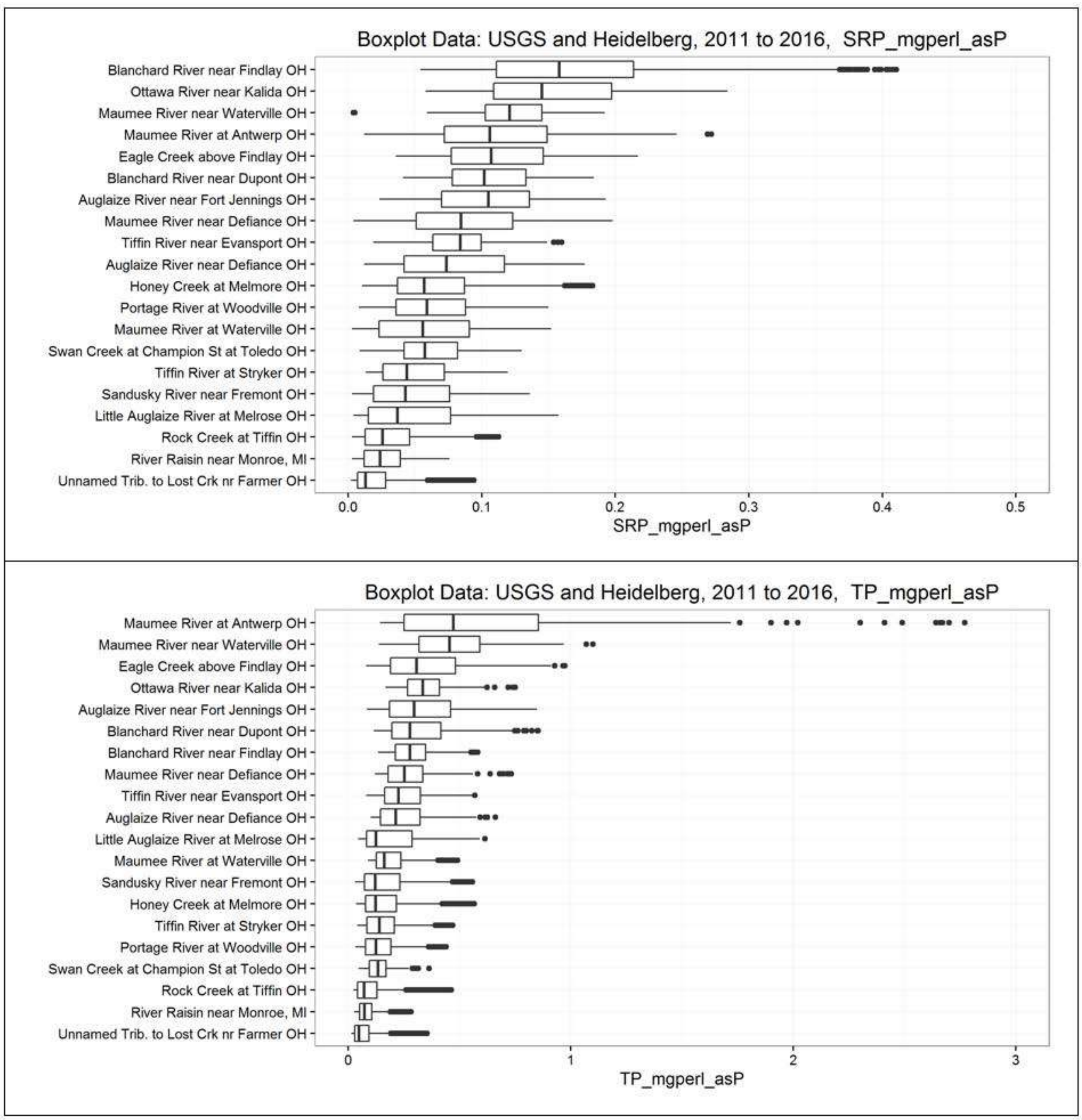

Figure 4-6. (Top) Boxplots of all analyzed SRP concentration data, ordered by overall value. (Bottom) Boxplots of all analyzed TP concentration data, ordered by overall value. Units are mg/L as P.

With this comparison of sample sizes kept in mind for context, it is important to note that only 9 of the stations reviewed have more than 500 samples each of TP and SRP concentrations. One of these nine is the station on the Blanchard River near Findlay; this station is the top ranked station for SRP concentrations and is in the top ten for TP concentrations. Its relative ranking at or near the top of the list is more likely a reflection of real conditions, rather than an artifact of data collection, but it also likely is not an indication of unusually high nonpoint P loading.

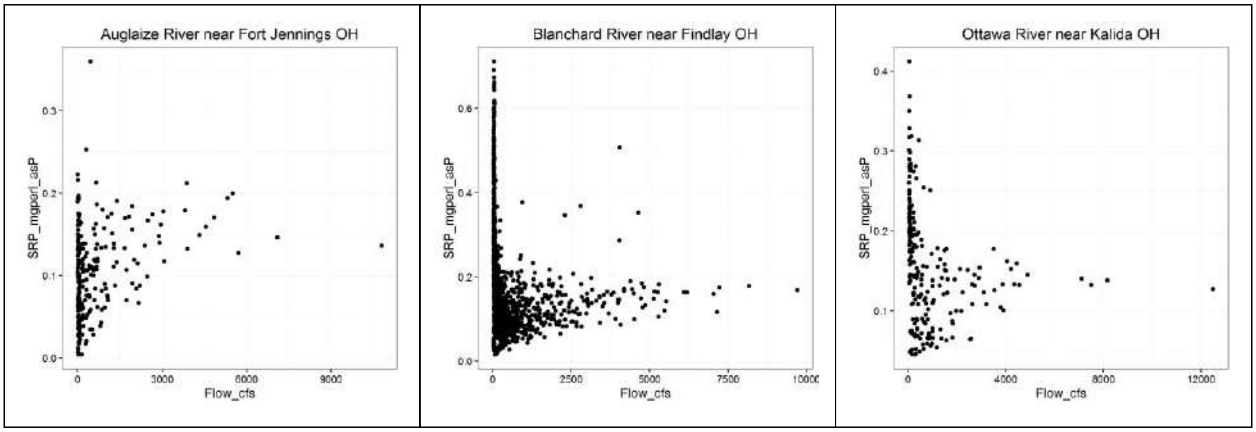

Figure 4-7. Flow (cubic feet per second [cfs]) plotted on the x-axis and compared to SRP (mg/L) plotted on the y-axis for three different stations, Auglaize River near Fort Jennings, Blanchard River near Findlay, and Ottawa River near Kalida, all in the state of Ohio. The period of record is 2011-2016.

One sampling tactic that might provide useful information in the face of these challenges is to position gages in areas with similar flow distributions. The three stations shown in Figure 4-7 all show maximum flows in the roughly 9,000 to 12,000 cfs range. Comparing the SRP concentrations in this manner allows for a more meaningful evaluation. Here, we can see that the Ottawa River and Blanchard River both

location, generally remain in the 0.1 to 0.2 mg/L range as the flows increase. Given the boxplot rankings in Figure 4-6, a comparison with Figure 4-7 shows that Ottawa near Kalida likely ranks higher than Auglaize near Fort Jennings due to concentrations measured at low flow and probably influenced by an upstream point source that is less diluted at low flow, a factor that should be considered when using monitoring data to determine future actions.

4.1.6.b Using Water Quality Time-Series Data to Help Answer the Legacy Phosphorus Question

The maps in Figures 3-15 and 3-23 show watersheds with relatively high application rates of fertilizer phosphorus and manure phosphorus compared to those locations with lower rates on an area-weighted basis. Building from what has been demonstrated here, a more statistically rigorous analysis could be used to identify areas where application rates have decreased, but in-stream concentrations remain high. This analysis would need to consider the differences in phosphorus concentrations which were due to point sources and measured changes in flow regimes. The monitoring data could be used to compute a comparable metric for all the available stations and mapping could be completed to compare and contrast all the source watersheds (example as in Figure 4-5) of these stations against the loading rates from known or estimated sources. Once complete, the data could begin to be used as a way to target smaller level HUCs for BMP implementation.

