Guidance Addressing Lake Erie Eutrophication in a Changing Climate Based on a Case Study with Agricultural and Coastal Managers

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Front cover photos (clockwise from upper left): Flooding from January thaw (K. Schneider, NRCS); Harmful algal bloom in western Lake Erie, August 10, 2015 (NRCS); No-till soybeans in rye (W. Swartzentruber, NRCS); No-till cover crops (NRCS). Page ii photos (top to bottom): Agricultural field near Ottawa National Wildlife Refuge; Soil in Van Wert County; Harmful algal bloom in western Lake Erie, September 29, 2014; Back cover photo: Old Woman Creek (M. Murray)

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Executive Summary

Lake Erie has experienced a return of highly eutrophic (nutrient-enriched) conditions over the past two decades, with impacts including annual harmful algal blooms (HABs) in the western basin and recurring hypoxia (low oxygen conditions) in the central basin. These impacts pose risks to the ecosystem – including fish populations – and multiple human activities, including drinking water supplies, commercial and recreational fishing, and other tourism activities, which for Ohio alone accounts for over $11 billion in visitor spending around Lake Erie annually. Though total phosphorus (a key nutrient) loads have decreased since policies were adopted in the 1970s, dissolved reactive phosphorus loads have increased over the past two decades. To further reduce phosphorus loads and resulting impacts, including HABs, research suggests that nonpoint sources of phosphorus including from agriculture need to be addressed. Moreover, climate change brings the potential for changes to the system (e.g. warmer temperatures, increased intensity of spring storms) which may pose additional challenges in addressing the problem.

To address these challenges in Lake Erie, a multi-institution team, with funding from the National Oceanic and Atmospheric Administration, organized a process that coupled stakeholder input and review with computer modeling of nutrient loads and the climate to identify potential approaches to meet phosphorus reduction targets, including those recently adopted through the Great Lakes Water Quality Agreement. The stakeholder process engaged representatives from multiple sectors, including agriculture, coastal management, nongovernmental organizations, and Great Lakes advisory groups, and entailed a survey, interviews, and two sets of workshops. The stakeholder input informed the selection of scenarios to consider and, in particular, which best management practices (BMPs) should be evaluated for use in meeting reduction targets through simulation using the Soil and Water Assessment Tool (SWAT).

While our original research goal planned to include a particular focus on climate change, results of the survey and the flow of discussion at the workshops highlighted a significant interest among stakeholders in consideration of BMPs in the current climate. Based on the range of BMPs of interest to stakeholders and modeling results of BMP performance, it was determined that subsurface application of phosphorus fertilizer (or incorporation through tillage) is the most effective practice at reducing dissolved reactive phosphorus loading. Other BMPs evaluated included perennial cover crops and vegetated filter strips; modeling results found these BMPs were less effective at reducing dissolved reactive phosphorus when deployed on their own. This suggests a modified approach is needed involving suites of BMPs to improve phosphorus reduction. Modeling results also showed that broad implementation of practices (across much of the Maumee River watershed) would likely be needed to meet recently adopted targets for Lake Erie.

Climate modeling revealed that mid-century climate would be generally warmer and slightly wetter in the region (in particular in winter and spring). However, as with some other recent studies, modeling of climate change impacts on nutrient loading provided a wide range of possible future loadings; more thorough studies including evaluating more climate models together with an analysis of best practices for incorporating these models into SWAT may be needed to determine the most likely future trends for climate impacted nutrient loading. Though less extensive than discussions around which BMPs to evaluate under current climate conditions, some discussions with stakeholders did touch on climate change-related issues (impacts and/or adaptation), including length of the growing season, water availability for agriculture, potential implications for nutrient hot spots, and the likelihood of large rain events.

In considering components of vulnerability to climate change impacts in Lake Erie, this project focused on the connection between the climate driver and land use (another key driver through a Driver-Pressure-State-Impact-Response conceptual framework applied to eutrophication), and considering vulnerability more broadly. Our research suggests that reducing vulnerability of Lake Erie to nutrient loading under the current climate requires broad implementation of BMPs throughout the Maumee River watershed. Given the uncertainty of the impacts of future climate and land use, the broad implementation of BMPs throughout the watershed will likely be required well into the future. Stakeholder interests and modeling limitations kept our focus on agricultural BMPs to address nutrient loads, precluding significant exploration of alternatives including coastal management approaches that could potentially contribute to reduced nutrient loadings to Lake Erie, though guidance and other resources on approaches to coastal habitat restoration (including wetlands), and adaptation more broadly, are increasingly available.

Two key conclusions of this project concerning the stakeholder process are the importance of transparency of the capabilities and limitations of the modeling approach used, as well as involving information users to the maximum extent possible, including in scenario development, review of model outputs, and consideration of outreach and communication of results. Given the complexity of the Lake Erie eutrophication problem, the multiple interests (including agriculture, tourism, agencies, and conservation organizations) in the watershed, and uncertainties (including climate, land use, and nutrient loadings) going forward, stakeholder-driven modeling efforts as described here offer the potential to help identify broadly-supported approaches to reduce eutrophication and impacts in Lake Erie.

NASA

I. Introduction

Lake Erie is a key component of the Great Lakes ecosystem, providing numerous ecosystem services related to drinking water, wildlife habitat, fish production, and numerous other services. Approximately 12 million people live in the watershed, and the lake contributes significantly to industrial activity and trade; Lake Erie tourism supports 119,000 jobs in Ohio alone and generates nearly $11 billion annually in visitor spending.[1] Fishing is an important component of the economy for Lake Erie, with anglers spending at least $300 million annually in the Ohio portion alone.[2]

Many factors contribute to the significance of the Lake Erie fishery. As the southernmost, shallowest, and warmest of the Great Lakes, Lake Erie has conditions that promote high productivity, or growth of aquatic organisms. Lake Erie also has the availability of nutrients, such as phosphorus and nitrogen, to support that productivity. Such nutrients contribute to growth of organisms at the base of the food web – i.e., the algae or phytoplankton that carry out photosynthesis and provide the energy for consumers in the food web, including zooplankton (or microscopic animals) eating the phytoplankton, forage fish eating the plankton, and piscivorous fish eating forage fish.[3] In freshwaters, phosphorus is typically the limiting nutrient, so increasing phosphorus levels generally means greater primary production or growth of phytoplankton or other aquatic plants.[4]

However, while increased primary production provides the potential for a more significant fishery, excessive nutrients can also lead to excessive production (or eutrophication), which in some cases can include algal blooms. These blooms may cause water quality problems because when algae die and sink to the bottom of the water body, the decomposition process consumes oxygen, leading to "dead zones", as occurs regularly in the central basin of Lake Erie, with risks to fish and other aquatic life.[5] One category of blooms of particular concern is harmful algal blooms (HABs), including cyanobacteria, or photosynthesizing bacteria that can produce toxic chemicals that pose risks to people, fish and wildlife, pets, and livestock.[6]

An important factor determining the nutrient content of lakes is the surrounding land use. Land use in the Great Lakes region is quite diverse, ranging from primarily forested and barren in the north, to significant agriculture and urban development in the southern portion of the basin.[7] The Lake Erie watershed, and particularly the portion draining directly to the lake's western basin, is heavily agricultural; over 70% of the Maumee River basin is planted annually in row crop agriculture (see Figure 1).[8] Commercial fertilizers and animal manures applied to crop fields can be washed or leach into surrounding ditches and tributaries, and these nutrients may be flushed into Lake Erie, as a form of "nonpoint source" pollution; these loads make up the majority of nonpoint source loading to the lake.[9] There are also "point sources" of nutrients from discrete sources in the watershed, including wastewater treatment plants and sewer system overflows.[10]

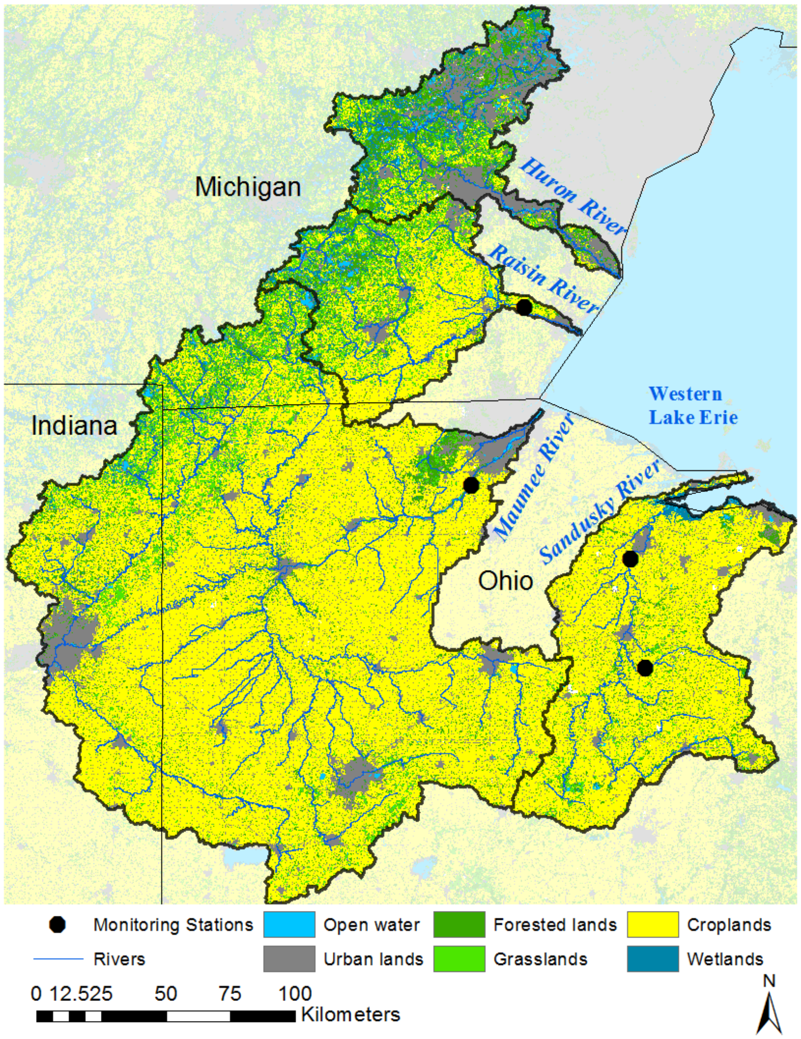

Figure 1. Map of four major western Lake Erie watersheds and land use. The major emphasis of this case study was the Maumee River watershed.

A recent estimate indicates at least 85% of the annual phosphorus loading from the Maumee River to Lake Erie comes from current or past fertilizer and manure application to farm fields.[11]

Phosphorus is measured in several forms, including particulate (associated with particles that remain on a filter) and "dissolved" phosphorus (the fraction passing through the filter), with the two together constituting "total phosphorus" (TP). The dissolved fraction is often termed "dissolved reactive phosphorus" (DRP) or "soluble reactive phosphorus." This fraction is particularly important ecologically, given DRP is the form most bioavailable to aquatic organisms.[12]

Eutrophication has been an issue in Lake Erie for decades. Significant HABs in Lake Erie in the 1960s were associated with elevated nutrient inputs, including from point sources. Following implementation of programs spurred by the binational Great Lakes Water Quality Agreement and federal legislation in the U.S. and Canada, nutrient loads were reduced significantly from point sources, leading to a decline in HAB problems into the 1990s.[13] However, by the late 1990s, HABs (in particular in the *Microcystis* group of cyanobacteria) were recurring with increasing frequency and magnitude in the lake's western basin, at a time when DRP loads in particular were increasing.[14] Several of the largest or most disruptive HAB events on record have occurred in the last five years, including the 2014 bloom which resulted in a drinking water advisory affecting over 400,000 people in the Toledo area.[15]

One type of conceptual framework used to highlight processes in social-ecological systems of the type we are dealing with in Lake Erie eutrophication is the Driver-Pressure-State-Impact-Response (DPSIR) framework.[16] Though the DPSIR framework has been used more in Europe and in other countries outside North America,[17] the framework is applicable to Lake Erie, and is useful for understanding the system and how to reduce the occurrence of HABs and dead zones. Figure 2 shows the DPSIR framework for the eutrophication context in Lake Erie including addressing nutrient loads, impacts, and management response. In this framework, a driver such as climate leads to pressures (such as more intense storms) flushing more nutrients into tributaries, leading to changes in the state (e.g. elevated nutrient concentrations), and subsequent impacts – in Lake Erie, including a larger or longer extent of western basin HABs or central basin hypoxia (low oxygen conditions).[18] Maumee River nutrient loads in the months of March – July are recognized as key determinants of the extent of HAB formation in a given year,[19] and thus the management response (including identifying key periods for reducing nutrient loads) includes an emphasis on spring/early summer loads.[20] In addition, research has shown that climate change may lead to changes in precipitation patterns in the basin, including increased intensity of spring storms and accompanying elevated nutrient loads.[21]