As an example, Figure 3-15 shows the application rates of fertilizer phosphorus (kg/ha) being generally greater in the Sandusky River watershed than in the Portage. This is also generally true in Figure 3-23, which shows manure application normalized by area. Figure 4-6 shows that, while the medians for TP are generally comparable between the Portage and Sandusky, Portage has a notably higher median concentration for SRP than the station along the Sandusky. Both of these stations are collecting data at a nearly daily time-step and have very similar total data counts for the period of analysis, so the difference is unlikely to be an artifact of the data collection methods. Both stations are downstream from relatively large cities (Bowling Green, Ohio for the Portage and Tiffin, Ohio for the Sandusky) and are therefore likely influenced by wastewater discharges. Once the discharge loading from the wastewater plants was compiled (and subtracted), a comparison of residual results from these two locations could provide interesting information regarding the likelihood of legacy phosphorus loading (regardless of whether the original source was point or nonpoint source pollution).

4.1.6.c Water Quality: Canadian Focus

Because of fewer stations, less effort was exerted on completing the above analysis for the Canadian side of the WLEB. However, the example above stands as proof of the conceptual approach and the following work provides an overview of some of the Canadian data available.

Surveillance Web Mapping Application using years 2009 to 2015. Not all stations had all phosphorus constituents considered, and the annual number of samples from any one station for any given constituent ranged from 1 to 171. No station had more than 264 samples for any one constituent. The two most common sample types were Total Phosphorus, and Soluble Reactive Phosphorus. Stations with fewer than 50 total samples were eliminated, as was one station that was positioned in the Detroit River on Bois Blanc Island (part of joint USGS-ECCC gaging and load estimation experiments on the river in 2014-2015).

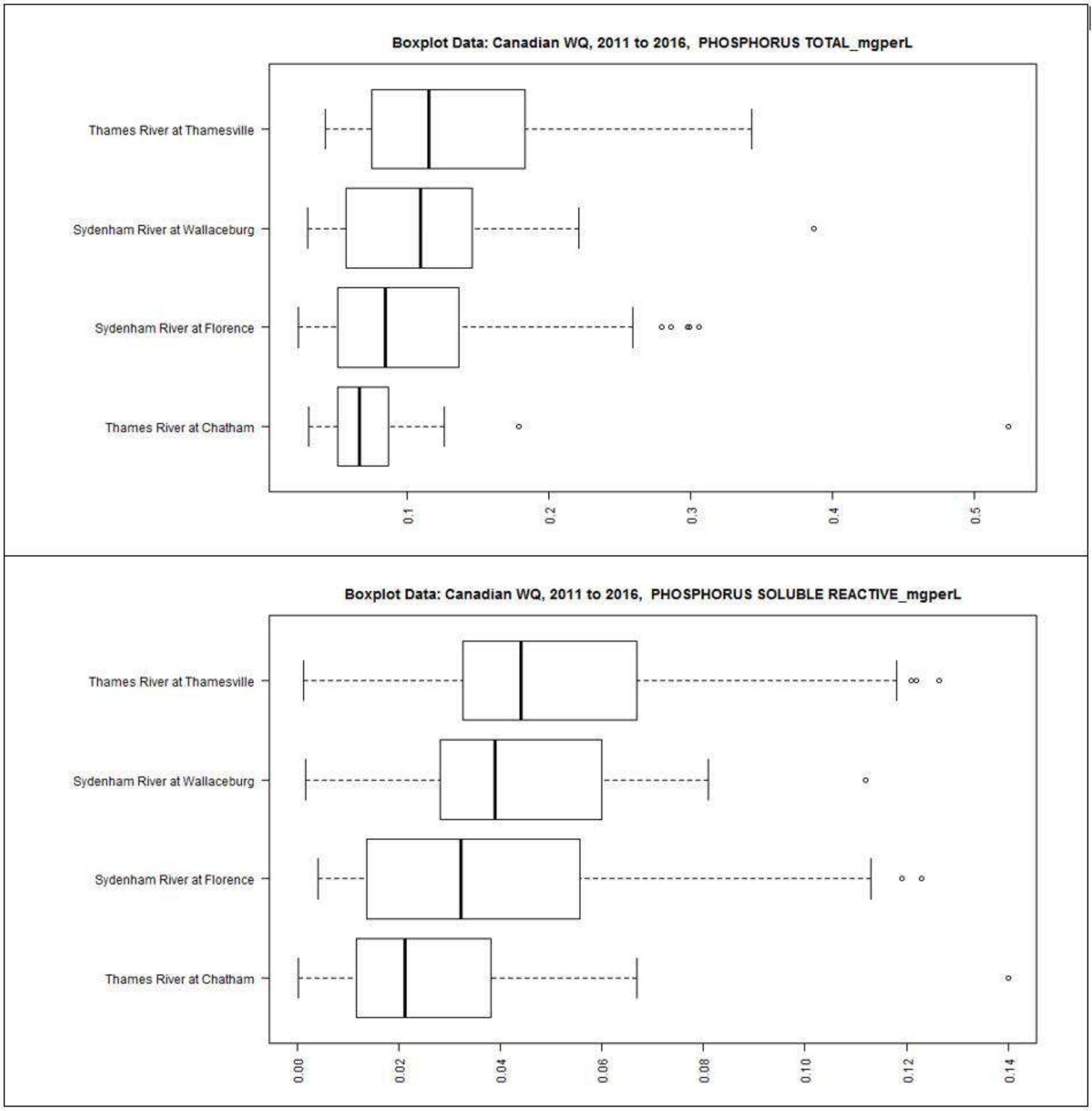

Figure 4-8. Boxplots of phosphorus-related water constituents from four Canadian water quality stations. Top panel is TP and bottom panel is DRP; units are mg/L.

In general, the concentration ranges displayed in Figure 4-8 are much lower than those seen in the previous boxplots (Figure 4-6). While there is a clear ranking in the medians at this scale, with Thames River at Thamesville generally coming out on top, these stations are much more similar than the group of U.S. stations which were reviewed. With the addition of new stations, or expanded sampling at existing stations, this analysis could be completed in a manner very similar to the one suggested for the United States side of the WLEB. Researchers would need to identify datasets describing the point source discharges, quantify urban nonpoint loads (especially in the Thames), and improve their understanding of fertilizer application across the tertiary watersheds in an area-weighted manner.

4.1.7 Recommendations for Linking Water Quality Monitoring to Management

Given data reviewed here, a few suggestions can be formulated for future sampling programs in the WLEB in the U.S. and Canada.

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  concentration. Strategically placed stations at the state boundaries could assist Indiana, Michigan, and Ohio in determining their relative contributions to HUC-8 level loads, and stations placed near the urban/rural boundaries of Fort Wayne, Indiana could provide useful information on appropriate targeting.
- Short term monitoring of small watersheds in the Upper Thames watershed should be undertaken to identify areas with the highest nonpoint P loading, and concentration data for small watersheds in the Leamington area should be combined with flow data to calculate loads.
- Stations that collect phosphorus data will be more useful if they a) collect concurrent flow data and b) sample at a frequency greater than once per week. 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.
- The analyses demonstrated here could be repeated with more statistical rigor and include additional stations throughout the WLEB. As greater effort is utilized to parse out the differences due to point sources and flow regimes, the data could begin to be used as a way to target smaller level HUCs for BMP implementation, and as a way to identify possible areas of concentrated legacy phosphorus buildup.

4.1.8 Summary

In this section key watershed, open water, and remote sensing monitoring programs were outlined. Additionally, a few emerging watershed monitoring and remote sensing research programs have been discussed, and monitoring data have been compared with fertilizer and manure application data for a subset of the watersheds. The watershed programs described above will help to identify areas of elevated phosphorus loading and the remote sensing, paired with lake monitoring, will continue to document the extent, composition, and characteristics of the HABs. Accompanying these reviews, data gaps and limitations were mentioned and additional monitoring to fill these gaps was suggested. Filling these monitoring gaps would help water quality modelers to better predict and understand nutrient loading and HABs. A description of databases that store and disseminate this information was also included.

4.2 Modeling

Here we review the current state of watershed modeling, documenting the processes and requirements for various watershed models and associated research projects in the Western Lake Erie Basin. This section of the report outlines the major watershed modeling codes that are most commonly used, and highlights the relevant modeling studies that have applied each model framework. In addition to the review of watershed model capabilities and current projects, a review of relevant open lake models is included, where inputs from the Western Lake Erie Basin are used to drive lake ecological processes. Finally, mass balance models are considered as an additional alternative approach to simulating nutrient processes and developing budgets for this system.

Models reviewed:

- Soil and Water Assessment Model (SWAT)
- 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

Table 4-1 provides a summary of the watershed models that were reviewed for this effort, including the hydrologic, phosphorus, and fertilizer or manure application capabilities as well as overall strengths and weaknesses. The capacity of each model for uncertainty analysis and sensitivity testing were not rigorously assessed, but both are important considerations in model selection and intercomparison. 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.

Table 4-1. Summary of watershed models.

Model Name	Hydrologic Capabilities	Phosphorus Capabilities	Fertilizer/Manure Capabilities	Strengths	Weaknesses
SWAT	Surface runoff, return flow, percolation, evapo-transpiration, ground water 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, ground water 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, 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.	Simpler to use than HSPF, while maintaining a lot of the same functionality.	The same limitations as HSPF apply. Additionally, 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, evapotransipiration, overland and channel flow, unsaturated zone, saturated zone, snowmelt, exchange between aquifer and rivers, snow, advection and dispersion. Tile drainage capabilities. Multi-dimensional	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.	Note widely used. Complex, difficult to parameterize with site specific data. Requires expensive licenses.
CANWET	Streamflow, surface runoff, subsurface runoff, evapotranspiration. 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.	Note widely used. 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

4.2.1 Watershed Models

Soil and Water Assessment Model (SWAT)

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-step. It should be noted that while the computations are typically performed at a daily time-step, many application 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 non-proprietary, public domain model with an open source code that can be accessed and downloaded by any individual at the following web site: http://swatmodel.tamu.edu/. Due to the open source nature of the code, it is possible for researchers to modify the algorithms, or add additional processes for custom purposes. The discussion of relevant projects utilizing SWAT will focus on the originally released source code, unless otherwise noted.

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, 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 4-9a shows the conceptual diagram of the nitrogen processes in SWAT, while Figure 4-9b shows the phosphorus processes. Limitations of SWAT and other models include their inability to distinguish legacy from recent P, so they are calibrated as if all P is current. This is really a problem with initialization as well, given that data to constrain starting P in soil are generally not available at most scales. Another similar constraint is the ability to incorporate the extent and locations of existing BMPs so that simulations are typically compared to a non-zero BMP baseline that is not explicitly recognized.

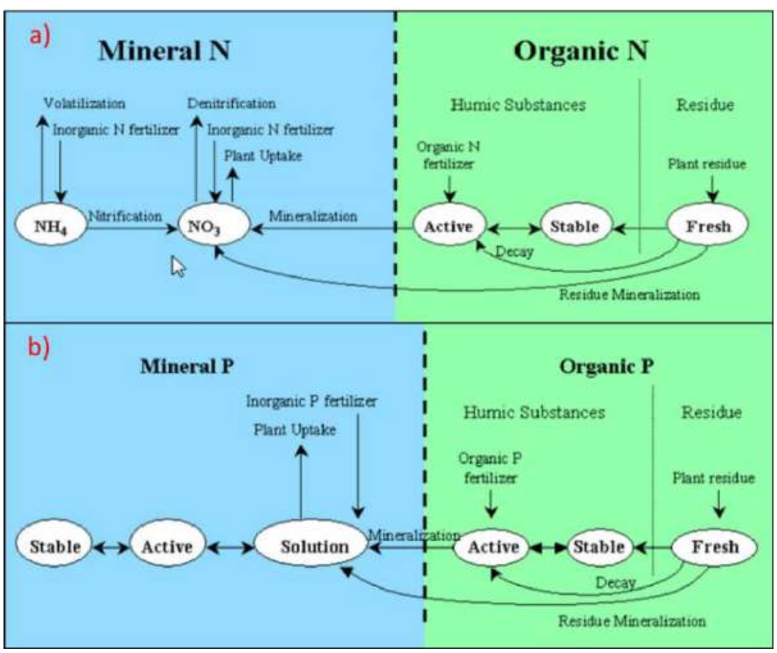

Figure 4-9. Conceptualized nitrogen (a) and phosphorus (b) processes in SWAT (Neitsch et al., 2011). *Permission for use of image will be requested prior to public release.*

Scavia et al. (2017) applied multiple watershed models to the Western Lake Erie system, including five unique SWAT models developed separately for the Maumee River basin. The goal of this project was to use the models to estimate the land management practices required to reduce total phosphorus and dissolved reactive phosphorus by 40% from the Maumee basin. The project simulated 11 different land management scenarios and ran each through the individual SWAT models. These scenarios included: No Point Source Discharges, Cropland conversion to grassland, In-field practices at 25% random adoption, Nutrient management at 25% random adoption, Nutrient management at 100% adoption, Commonly recommended practices at 100% random adoption, Continuous no-tillage and subsurface placement of P fertilizer at 50% random adoption, Series of practices at 50% targeted adoption, Series of practices at 50% random adoption, Diversified rotation at 50% random adoption, and Wetlands and buffer strips at 25% targeted adoption. The key findings of this work suggest that to achieve the targeted load reductions, combinations of the 11 different practices would be required, as well as widespread adoption of them. The report also notes that targeted land management practices were more effective than random placement. This project included five of the most current SWAT models applied to the Western Lake Erie Basin, and the report and associated manuscripts for each model detail their development. By using the multiple model approach, the findings are considered more reliable as independent decisions on calibration, validation, resolution, and structure were made by each group. Bosch et al. (2013) also found similar results using a separate SWAT model of the Huron, Raisin, Maumee, Sandusky, Cuyahoga, and Grand watersheds. The authors also concluded that subwatersheds with high DRP and TP yields were not uniformly distributed within the larger watersheds, and therefore targeted management practices would be required to reduce loading. Additionally, collaborators from Ohio State University, led by Jay Martin and Margaret Kalcic, are currently working on a project to sustain and maintain the multiple model framework that was developed in Scavia et al. (2017).

One of the SWAT models used in the Scavia et al. (2017) project is also being used to assess the 4R nutrient stewardship and certification programs. The model is being used to estimate the benefits in turbidity and HABs in Lake Erie under of 4R Nutrient Stewardship practices in agricultural lands in the WLEB. This study is being led by USDA Agricultural Research Service, and more information is available at http://4rcertified.org/research/

The University of Michigan Water Center (UMWC) has started a research project on nutrient load assessment from the Huron-Erie corridor in 2016 titled,
for Detroit River Nutrient Loads to La SWAT 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. The researchers are using SWAT to simulate the impact of land management practices in reducing nutrient loads to the system. The UMWC project also includes an ELCOM-CAEDYM model for Lake St. Clair. A SWAT model is also being developed for Eagle Creek sub-basin, which is a targeted subwatershed in the Maumee Basin (Merriman, 2015). This project will use the model to assess the impact of management practices that are to be implemented in the sub-basin, and funded by the GLRI.