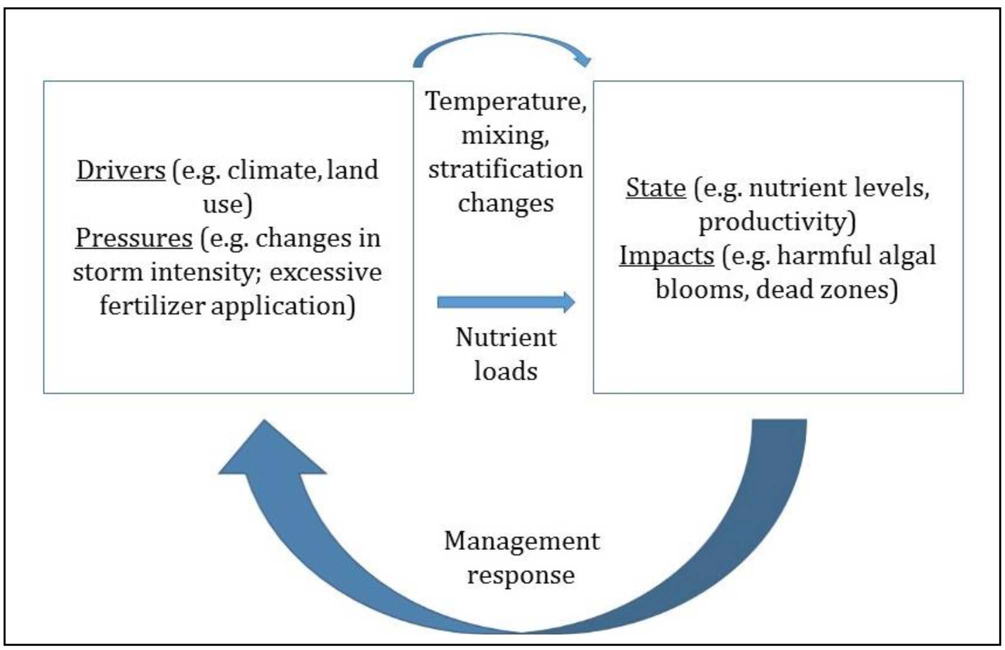

Figure 2. One potential approach to indicate relationships among various components in addressing Lake Erie eutrophication, following a Driver-Pressure-State-Impact-Response framework. In this simple formulation, the drivers and pressures are largely in the watershed, and the state and impacts of concern are mostly in the lake. While other factors (e.g. in-lake processes such as nutrient cycling involving sediments, invasive mussel filtering, etc.) also play roles, these were not formally addressed in this project and so were not included in the conceptual framework.

Land use (with an emphasis on land cover in this framework) is another important driver in the system, which in turn can lead to pressures (including particular management activities), with potential to increase nutrient loads. Even within agricultural lands, multiple factors can affect nutrient runoff, including physical features of the land (slope and soil type), crop rotations, tillage, fertilization application approach, and extent of surface and subsurface drainage systems.[22]

Regarding recent increases in HABs in western Lake Erie, one potential contributor is the general increases in DRP loads over the past two decades.[23] However, a number of other factors (not necessarily independent) may also be contributing, including related to agricultural practices, in-lake processes, and changes in climate,[24] all of which can interact in complex ways. Increasingly, research is identifying multiple climate change risks for the Great Lakes (including affecting other systems in the Lakes such as coastal habitat), highlighting the importance of planning for such changes.[25]

The overall purpose of this project was to work with stakeholders to identify potential actions (based on modeling) that could be taken that would help meet existing nutrient reduction goals for Lake Erie, while also considering implications of climate change. The following sections describe general climate adaptation principles, nutrient reduction targets for Lake Erie (and modeling approaches to estimating loads), the stakeholder process and development of management scenarios, outcomes of the overall process, and recommendations on potential adaptation approaches and additional needs.

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II. Climate Adaptation Principles and Framework

Lake Erie eutrophication and impacts are indelibly linked to climate, given the importance of climate-related components such as storm events and their frequency, water temperatures, and stratification patterns.[26] Addressing Lake Erie eutrophication while taking into account potential future climate change impacts (i.e., via climate change adaptation) may therefore be relatively straightforward (at least conceptually) compared to some other conservation challenges.[27]

Both the practice and the science of climate change adaptation in general have been growing dramatically in the past decade, as reviewed by Stein et al. 2013.[28] Several adaptation principles have been identified, including: embracing goals focused on the future; linking actions to climate change impacts (both direct and indirect); considering the broader landscape context; pursuing strategies that are robust (or useful) in an uncertain future; and following agile management (such as adaptive management) approaches. An important aspect of planning for climate change impacts is consideration of vulnerability of the system of interest (e.g. of a species or habitat); this vulnerability can be seen as consisting of three components: 1. Exposure, or the degree of change related to climate or associated problems; 2. Sensitivity, which could include, for example, the response of individuals of a particular species to temperature changes; and 3. Adaptive capacity, or the extent to which a species or system can accommodate to or cope with the changes. As implied schematically in Figure 3, reducing vulnerability can entail reducing the climate-related exposure, reducing the sensitivity (e.g. of the system to climate-related change), or increasing the adaptive capacity.[29]

One framework developed to help guide adaptation planning and implementation incorporates the aforementioned principles, and includes the following steps:

- Define the planning purpose and objectives
- Assess climate impacts and vulnerabilities
- Review/revise conservation goals and objectives
- Identify possible adaptation options
- Evaluate and select adaptation actions
- Implement priority adaptation actions
- Track action effectiveness and ecological response[30]

The process is an iterative learning process, with potential to incorporate new information at a given stage. For example, the process of establishing goals and objectives may lead to the need to consider vulnerabilities of certain species or other aspects of an ecosystem, and potentially a formal vulnerability assessment of those components, which in turn could lead to revision of goals and objectives.

Adaptation planning is being increasingly pursued in the Great Lakes region. For example, in another NOAA-funded project the National Wildlife Federation and colleagues described an approach to adaptation for coastal habitat restoration in the Great Lakes[31] that included a framework similar to that of Stein et al.[32] The project included working with restoration partners in the planning stages of seven local restoration projects as case studies, which typically involved consideration of climate vulnerabilities at individual sites and identification of potential adaptation approaches. For example, projections of potentially more extreme water levels in the lower Black River in Ohio led to recommendations that fish habitat shelves be installed at different elevations in a given river segment.[33]

As noted in the Introduction, the purpose of this project was to work with stakeholders to identify (via modeling) potential actions that could be taken that would help meet existing nutrient reduction goals for Lake Erie, while also addressing implications of climate change. Thus, this project addressed components of the adaptation planning process outlined above, in particular summarizing assessments of climate impacts on another stress (nutrient loads) and identification and evaluation of options to address that stress (i.e., potential approaches to reduce loads, including with climate change).

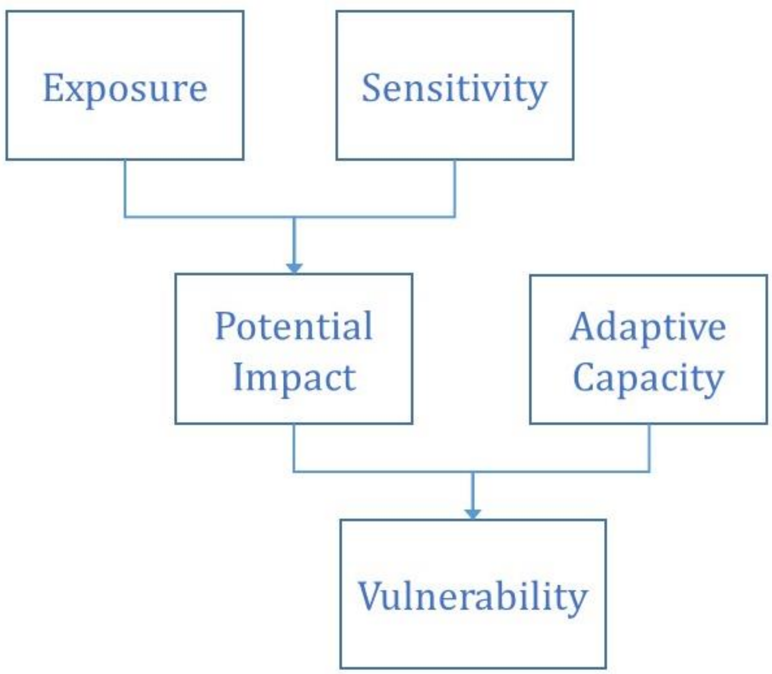

Figure 3. Schematic (redrawn from Glick et al. 2011 (reference 29)) showing climate change vulnerability components of exposure, sensitivity, and adaptive capacity. Reducing vulnerability can entail reducing the impacts (i.e., through addressing exposure or sensitivity) or increasing the adaptive capacity of the target (e.g. species, ecosystem) of interest.