SWATDRAIN/DRAINMOD

SWAT has also been integrated with a subsurface soil drainage model named DRAINMOD. DRAINMOD is a surface and subsurface flow model that is capable of simulating Infiltration, evapotranspiration, surface runoff, drainage/subirrigation, soil water distribution in the vadose zone, and water table fluctuations. It can also simulate fertilizer and manure applications, as well as tillage and management practices. The combination of these models, term SWATDRAIN, has been used to simulate hydrology in subsurface tiles (Golmohammadi et al., 2016). SWATDRAIN has been applied in a small tile drained watershed in southern Ontario to simulate hydrology and sediment, however has not yet been applied to simulate nutrient loading. The official release of the current DRAINMOD model contains a nitrogen submodel, but does not contain phosphorus calculations. However, Morrison et al. (2013) used DRAINMOD to simulate phosphorus fate and transport in a tile-drained system.

Agricultural Policy/Environmental eXtender Model (APEX)

APEX is a state-of-the-science watershed model that is the most spatially resolved of the commonly used models. APEX can model hydrology, sediment, nutrients and pesticide loading from watersheds with highly variable land use and land cover. It also incorporates transport via groundwater and reservoirs. The spatial resolution of APEX is completely user-defined, where land units can be divided to as small as field scale units. This allows the modeler to resolve the domain as needed, based on the availability and differences in land use/land cover, agricultural practice, soil properties, and meteorological data. This level of spatial resolution allows for detailed simulation of farming practices, including crop rotation, fertilizer use, irrigation, drainage, grazing patterns, and plant competition.
APEX requires a significant amount of user inputs to describe the detailed agricultural practices. The amount and type of fertilizer or manure is specified for nitrogen, phosphorus, and potassium, as well as . The user must also define a schedule for each farming operation used in each unit of the model domain. The general model inputs and structure are shown in Figure 4-10. An APEX model can be coupled or nested within a SWAT model. One approach to this has been described by Saleh and Gallego (2007) as a SWAPP program application.

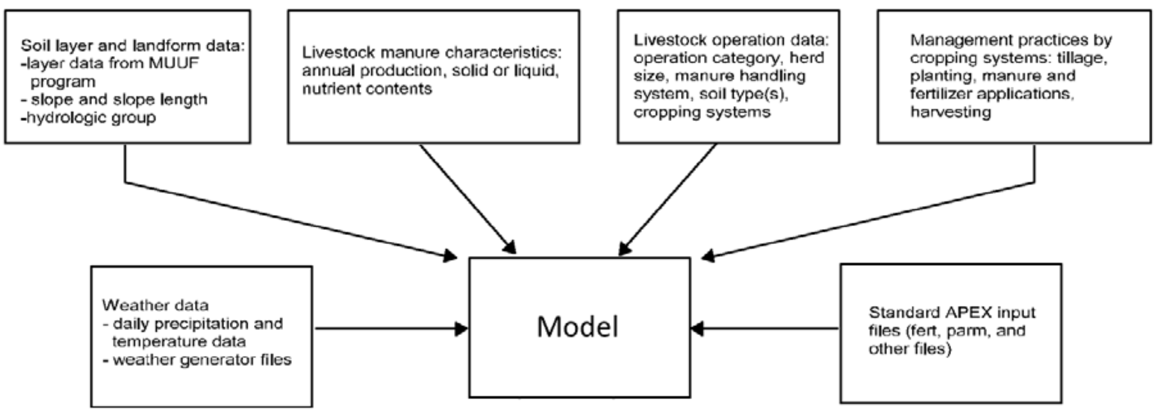

Figure 4-10. Example input structure for APEX (adapted from Gassman et al., 2010)

A large scale APEX model was developed for the entire US side of the Great Lakes drainage basin by the NRCS and USDA-ARS (USDA-NRCS, 2011). The model applied farm scale observed data and quantified the effects of land management practices, based on survey data from 2003-2006. For the Lake Erie Basin, the study found phosphorus runoff from cultivated cropland in the basin contributed 61% of the entire phosphorus load to the lake. The analysis also estimated that total phosphorus loading to the lake would increase by 32% if the existing BMPS (in 2006) in the watershed were not in place.

The Great Lakes basin APEX model was later refined for the Western Lake Erie Basin using updated agricultural survey data from 2012. (USDA-NRCS, 2016). Input data such as soil conditions and meteorology were also refined for the WLEB version of the model. The study found that annual phosphorus fertilization rates decreased from 21.5 to 18.7 pounds per acre from 2003-06 to 2012. Additionally, application methods that reduce the risk of phosphorus runoff increased from 45 to 60% of land, and edge-of-field trapping methods increased from 18% to 31% of land. The analysis also estimated that total phosphorus losses from the land were reduced 75 percent via conservation practices in use in 2012. Similarly, nitrogen losses from land were reduced by 36 percent by conservation practices.

Hydrological Simulation Program—FORTRAN (HSPF)

HSPF is an EPA-supported watershed modeling program capable of simulating water quantity and quality for a range of pollutants (Figure 4-11). Hydrology, sediment, and nutrient generation and transport are simulated for multiple pervious and impervious land use and land-cover categories. Hydrology is modeled as a traditional water balance in surface and soil layers using rainfall and meteorological data. Sediment, nutrient and pesticide loading is a function of simulated hydrology and agricultural operations and land management practices. It also simulates the in-stream fate and transport of nutrients, sediments, tracers, dissolved oxygen/biochemical oxygen demand, temperature, bacteria, and user-defined constituents. HSPF includes an option for simulating crop rotation, fertilizer, and pesticide activities. The timing of

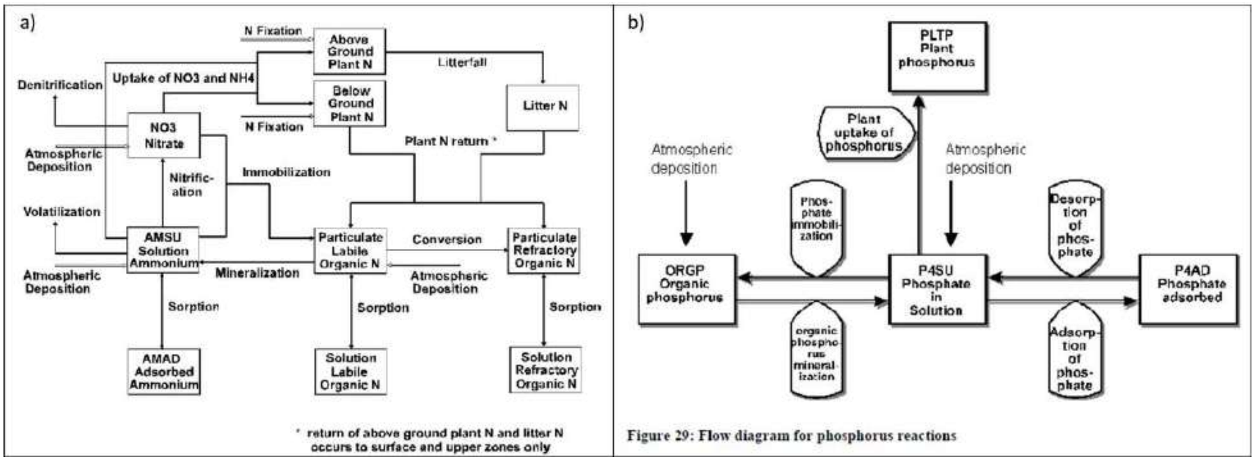

Figure 4-11. Conceptualized nitrogen (a) and phosphorus (b) processes in HSPF (Bicknell et al., 1997). *Permission for use of image will be requested prior to public release.*

Loading Simulation Program in C++ (LSPC)

LSPC is based on HSPF, although it is generally intended for use in larger watersheds. The model was developed to simplify and streamline the process oriented algorithms of HSPF into a robust data management system for large and complex watersheds. As such, its process description and input requirements are similar to HSPF, although the LSPC requires additional use of auxiliary software packages, such as Microsoft Excel and a Geographic Information System.

Ohio EPA (2011) released a TMDL for *E. coli* bacteria, nutrients, oxygen-demanding substances, sediment, and habitat quality in the Portage River. As part of this effort, an LSPC model was developed by TetraTech for the Portage River basin. The LSPC model found that in order to achieve the target instream TP concentration of 0.17 mg/L, a global 32.5% reduction in TP load from the watershed would be required.