III. Nutrient Reduction Targets and Computer Models to Estimate Nutrient Loads

Given the fundamental importance of nutrient loads in Lake Erie eutrophication and associated impacts, the focus of recent policy initiatives (e.g., management response measures (Figure 2)) has been on setting nutrient reduction targets, in particular for phosphorus. In setting load reduction targets, recent considerations have included the problem (e.g. western Lake Erie basin harmful algal blooms); geographic scope for implementation (e.g. western basin vs. entire lake); nutrient parameters (e.g. total phosphorus (TP) or DRP); loading period (e.g. spring, annual); and baseline year or period (to which reductions are applied). Recent nutrient reduction targets for Lake Erie have emphasized phosphorus, and targets identified through several agreements/reports are summarized in Table 1.

Table 1: Recent Phosphorus Reduction Targets for Lake Erie[a]

Agreement/ Report	Scope, Period	Parameter	Baseline period to which reductions applied	Target (or reduction from baseline, %)
Great Lakes Water Quality Agreement, Annex 4[b]	Western Basin: Maumee River (March - July)	TP	2008	860 metric tons[c] (40 %)
	Western Basin: Maumee River (March - July)	DRP	2008	186 metric tons (40 %)
	Central Basin (annual) (reduce hypoxia)	TP to Western Basin, Central Basin	2008	6,000 metric tons (40 %)
Western Basin Collaborative Agreement[d]	Western Basin (annual)	TP and DRP	2008	40 %
A balanced diet for Lake Erie report[e]	Western Basin: Maumee River (March - June)	TP	2007-2012	800 metric tons (37 %)
	Western Basin: Maumee River (March - June)	DRP	2007-2012	150 metric tons (41 %)
	Western Basin: Maumee River (annual)	TP	2007-2012	1,600 metric tons (39 %)

Notes: a. Unless noted (in Scope, Period column), targets are to reduce HABs in western basin; b. Western basin targets to reduce western basin HABs, central basin targets to reduce hypoxia[34]; c. One metric ton = 1,000 kg, or approximately 1.10 short tons; d. Western Basin of Lake Erie Collaborative Agreement (between Michigan, Ohio, and Ontario)[35]; e. International Joint Commission, *A balanced diet for Lake Erie,* Lake Erie Ecosystem Priority.[36]

As indicated in Table 1, most phosphorus reduction targets developed in the past few years have targeted a reduction in phosphorus of approximately 40% from a baseline (e.g. 40% reduction from loadings for 2008), and cover both DRP and TP, with a particular emphasis on spring-time loadings (where "spring" extends through all of June or July, as indicated in table).

While targets are important, by themselves targets do not solve the problem; the challenge lies in implementing actions to actually meet the targeted reductions. In considering different approaches to meeting the targets, one needs to account for the various nutrient sources (e.g. agricultural runoff), and changes in other key factors affecting nutrient loads, in particular climate. Computer models are often useful tools for examining different scenarios (e.g. for climate as well as agricultural practices), and are thus helpful for exploring approaches to meet nutrient loading reduction targets.

Computer models that simulate climate represent physical processes occurring in the atmosphere, and can be applied at a variety of spatial scales. For this project, three sets of model output were used to understand the simulation of historical climate as well as project future climate change in the region, drawing from both global and regional climate modeling projects.[37] The robustness of the models can be assessed by comparing the present-day model estimates to actual historical data, and differences can be observed (e.g. one model may predict wetter conditions than has actually been experienced in the past for a given month, and another may predict drier conditions for the same month). For this work, 1980 – 1999 was the historical period. The models can also be used to project conditions in future years. For this project, a high greenhouse gas emissions scenario was used, leading to projections for mid-century (2041-2065) of monthly temperatures and precipitation for the region compared to historical model results (see below).[38]

Watershed models are used to simulate hydrology and sometimes water quality, including phosphorus and nitrogen. The Soil and Water Assessment Tool (SWAT), a model frequently used in regions with significant agriculture (and thus appropriate for the western Lake Erie basin) was used in this project. SWAT is a physically-based model that allows for user input of detailed farm management operations and a wide variety of conservation practices (i.e., best management practices, or BMPs). Input data of topography, streams, land use, soil type, and climate, as well as farm management data (e.g. crop rotations, drainage systems, fertilizer application rates) are used to create baseline conditions in the model. The model can predict outputs such as TP and DRP loading in the Maumee River, and in the model calibration process, key parameters are adjusted to improve the fit to measured daily or monthly loads for a particular historical period.[39] Then the model can be run multiple times with many different types of scenarios, considering both changes in climate and agricultural practices, as described in the following sections.

IV. Stakeholder Process and Development of Scenarios to Meet Lake Erie Nutrient Targets

Stakeholder processes have been increasingly used in natural resource management over the past decade. While there are many different ways to involve stakeholders and correspondingly different levels of stakeholder engagement, an approach that is common in the climate change community is to involve potential information users earlier on in the production of scientific knowledge. More substantive involvement of users in a process of mutual learning in the context of problem-driven research can lead to "coproduction" of knowledge, a process that often leads to more useful information available to users.[40]

This project entailed involvement of stakeholders through a survey, follow-up interview questions, and a series of coproduction workshops. Given the importance of agricultural regions for nutrient loads in Lake Erie, stakeholders were largely drawn from the agriculture sector, including agricultural producers, county soil and water conservation specialists, agricultural advisors, as well as non-governmental organization representatives, researchers, and staff at state, federal, and intergovernmental agencies. An online survey was administered in advance of the first series of workshops, soliciting input on types of agricultural conservation practices of interest to stakeholders for their nutrient reduction potential. Though not intended to be representative of the entire watershed, responses (36 of 74 individuals, or 48% response rate) did provide information on the range of practices of interest to a diverse group of stakeholders.[41] Interviews allowed for more in-depth probing of stakeholders on different conservation practices of interest.