USACE Hydrologic Modeling System (HEC-HMS)

HEC-HMS was developed by the US Army Corps of Engineers Hydrologic Engineering Center. The model focuses mostly on hydrology, simulating runoff from user-defined urban and agricultural watersheds. However, an option water quality component is available in the model, which simulates in stream fate and transport of nutrients and eutrophication related responses. Runoff, and therefore loading, is estimated as a function of meteorology, watershed characteristics such as land use, slope, area, and soil conditions. When the optional water quality module is activated, the user can also define fate and transport rates and coefficients to describe nutrient cycling. While there is no direct input of fertilizer use or farming practices, the model is capable of estimating loads as a function of the simulated hydrology, and user defined time-series of boundary condition concentrations for nitrogen and phosphorus. Estimates of these boundary conditions could be determined from observed upstream data, or from the use of larger scale models such as SPARROW.

There are current efforts to incorporate a more robust water quality component into HEC-HMS, utilizing the Nutrient Sub-Modules (NSMI, and NSMII), developed by Zhang and Johnson (2014). These modules contain two different levels of complexity for defining nutrient transport and pathways: NSMI uses relatively simply kinetics, while NSMII is more complex. Incorporation of these components in HEC-HMS is still under development, however. A schematic of the relevant transport pathways in the soil layer are shown for nitrogen (Figure 4-12a) and phosphorus (4-12b), as described in the NSMI module. To date, water quality module of HEC-HMS has not been applied in the WLEB.

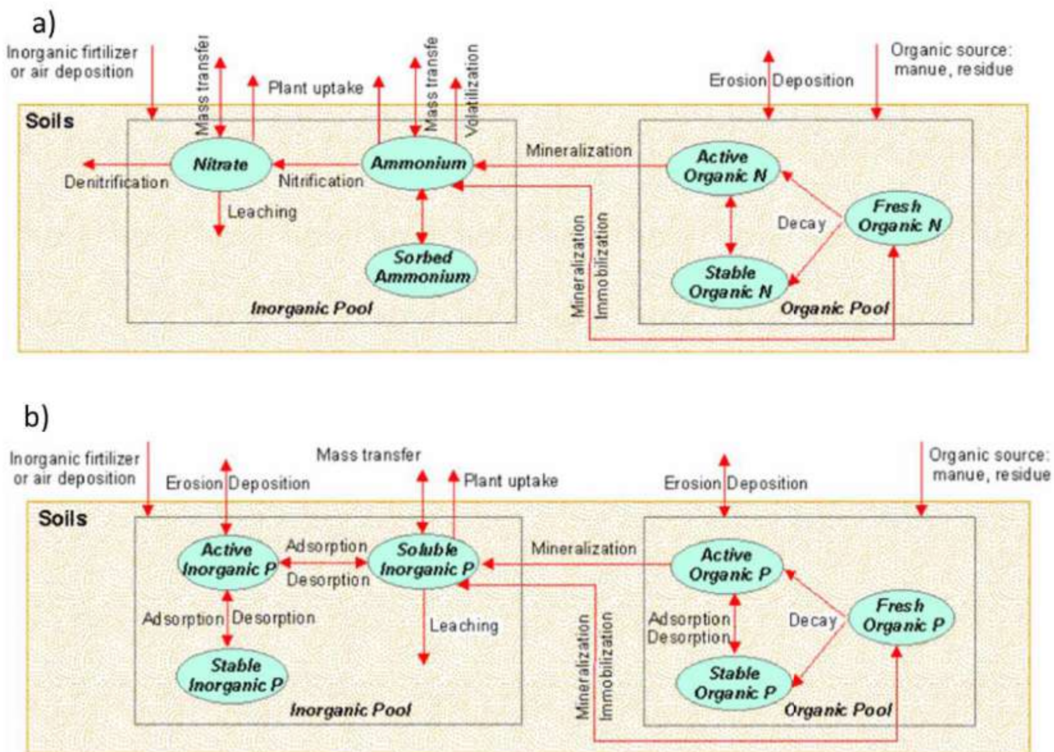

Figure 4-12. Conceptualized nitrogen (a) and phosphorus (b) soil processes in the Nutrient Sub-Module (Johnson et al., 2006). *Permission for use of image will be requested prior to public release.*

SPAtially Referenced Regressions on Watershed Attributes (SPARROW)

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+ 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. In stream 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, sewered 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. Additionally, the model quantifies uncertainties in the estimates, such as coefficient of error and variability in the observed data.

Fertilizer use is accounted for in SPARROW by geospatial data inputs that define where the fertilizer and/or manure are applied. That is, areas where these agricultural practices are most likely to occur act as a forcing function for the model algorithms.

Robertson and Saad (2011) have developed and published 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 on the HUC-11 scale, or approximately 100 km^2 subbasin size. Based on 2002 input data, the model estimated that farm fertilizer was the source of approximately 26% of the delivered phosphorus load to Lake Erie, and approximately 30% of the delivered nitrogen. Further, the input from all agricultural practices (including fertilizer, manure, and organic matter decomposition) was estimated to be approximately 58% of the total load to Lake Erie. The Great Lakes basin SPARROW the Scavia et al. (2017) multi-model project for the WLEB, demonstrating that the coarse spatial resolution of SPARROW resulted in different delivery ratios in comparison with SWAT results. A binational project between USGS, the International Joint Commission (IJC), and the National Research Council (NRC) of Canada is currently underway, and working to refine the Great Lakes region SPARROW model to include the basins on the Canadian side as well.

AGricultural Nonpoint Source Pollution Model (AGNPS)

AGNPS is a USDA supported public domain suite of computer models that simulates nonpoint source pollutant loadings in agricultural watersheds. AnnAGNPS is the annualized version of this model. AGNPS contains a watershed-scale, daily time step simulation model capable of predicting agricultural and land management impacts on hydrology, sediment/erosion, nutrient and pesticide loading and plant growth. The model includes processes for surface hydrology, erosion, nonpoint and point source nutrient loading, and hydrologic routing. Advanced features of the model include ephemeral gully erosion, bed and bank erosion, feedlots, impoundments, crop growth and irrigation, tile drains, and agricultural management practices. The user must define input parameters that described the nutrient cycling rates, as well as soil conditions and fertilizer or manure timing and application rates. While the model does not include complex in-stream chemical cycling, the user does have the option for specifying simple 1st order decay rates for pollutants instream. A schematic showing an example watershed with agricultural practices and hydrologic structures is shown in Figure 4-13.

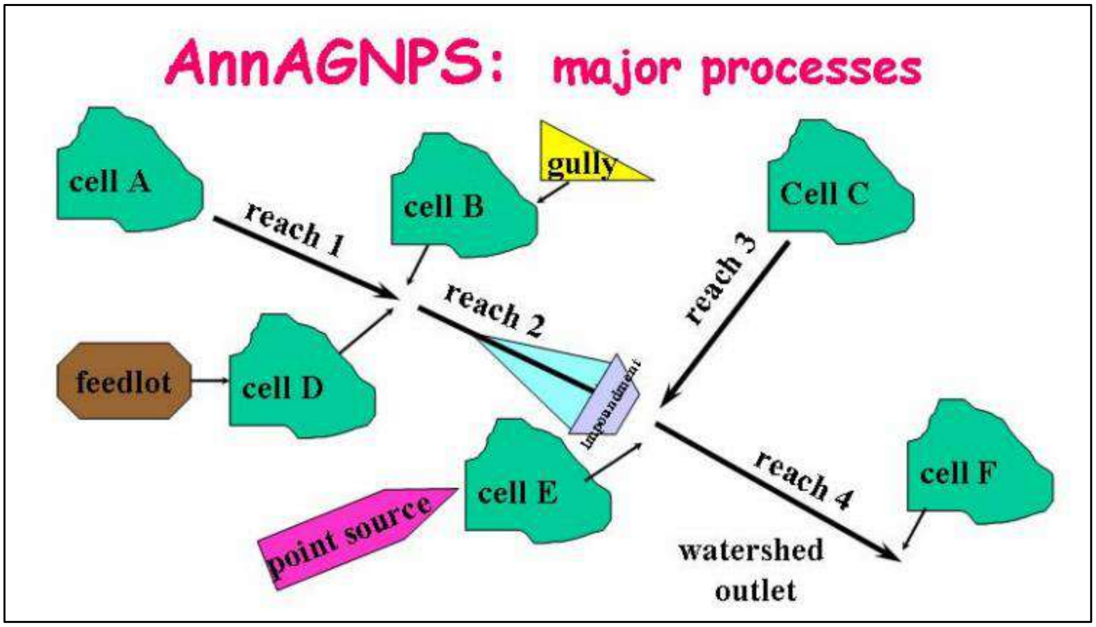

Figure 4-13. Example of the source tracking in AGNPS (Bingner et al., 2009). *Permission for use of image will be requested prior to public release.*

Bingner et al. (2005) developed an AGNPS model for the Upper Auglaize subbasin of the Maumee River basin that focused primarily on sediment erosion and delivery. Yuan et al. (2011) expanded the model to include nutrients and assessed the impact of phosphorus load from fertilizer applications. The analysis specified different initial soil phosphorus concentrations and fertilizer rates in the model and assessed the resulting loads from the watershed. The conclusions were that after long-term high fertilizer application rates, the soil becomes saturated with phosphorus and soil phosphors loss increases dramatically, resulting in significant increases in loading compared to short term fertilizer applications at the same rate.

An AGNPS model for the Blanchard River watershed (a subbasin of the Maumee watershed) has been developed by LimnoTech (2010). The model was calibrated to streamflow, sediment, and nutrient data from 2002-2009, and confirmed for the period of 1995-2001. The study utilized AGNPS to simulate a number of land management practices, including tile drain management, conservation tillage, cover

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settlement watershed condition. The study found that the total phosphorus could be reduced by 25% under the cover crop scenario and 21% by a 60% reduction in fertilizer application. The reduction in nitrogen loading from these scenarios was found to be 39% and 60%, respectively.

Coon et al. (2011) also compiled a list of all watershed models that were developed as of 2010 in the Great Lakes Basin.

MIKE Système Hydrologique Européen (MIKE SHE)

MIKE SHE is part of an advanced, integrated hydraulic and hydrologic modeling package that can combine watershed, in-stream/waterbody, and urban runoff or sewer processes into a single framework. MIKE SHE simulates the hydrological cycle of surface and subsurface zones, including surface and saturated and unsaturated subsurface flow, evapotranspiration, overland flow, and exchanges between surface water and groundwater. A schematic of the hydrologic processes simulated by MIKE SHE is shown in Figure 4-14. It can use the processes developed in MIKE11 (1-dimensional open channel flow model) for instream and open water hydrology, and can also be linked to the sewer model program MOUSE. The applicable spatial scale for MIKE SHE is highly variable, ranging from large regional applications, to field scale applications analyzing crop growth requirements. A relatively simple water quality submodel is directly integrated into MIKE SHE, which can include transport, decay, sorption and selective uptake to user-defined constituents such as nutrients, sediment or pesticides. For more advanced applications, MIKE SHE can be combined with ECO Lab, which allows for complex user-defined interactions between multiple species of constituents. MIKE SHE has been applied to several watersheds in the Thames River basin, and is also being used in a study of L. St. Clair by MOECC and ECCC that is currently underway.

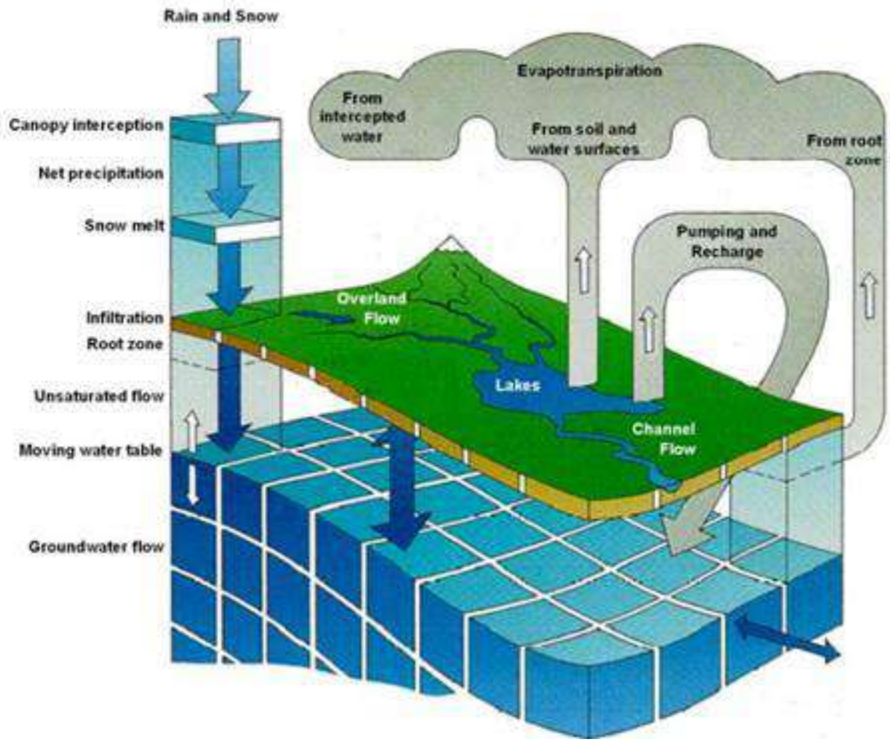

Figure 4-14. Schematic of hydrological processes included in MIKE SHE (DHI, 2012). *Permission for use of image will be requested prior to public release.*

CAnadian Nutrient and Water Evaluation Tool (CANWET)

CANWET is GIS-based application that adapts the Generalized Watershed Loading Function (GWLF) to simulate hydrology and water quality in watersheds. The model is essentially a simplified version of HSPF which uses limited number of parameters and limited temporal variability in inputs. The model is capable of simulating streamflow, surface runoff, subsurface runoff, evapotranspiration, sediment, nitrogen, phosphorus, and bacteria concentrations for a watershed, based on land use categories and point source locations. Management practices are accomplished in CANWET by scaling the loading rates using area weighted values. The software package also contains pre-defined climate scenario input data, as well as guidance for estimated unit area loads for nutrients and solids. The model can use GIS-based spatial representation of where artificial tile drainage systems are installed.

In the Lake Erie basin, CANWET has been applied to the Canagagigue Creek watershed of the Grand River in southern Ontario and compared to HSPF for performance. While CANWET was found to be useful on watershed scale applications, the limitations in temporally variable input data resulted in less accurate simulated hydrology and sediment yield on monthly scales, as compared to HSPF.

LandMapR

LandMapR, and the associated FlowMapR applications were developed by MacMillan (2003) to process digital elevation models (DEMS) of topography and bathymetry. In this sense, the application does not perform calculations consistent with a watershed model, however, it can be useful to determine flow paths, ponds or reservoirs, and estimating surface runoff from a given storm. The application is a GIS-based framework that uses the 8-directional flow path calculation to estimate where water from each DEM cell will flow to. Along with advanced calculations to determine where unrealistic values are, the application can be powerful to defining watershed boundaries and transport pathways, which could be used in a watershed model, such as the ones described above.

4.2.2 Lake Models

Western Lake Erie Ecosystem Model (WLEEM)

WLEEM is a highly spatially resolved three-dimensional mechanistic lower food web model for the Western Basin of Lake Erie (Figure 4-15). The algorithms in the model are consider

to multiple classes of phytoplankton (including cyanobacteria) and zooplankton, dreissenid mussels, and benthic algae and an advanced sediment diagenesis submodel. This lower food web model is referred to as the Advanced Aquatic Ecosystem Model (A2EM). WLEEM is also linked to the fine-scale hydrodynamic model Environmental Fluid Dynamics Code (EFDC), while sediment transport and wind-drive resuspension are driven by Sediment Transport Model (SEDTRAN) and Simulating Waves Nearshore (SWAN), respectively. WLEEM requires specification of the nutrient concentrations at the major tributary entry points in the model domain (i.e., boundary conditions). These values are typically obtained from long-term monitoring efforts, or from model estimates. The user can model hypothetical or realized conditions, such as reduced agricultural runoff, or best management practice implementation, by altering the boundary condition values for nutrient and sediment loads.