Two sets of three workshops were organized to obtain more detailed input from stakeholders, including an initial set in summer 2014 involving 18 stakeholders. The format involved interactive presentations followed by facilitated discussions and brainstorming around conservation practices (BMPs) of particular interest. Individual practices and suites of practices were then incorporated into scenarios, for which modeling was then done, leading to results (e.g. nutrient loads) that could be compared to load reduction targets as noted in Table 1. Types of practices modeled in this project are summarized in Table 2. Extensive notes were captured from the workshops, forming the basis for workshop reports shared with stakeholders and used to inform the modeling efforts. A second set of workshops involving 20 stakeholders was organized in the summer of 2015, with objectives of presenting modeling results, obtaining input on additional scenarios of interest (some of which could potentially be modeled in this project), and obtaining input on the types of outputs (e.g. graphical) most useful to stakeholders.[42]

In the end, scenarios across a series of conservation practices covering seven types were modeled (as summarized in Table 2). The extensive input from stakeholders was extremely useful in identifying and modifying the scenarios, clarifying model assumptions, generating additional research questions, and better ensuring modeling results would be policy-relevant.[43]

Table 2. Agricultural Conservation Practice Scenarios Modeled in This Study.[a]

Type	Scenarios
0	Baseline (e.g., mix of no-till and conventional tillage, tile drainage, nutrient management, etc., based on best available historical information)[b]
1	Nutrient placement (4 scenarios) (e.g., fertilizer broadcast or subsurface applied, with particular tillage practices)
2	Nutrient timing (5 scenarios) (e.g. spring or fall application, with variations in the season of tillage)
3	Cover crops (4 scenarios) (tillage radish and/or cereal rye after particular cash crops in rotation)
4	Vegetated filter strips (3 scenarios) (varying in the portion of surface flow intercepted and the quality of nutrient treatment)
5	Systems approach/combinations (6 scenarios) (combinations of stakeholder-chosen scenarios above)
6	Feasible (3 scenarios) (similar to type 5, but applied to a smaller fraction (e.g. 25 – 33%) of randomly selected cropland in the watershed)

Notes:
a. Individual scenarios identified in Kalcic et al. 2016[44]
b. Cover crops aside from winter wheat, filter strips, and some other conservation practices were not included in the baseline scenario due to inadequate data

From inception, this project explored issues with meeting nutrient reduction targets for Lake Erie in both the current (or recent) climate and in a future climate. Concerning future projections, research has shown the potential for changes in factors relevant to nutrient loading and impacts in Lake Erie by mid-late 21st Century, including increases in average air temperatures and increased springtime precipitation across the region,[45] slight increases in water runoff and streamflow in the Maumee River basin,[46] increased winter – early spring (January – April) monthly precipitation,[47] and increased chances of larger spring (March – May) precipitation events.[48] Large spring events have already been noted as a key factor (along with nutrient management practices) in the development of the extensive 2011 Lake Erie HAB event.[49] Recent research sometimes shows mixed results on projected changes in phosphorus loads to Lake Erie with climate change, including, for example, a SWAT modeling study which found a slight reduction in Maumee River TP loads by the middle of this century and slight increases at end of the century.[50] In general, any scenarios indicating potential climate change-induced increased phosphorus loads[51] implies more aggressive (or alternative) implementation of BMPs and other measures would be needed to meet the same targets.[52]

V. Outcomes of Modeling and Stakeholder Processes

A key general finding derived from both sets of stakeholder workshops was significant interest in modeling multiple agricultural BMPs in combination under the current climate, with much less organic discussion on potential scenarios in a future climate (though see climate discussion below). This type of pattern in perspectives of stakeholders or resource managers considering climate has been seen in other areas, including around Great Lakes fisheries (with managers in one study most interested in nearest-term climate change scenarios).[53] In addition, given the composition of stakeholders involved in the effort, the focus of discussions was on implications of different practices in agricultural areas to nutrient loadings to Lake Erie, rather than implications of other coastal resource management practices (e.g. related to coastal habitat restoration) or urban nutrient reduction efforts. While interest in exploring coastal habitat restoration – including wetland restoration – and urban nutrient reduction efforts did emerge on several occasions during stakeholder discussions, the focus on agricultural management practices was necessary given the use of the SWAT model which does not have capabilities to model the impacts of coastal wetlands or urban areas on nutrient transport, though the topics were identified as areas for future work.

Identification of BMP Scenarios

Given the strong stakeholder interest in current climate and the capabilities of the SWAT model, and the fact that so many different BMPs could be considered (including suites of BMPs), much of the modeling emphasis in this project was on modeling and presenting various BMP scenarios in the current climate. Stakeholder discussions revealed significant interest in several aspects of the modeling, including "ground truthing" of the model inputs (particularly with respect to existing farm practices), the sensitivity of outputs to model assumptions (such as the timing of fertilizer applications), and the model's ability to accurately predict results for specific practices (e.g., whether a no-till scenario accounts for broader soil health benefits).[54]

Concerning individual best management practices, the survey included questions on specific individual BMPs, and revealed particular interest in nutrient management practices (i.e., the 4Rs of nutrient management, or right source, right rate, right time, and right place)[55] along with conservation tillage and manure application practices. These were followed by soil erosion control practices (such as tillage management and cover crops) and practices addressing flow (e.g. filter strips, drainage tiles), with the least interest in wind erosion control practices as well as conversion of land to long-term conservation cover.[56] The survey formed the basis of BMPs selected for particular focus in the initial series of workshops. Workshop discussions led to refinement of individual BMPs and identification of additional BMPs (e.g. drainage water management, use of wetlands) and suites of BMPs for potential consideration, and combined outcomes of the survey and initial workshops formed the basis of scenario modeling carried out by the team.

Additional interests surfacing among stakeholders at the workshops were identifying BMPs that would be particularly effective at addressing phosphorus export (in particular DRP) from the Maumee River watershed, exploring implementation of multiple BMPs at one time (including in-field, edge-of-field, and in-stream), and considering economics. The workshops also allowed for more in-depth (and sometimes nuanced) discussion on specific BMPs; for example, it was noted that wider filter strips may not perform better in reducing nutrients, given they can be accompanied by berm formation, leading to rerouting of flow alongside the filter strips (and thus decreasing their effectiveness).[57]

Ultimately, following calibration of the model, modeling was done for multiple groups of scenarios (Table 2), with groups consisting of nutrient placement, nutrient timing, cover crops, vegetated filter strips, combinations (e.g., particular tillage and nutrient management (with particular cropping) practices), and "feasible" scenarios (e.g., 25-33% adoption on randomly identified acreage of particular type), covering 25 individual scenarios altogether.[58]

Scenario Modeling Results and Stakeholder Discussions

The modeling included an analysis of current conditions in the Maumee River watershed, which were approximated to the extent possible, given available data on factors such as cropping patterns, tillage practices, drainage approaches, and nutrient management practices; running the model with this information gave "baseline" conditions for nutrient and sediment export from the watershed, against which all other individual scenarios (whether involving different BMPs or climate change, or both) could be compared.

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Cover crops were modeled to explore their effectiveness at reducing phosphorus loads measured in the Maumee River (close to the outlet to Lake Erie, a point where nutrient loads are commonly estimated based on monitoring data), and Figure 4 shows results.

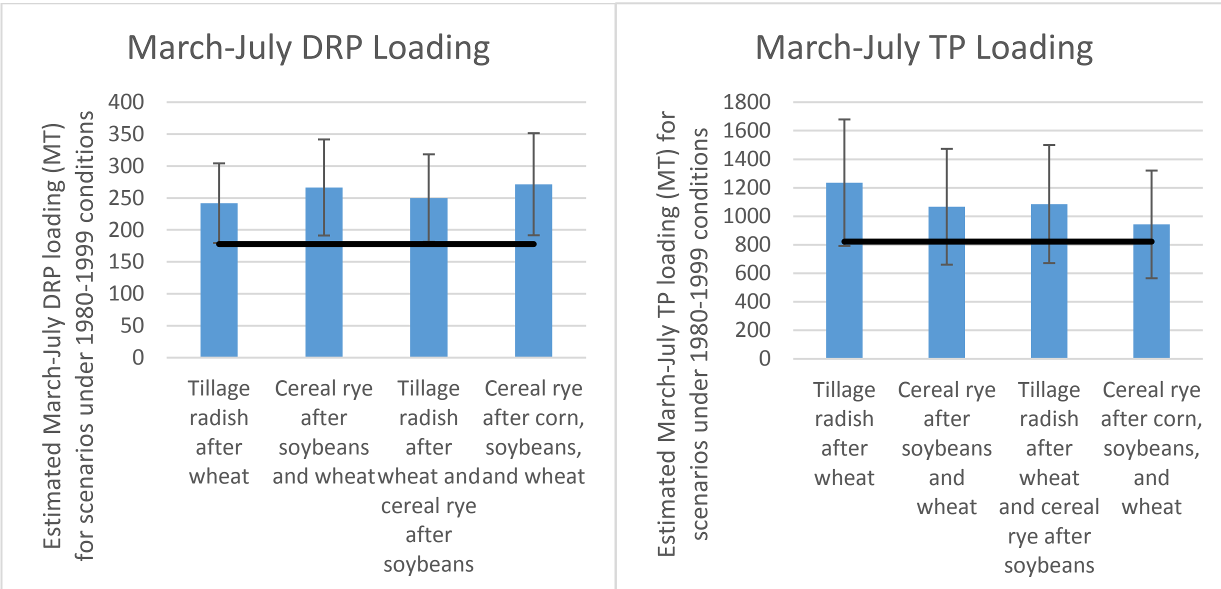


Figure 4. Simulated March-July DRP (left) and TP (right) loading (in metric tons (MT)) at Waterville (OH) for full implementation of four different uses of cover crops in crop rotations. The error bars give standard deviation of the years 1980-1999. Baseline simulations were 240 and 1238 MT for DRP and TP, respectively, and the black line represents the target loading.

As shown at right in Figure 4, widespread adoption (i.e. across all crop fields in the watershed) of cereal rye after all row crops would nearly lead to meeting the total phosphorus target for Lake Erie. However, cover crops perform worse in mitigating DRP loading. As shown in the panel at left in Figure 4, the target for dissolved reactive phosphorus loading would not be met by cover crop implementation alone; other BMPs (or combinations) are necessary to meet DRP loading targets. This pattern also illustrates the apparent potential tradeoffs in effectiveness of individual BMPs for TP vs. DRP. It is important to note the model did not account for some benefits of cover crops (e.g. increased organic matter content), with implications for nutrient export.

The effects of timing of fertilizer application was explored through a number of scenarios, with example results shown in Figure 5. As indicated, spring vs. fall timing of fertilizer did not appreciably affect TP loading; however, fall application resulted in significantly reduced March-July loading of DRP to the lake. As previously stated, research suggests March-July DRP loading is strongly associated with harmful algal bloom development in Lake Erie. Therefore, reducing spring-time phosphorus application (and increasing fall application) may contribute to reduction in summertime HABs.

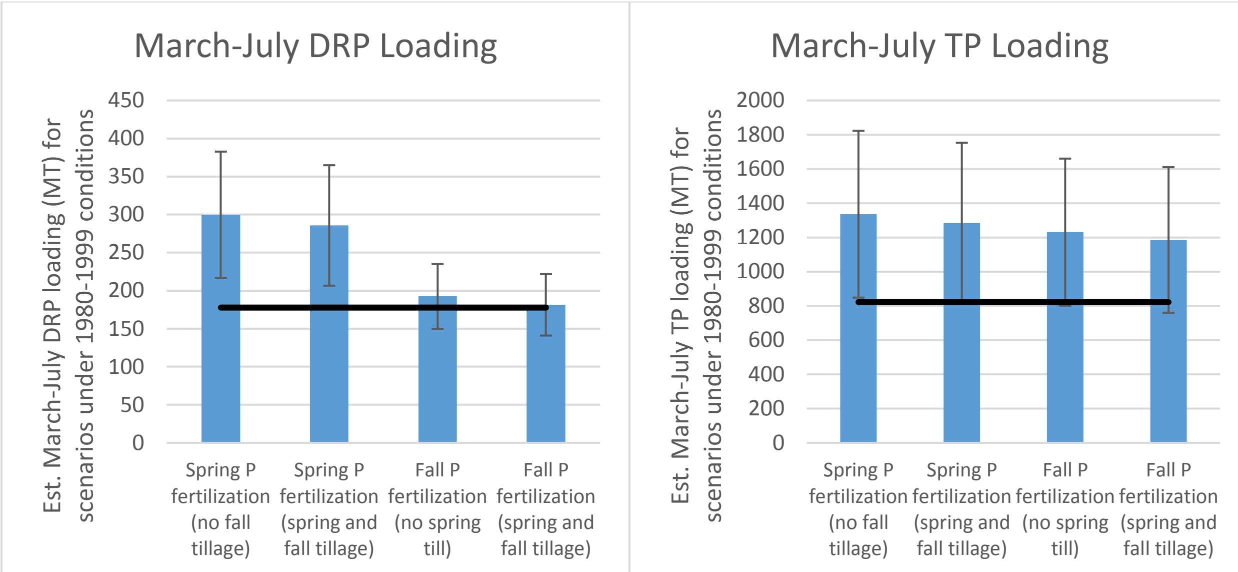


Figure 5. Simulated March-July DRP (left) and TP (right) loading (in metric tons (MT)) at Waterville (OH) when comparing spring vs. fall application of fertilizer. The error bars give standard deviation of the years 1980-1999. Baseline simulations were 240 and 1238 MT for DRP and TP, respectively, and the black line represents the target loading.

Among all BMP scenarios evaluated, subsurface application of fertilizer was identified as particularly effective at reducing DRP export from the watershed. This was also reflected in "combination" scenarios, where scenarios including subsurface placement uniformly resulted in reduced phosphorus export, with the largest reductions seen for subsurface placement coupled with cereal rye cover crop (after corn, soybean, and wheat), and use of "high quality" filter strips. While combination scenarios reduced phosphorus export, modeling results suggest that use of multiple practices was not additive, likely due to diminishing returns obtained from each subsequent practice added in combination.

Modeling was also done for suites (or combinations) of practices implemented on 25-33% of farmland, an extent identified as "feasible" based on stakeholder input. These practices included reduced tillage, subsurface fertilizer application, cover crops, and vegetated filter strips. While "feasible" implementation rates of suites of practices achieved modest changes from baseline, implementing at "feasible" levels of adoption did not result in meeting targets for either TP or DRP on average. Rather, if these practices (that are already being increasingly used in the watershed) are implemented more extensively, results suggest that meeting the new Lake Erie phosphorus reduction targets should be attainable in most years.[59]

Climate Modeling Results and Stakeholder Discussions

Climate simulations evaluated for the Great Lakes region showed that by mid-century the region will likely face an increase in surface air temperature warming across all months throughout the year, a higher chance of larger precipitation events, and a general increase in monthly average precipitation, in particular for winter and spring.[60] Temperature and precipitation data from five of the model simulations were used as inputs to the SWAT model, allowing for calculation of mid-century streamflow, and TP and DRP loads as shown in Figure 6 below.