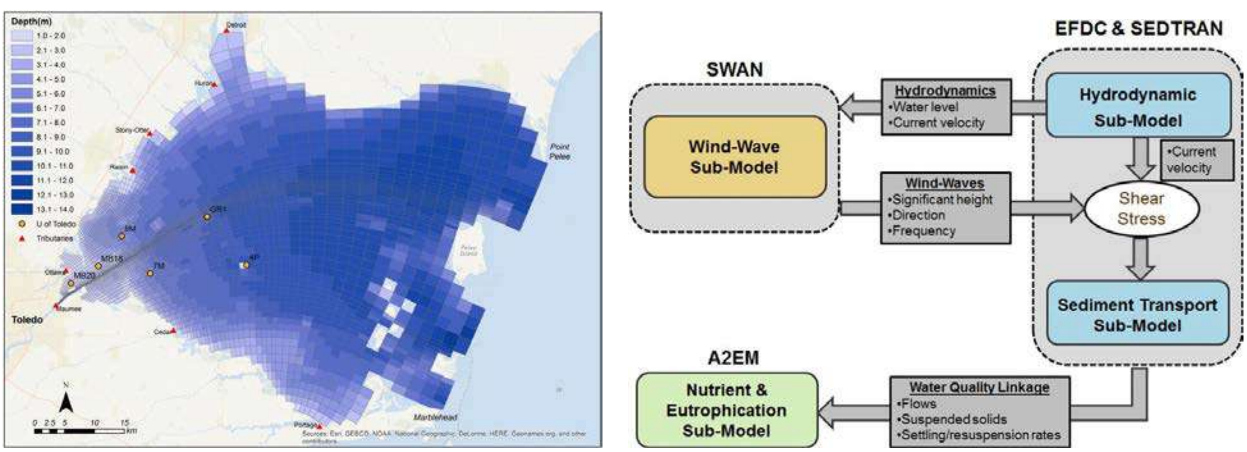

Figure 4-15. Model grid area and schematic diagram of WLEEM.

Verhamme et al. (2016) applied the WLEEM model for 2008, 2011, 2012, 2013, and 2014 meteorological and loading conditions. -a and cyanobacteria biomass, to help in development of loading response relationships, i.e., an estimate of how the Western Basin water quality indices would respond to a given phosphorus load. The analysis was extended to include hypothetical reductions in phosphorus loads from the Maumee and Detroit Rivers, and determined that a reduction in the nutrient loads from the Maumee basin would reduce chlorophyll-a and cyanobacteria more significantly than an equal load reduction from the Detroit River.

As part of the Annex 4 effort to determine appropriate loading targets for Lake Erie, the Science advisory Board (SAB) expressed a desire to adapt the WLEEM to the entire Lake. The WLEEM is restricted in its ability to characterize the nutrient transport from the central to the western basin of the lake, due to its spatial domain only incorporating the western basin. By adapting the domain to the whole lake, the model can more accurately assess the impact of the inter-basin transport and nutrient dynamics, as well as simulate other impacts of agricultural loading, such as hypoxia in the central basin, and cladophora growth in the eastern basin.

ELCOM-CAEDYM

ELCOM-CARDYM is a model suite that links a three-dimensional hydrodynamic model (ELCOM) with an advanced water quality model (CAEDYM). The package has been applied several times for the Lake Erie as a whole. The most developed and published version of the Lake Erie model contains a homogenous 2km horizontal grid, with 40 vertical layers (Leon et al., 2011). Similarly to the WLEEM model, this open lake model requires specification of boundary conditions for the major tributaries to represent inflowing concentrations of nutrients. Leon et al. (2011) used observed data for these values. The model has been calibrated and validated for chlorophyll-a and total phosphorus in all three basins of the lake, demonstrating reasonable agreement with data, however the simulated cyanobacteria blooms in the western basin were significantly lower than observed.

Bocaniov et al. (2016) also applied the same framework to assess the impact of nutrient load reduction scenarios. In this application, the tributary loading boundary conditions were artificially reduced by a series of scaling factors, intended to represent agricultural management practices, primarily in the Maumee River watershed. The analysis focused on reductions in central basin hypoxia, although the model also simulated reductions in western basin phytoplankton (chlorophyll-a) concentrations when total phosphorus loads were reduced. An overall 40% reduction in total phosphorus load was estimated to reduce summer total chlorophyll-a concentrations by approximately 25% in the western basin.

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 dependent variables when the July water temperature was below 17^{o} C (i.e., the 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), and Ho and Michalak (2017).

4.2.3 Mass balance models

Models that attempt to balance all the major external and internal sources and sinks of an element or compound, providing an alternative and integrated approach to analyzing coupled human and natural systems. The element of choice would be P in this case, but similar models have been developed for carbon and nitrogen, among other elements and compounds (Bosch and Allan, 2008; Hong et al., 2012). One such approach is referred to as a Net Anthropogenic P Input or NAPI model (Han et al., 2011 and 2012). In addition to soil P inputs from fertilizer and manure, and losses to surface water, NAPI includes P in net food and feed imports (surplus or deficit) and non-food use of P by humans (e.g., detergents), as well as human waste loading. Han et al. (2012) calculated NAPI for 18 Lake Erie watersheds for agricultural census 72 years. In this study, NAPI increased through the 1970s and then declined through 2007 back to the starting level at the beginning of the period of record. This approach makes it easier to isolate the drivers of change in a watershed model in a more comprehensive way than simply looking at the agricultural components, even if the output is linked and calibrated to water quality data. One reason for this is that there are non-unique pathways to similar water quality results, so that a model may produce output that agrees with observations, but the pathway to produce these results may be via an unrealistic simulation due to incomplete accounting of all P sources and sinks. As with other types of approaches to isolating drivers of changes in a complex environmental system like a large watershed, data gaps and limitations may be the primary constraints on mass balance model accuracy.

4.3 Monitoring and Modeling Summary and Gaps

Monitoring of offshore lake conditions and lower watershed water quality for larger tributaries are reasonably robust for the western Lake Erie region, especially when compared to other parts of the Great Lakes or similar large ecosystems such as Chesapeake Bay. There are many governmental, non-profit (e.g., Canadian conservation authorities), and academic monitoring programs that include parameters relevant to nonpoint nutrient loading and impacts. Data availability is generally fair overall, although time lags between sample or measurement collection and data release are commonly from one to three or more years. Real-time gauges and sensors are becoming more common in the region, and networks for delivering these data such as the Great Lakes Observing system portals are becoming more sophisticated and user friendly. Not all important nutrient-related parameters, however, can be measured by real-time instruments deployed in field settings.

Water quality models have been developed or are currently being developed at a variety of scales for much of the study area at varying degrees of temporal resolution. Numerous numerical modeling programs (software) exist that simulate agricultural P cycling and the lower trophic levels of lake food webs reasonably well. These computer programs has been created by government, academic, non-profit, and private sector developers; 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 (not necessarily operational mode) at multiple institutions in the region.

Often monitoring and modeling programs are designed independently, and the objectives and resolution of these programs do not interface well, even though they may be working toward a common purpose. It often appears that these programs are not designed with sufficient coordination among the water quality modelers or monitoring groups that create the programs. The communication gap in these programs could be reduced by integrating modeling and monitoring design into single operational programs. The outcome could be a unified operationalized monitoring and modeling program that could be used to simulate current conditions, hindcast and learn from the past, and forecast conditions in the future, which could be used to warn the public of imminent blooms or to create scenarios to evaluate mitigation alternatives. These unified monitoring and modeling programs could give feedback to each other and modifications would be made to the monitoring or modeling programs as needed in an adaptive manner.