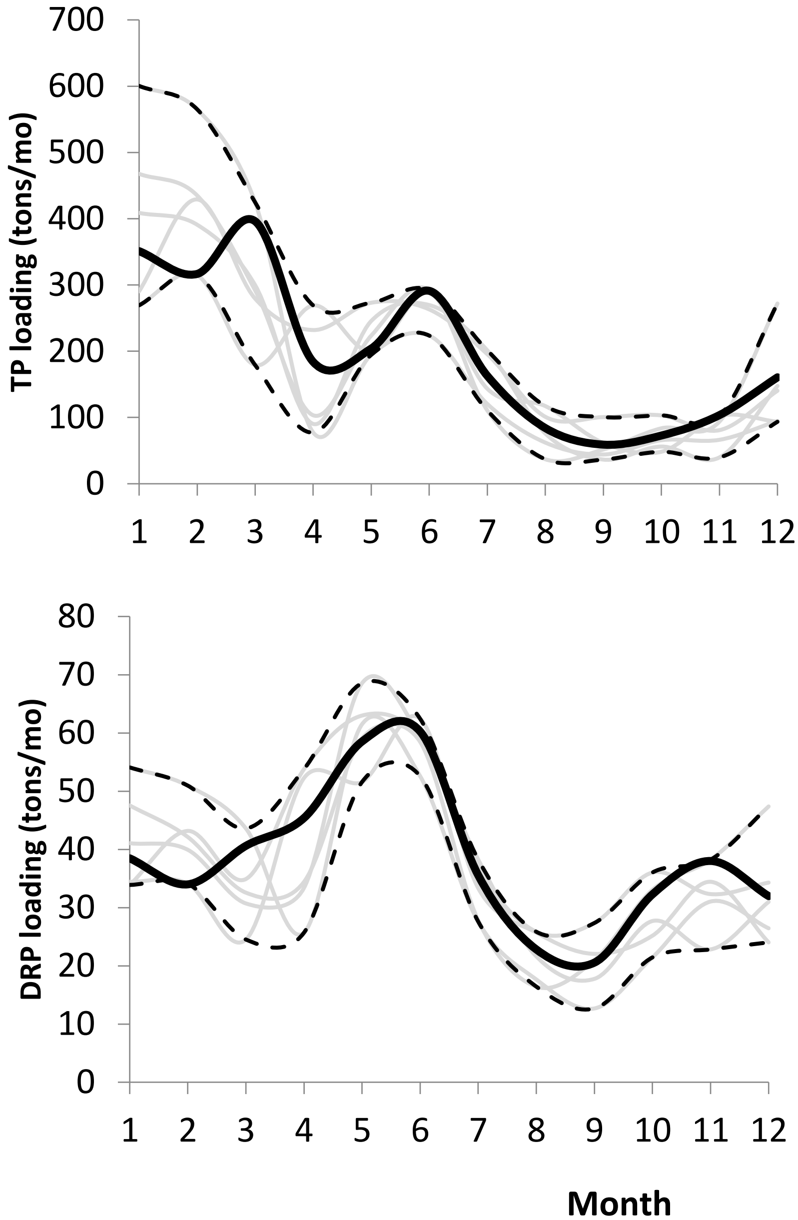


Figure 6. Projected mid-century (2041-2065) monthly total phosphorus loading (top) and dissolved reactive phosphorus loading (bottom) to Lake Erie from the Maumee River derived from SWAT model outputs. The SWAT model used five climate models (data indicated in light gray lines), with the baseline simulation (i.e., the SWAT model using historical climate station data for 1980-1999) indicated by the solid black curve, and the range of all projections indicated by the dashed curves. To have more interpretable results not confounded by model bias, climate model data was calculated as a percent change from the climate model prediction in the historical period to the future period, and that percent change was applied to the baseline data.

Patterns of both more variability and more consistency were seen in the results. For example, variability between models is indicated in some cases where two or three models show an increase while the other models show a decrease in phosphorus loading compared to the baseline for a given month. On the other hand, results also show periods with more consistent results between models, including where they generally depict higher loads (e.g. winter), and lower loads (e.g., March-April) compared to baseline. Other recent research found similar results, including a study projecting higher loads over baseline in winter and generally lower than baseline loads in summer (though they also found increased loads in April-May).[61] While our modeling results focus on phosphorus loading at Waterville, it is important to note that other factors influence eutrophication and impacts, including climate-driven changes in the lake such as warmer temperatures and a longer period of stratification, as well as other ecosystem changes (e.g. changes in invasive mussel abundance and internal phosphorus cycling),[62] issues not addressed (beyond limited stakeholder discussion) in this project.

The presentation of future projections to stakeholders resulted in some concerns around the uncertainties and wide range in projections in some cases. As with any type of projection, there is uncertainty in modeling of phosphorus loads, and in the case of this project, multiple factors contribute, including some differences in matching climate data for the historical period, the fact that current loads may be different from the baseline historical period (1980 – 1999), use of the SWAT model with climate data outside of the calibrated range, and uncertainties in future climate projections. The team noted these concerns among stakeholders, and agreed there is a need for additional modeling to attempt to clarify likely outcomes with future climate scenarios, including the direction of change.

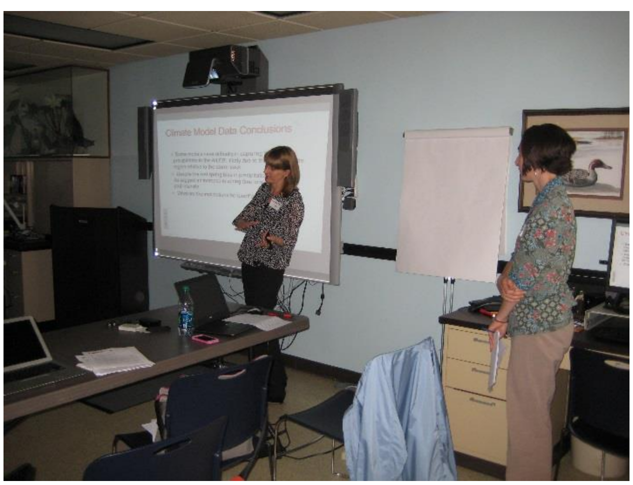
Strong stakeholder interest in exploring impacts of various BMPs on nutrient loads in the current climate, the plethora of BMP scenarios to consider, and the uncertainties in projected impacts of climate change on nutrient loads led to relatively limited stakeholder discussions on how management approaches might need to change in a future climate, though climate change did arise in several contexts, including:

- <u>Growing season</u>, which has lengthened in recent years, and farmers have already begun adapting to this by growing longer-yielding corn varieties;
- <u>Water availability</u>, with implications of drier periods on crop yields, the potential need for more irrigation, and potential interest in holding water back on fields during drought periods;
- <u>Nutrient hotspots</u>, i.e. areas with high potential for phosphorus transport, and potential to see increased phosphorus export;
- <u>Period of focus</u>, aligning climate projections with the spring-time period for nutrient targets;
- <u>Large events</u>, and implications for changes in frequency or intensity (including on relative contribution to annual phosphorus loads)

VI. Adaptation Guidance and Recommendations

Any consideration of climate adaptation in the context of Lake Erie eutrophication must recognize the intrinsic connection between the climate driver and eutrophication (Figure 2). For example, Lake Erie eutrophication was evident as early as the 1920s,[63] and data for multiple decades prior to 2002 showed phosphorus loads generally varying with hydrology in a given year.[64] With signals of anthropogenic climate change clearly apparent globally, the importance of considering both direct and indirect effects of climate change (e.g., on other stressors such as nutrient loadings) has been recognized.[65] Thus, discussion here considers adaptation in a broad context, in particular involving the indirect effects of climate change.