5 Conclusions and Recommendations

This assessment of fertilizer and manure application and impacts in the Western Lake Erie Basin consisted of the following elements:

- compilation and analysis of data on inorganic fertilizer, manure, and related product use;
- distinguishing of the importance and role of nutrient management of fertilizers relative to nutrient transport;
- evaluation of the capabilities of existing watershed models to distinguish nutrient loads and impacts from different fertilizer sources and application practices;
- evaluation of current monitoring programs;
- identification of gaps in spatial coverage, temporal resolution, and knowledge related to data, modeling, and monitoring in this area;
- development and presentation of graphical displays of resulting fertilizer use and other data; and
- assessment of the state of knowledge concerning the potential contribution of each fertilizer type to eutrophic conditions in Lake Erie.

Data-Based Findings

- Inorganic fertilizer is the primary source of phosphorus used for agricultural purposes in the study area, and typically accounts for approximately 70 to 80 percent of the total phosphorus applied, including P from all manure generated by livestock in the watershed.
- Current inorganic P application rates are comparable in much of Canada and the U.S., with some local variation. Canadian data are less accessible, but average manure generation overall appears to slightly exceed inorganic fertilizer P application in the Ontario portion of the watershed based on 2007 data.
- Recent trends show steady or declining inorganic fertilizer application rates overall. Source percentages and ratios of P application/generation may not necessarily reflect corresponding percentages of contributions to P loads to Lake Erie.
- Manure accounts for approximately 20 to 30 percent of total agricultural P applied or generated in the study area, but localized concentration of sources and of application increase the relative percentage in some areas, as noted above. Total numbers of animals in the basin have remained fairly constant over time, but there is a trend toward higher concentrations of animals per farm.
- Information on permitted Concentrated Animal Feeding Operations (CAFOs) in the U.S. is publicly available, although not easily aggregated; Canadian CAFO data are generally not available to the public.
- Estimated overall application and generation values for fertilizer and manure combined, converted to elemental P, for the U.S. watershed total 41,687,180 kg (72 percent) and for the Canadian watershed total 16,326,671 kg (28 percent) based on 2007 data. This difference in contributions is comparable to differences in the surface area of the two watersheds.
- Important agricultural trends include gradually increasing yields with gradually decreasing fertilizer application, and an overall reduction of fertilizer application to equal or fall below crop

needs; legacy soil P from prior years of excess application has made up the difference where deficits between current-year application and crop needs exist.

- An increasing trend of bioavailable dissolved phosphorus loading from U.S. study area tributaries may be contributing to larger algal blooms in western Lake Erie and large hypoxic areas in central Lake Erie that have been observed in recent years. This increasing trend is coincident with increasing rates of drainage tile installation, as well as less intensive tillage practices and wetter spring climate conditions. to Lake Erie, whether in inorganic or organic (manure) forms, have not been documented.
- Mass balance analyses indicate that losses of P from new fertilizer and manure may not be sufficient to account for total nonpoint P loads to Lake Erie, and that legacy P may also be an important component of river P export.
- There are some indications that nutrient ratios (e.g., N:P) may be important in initiation, growth, toxicity, and species dominance for algal blooms. Ratios in different fertilizer and manure sources are variable and may play a role in the large variation observed.
- No general patterns of greater loss of P from fields where inorganic versus manure P has been applied have been documented. Loss rates tend to be more closely correlated with other factors.

Monitoring and Modeling Assessment Findings

- 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. 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.
- 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.

Data and Knowledge Gaps

- Numerical models are handicapped by gaps in watershed characterization, monitoring data, and process understanding. Data availability limits their 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.
- 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.
- Important P knowledge gaps include the detailed characteristics and drawdown dynamics of legacy phosphorus pools; the extent of tile drainage networks; the full influence of manure management on local and regional P loading on surface water quality.
- Data gaps and obstacles that limit assessment and modeling of P sources and impacts include details of inorganic fertilizer and manure application and management; insufficient resolution of data; and data accessibility challenges.

Recommendations

Recommendations related to water quality and agricultural practice monitoring, in order to sustain and improve awareness of system status, and to fill important data gaps include:

- 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.
- Collect and regularly update a statistically representative binational data set of phosphorus concentrations and vertical stratification in agricultural soils and other reservoirs of legacy P.
- Continue to develop 4R guidelines for fertilizer application, and invest in outreach, education, and technology to enhance adoption and effectiveness of 4R practices.
- Support research monitoring (watershed and lake) to improve process understanding and characterization of agricultural practices, to inform watershed management actions, and to increase the accuracy and reduce the cost of monitoring and characterization over time.
- Standardize methods for sample and data collection, processing, analysis, and reporting as much as possible, including across political boundaries, to allow for inter-comparison of data collected by different institutions and agencies.
- Cross-link sample collection programs more closely with continuous in situ monitoring networks, remote sensing programs, and operational modeling programs. Also investigate emerging imaging technologies that can be deployed at low altitudes over land or water.
- Develop and maintain stable and up-to-date repositories and user-friendly online access portals that effectively serve and integrate accurate data from all monitoring and survey programs.
- Develop stable funding mechanisms and institutional stewards for sustained binational monitoring and data management.

Recommendations related to modeling include:

- Continue financial and policy support for development and application of research models at various scales to improve process understanding of phenomena and dynamics, as well as to simulate alternate management scenarios.
- 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 interannual or within-season adaptive management decisions.
- Create regional modeling centers of excellence to run and maintain operational watershed and lake models, and associated output products, and to facilitate ongoing modeling research and technology transfer.

Recommendations for future research to fill gaps in understanding and to inform policy development include:

- Improve spatial resolution of data on legacy phosphorus, as well as linkages between P fluxes from reservoirs, and lake phenomena including algal blooms and hypoxia.
- Refine existing data on tile drainage networks and their impact on P form and mass transport, including interactions with tillage practices, fertilizer and manure application, and the relative role and rates of tile discharge of P in comparison with surface runoff.
- 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.

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7 Appendices and Electronic Supplement

Appendix A: Work Group Members

Mike Murray, National Wildlife Federation (Work Group Co-Chair)
Dave Allan, University of Michigan (Work Group Co-Chair)

Tom Bruulsema, International Plant Nutrition Institute
Patricia Chambers, Environment & Climate Change Canada
Anne Cook, The Andersons
Irena Creed, University of Western Ontario
Steve Davis, USDA National Resources Conservation Service
Joe DePinto, Independent consultant
Brad Glasman, Upper Thames River Conservation Authority
Pradeep Goel, Ontario Ministry of the 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, USDA-Agricultural Research Service
Andrea Kirkwood, University of Ontario Institute of Technology
Craig Merkley, Upper Thames River Conservation Authority
Rebecca Logsdon Muenich, University of Michigan Water Center (now Arizona State University)
Dale Phenicie, Council of Great Lakes Industries
Jeff Ridal, St. Lawrence River Institute
Clair Robinson, University of Western Ontario
Craig Stow, NOAA-Great Lakes Environmental Research Laboratory
Chris Winslow, The Ohio State University and Ohio Sea Grant
Santina Wortman, USEPA-Great Lakes National Program Office

International Joint Commission Team:
Matthew Child, IJC Great Lakes Regional Office
Glenn Benoy, IJC Canadian Section Office
Mark Gabriel, IJC U.S. Section Office

LimnoTech Contractor Team:
John Bratton (Project Manager), Noemi Barabas, Chelsie Boles, Renn Lambert, Brian Lord, Dan Rucinski, Derek Schlea

Electronic Supplement Directory

Additional electronic data tables, graphs, method descriptions, and GIS files including metadata have been uploaded to the IJC-SPC Sharefile site. Brief descriptions of folder contents are listed below.

ES-1: Fertilizer data and calculations in subfolders Fert1 Fert8

ES-2: Manure data

ES-3: Tile drainage and greenhouse GIS

ES-4: Fertilizer GIS geodatabase