As noted in Section II, this project entailed components of what might otherwise be undertaken in a broader adaptation planning process related to eutrophication, with an emphasis on briefly summarizing assessments of climate impacts on another key stressor (nutrient loads) and identification and evaluation of adaptation options (i.e., in this case, potential changes in implementation of BMPs in the watershed to achieve nutrient loading targets in the context of climate change). A formal vulnerability assessment was not carried out, though significant research in Lake Erie over the past decade could inform such an assessment, as information would be available relevant to the three components (exposure, sensitivity, and adaptive capacity) at a broad scale in the lake. For example, though not directly reflecting climatic sensitivity, research indicates that the lake itself may have become more susceptible to HABs over the past 15 years, which could be due to one or more factors, including climatic (e.g. calmer summers), effects of invasive zebra and quagga mussels, or a reservoir of *Microcystis* seed colonies in lake sediments.[66] Researchers have suggested that these systemic changes should be considered in development of phosphorus loading targets for the lake.[67]



C. Kirchhoff

Concerning possible adaptation options to address the system vulnerability, one could consider attempting to reduce sensitivity or increase adaptive capacity. However, when considering management opportunities applicable at a scale of at least the western basin of Lake Erie, these would be very large undertakings. Furthermore, consideration of in-lake processes was largely beyond the scope of this project.[68] (General resources on adaptation are indicated in Section VIII.)

Addressing exposure in the context of Lake Erie eutrophication is more feasible. From the perspective of Lake Erie eutrophication, exposure can include climate factors that can directly contribute to impacts (e.g. warmer temperatures, calmer periods) as well as climate factors that indirectly contribute to impacts (e.g. increased intensity of spring storm events), which in turn may cause increased nutrient loads to the lake (as discussed earlier, and schematically in Figure 2). Nutrient export independent of climate is of course important as well, and thus any practice with the potential to affect nutrient export out of the watershed would be of interest concerning approaches to reduce eutrophication. As discussed above, numerous BMPs – including subsurface fertilizer application, cover crops, and vegetated filter strips – have the potential to contribute to reducing phosphorus in the western basin of Lake Erie. Projections of phosphorus loads to Lake Erie in a future climate include additional uncertainties, though results from this study suggest at most modest increases in phosphorus loads with climate change by mid-century. Beyond potential loading changes associated with climate change in the coming decades, there are also potential changes in other drivers, such as broader-scale changes in agriculture (e.g., in use of biofuels) and urban development, with their own uncertainties.[69]

In this type of situation with significant uncertainty, "low regrets" or "no regrets" actions are often promoted. Such actions are viable in addressing other conservation needs, are robust (or useful) in different climate scenarios, or both.[70] In the context of addressing nutrient loss from agricultural lands in the western basin of Lake Erie, any actions to reduce nutrient export should be positive, both from the benefit of farmers (e.g., potentially meaning lower costs) and the lake. Such efforts can include actions that improve soil health (including related to soil structure, organic matter content, and water holding capacity), which in turn can help reduce export of nutrients.[71] A number of the BMPs assessed in this project could contribute to both objectives of reducing nutrient export while improving soil health, including nutrient management and cover crops.

Recommendations for reducing phosphorus export from agricultural watersheds in the western basin to meet targets for Lake Erie (in the current climate) include the following:

- Subsurface application of phosphorus fertilizer (or incorporation through tillage) may be the single most effective practice that can reduce DRP loading
- Timing of fertilizer application is important, and though consideration of spring vs. fall application did not appreciably affect TP loadings, simulation of fall application resulted in significantly reduced March-July DRP loadings to the lake
- There is a need to consider the potential for trade-offs (e.g., some measures may contribute towards TP or DRP targets, but not necessarily both)
- Relatively broad implementation of practices is needed to meet recently adopted targets for Lake Erie, including particular practices (such as subsurface fertilizer application) over a broader extent of agricultural land than the "feasible" scenarios modeled in this project[72]

It is important that any subsequent implementation of such agricultural practices on a broader scale include monitoring and evaluation (consistent with the adaptation framework noted in Section II). Such efforts – which should include research studies – would ideally be occurring at various levels (e.g., field, subwatershed, basin, etc.) to evaluate effectiveness of both individual BMP efforts as well as aggregate impacts on nutrient loadings at the basin scale. Monitoring and evaluation efforts need long-term commitment (e.g., a number of years), both to capture the substantial variability in climate variables that can occur between years and to assess longer-term trends in nutrient loads (and coupled with data on impacts in the lake).

M. Murray

An additional approach to addressing Lake Erie eutrophication in an adaptation context is through coastal management. As noted previously, based on the composition of stakeholders and the direction of discussions, the emphasis in this project shifted to agricultural practices and nutrient loadings, though there was interest and limited discussion of coastal management issues, in particular involving coastal wetlands. Given the limitations of the SWAT model as previously noted, the potential for wetlands construction or restoration to contribute to nutrient reductions was not assessed in this project, though there have been a handful of studies examining the potential for wetlands to reduce nutrient loads in Lake Erie.[73] Given the significant historic losses of coastal wetlands in the region (in particular in the western basin of Lake Erie), the significant ongoing efforts at wetland restoration across the region (including through the Great Lakes Restoration Initiative) and the potential significance in contributing to nutrient reductions, there is a need for further research on issues such as targeting locations for restoration within the watershed.[74] Pending such research, there are increasingly resources available to assist ongoing efforts at wetland restoration (or construction) in the region while considering climate change, including a recently developed toolkit that identifies best practices in a number of areas, including for vulnerability assessments, adaptation performance indicators, and monitoring.[75]

Urban areas – both along the coast and elsewhere in the western Lake Erie watershed – also need to be considered in efforts to address Lake Erie eutrophication, though again, these areas were not a focus of this project. Although urban sources (including wastewater treatment plants and sewer overflows) overall represent a relatively small portion of phosphorus delivered to Lake Erie,[76] there is potential for further growth and development in urban areas in coming decades, with implications for phosphorus loads.[77] Furthermore, a number of BMPs applicable in urban areas are available, though further study on effectiveness at reducing nutrients is warranted.[78]

In addition to recommendations regarding agricultural practices, coastal management, and urban areas, two broad insights related to stakeholder efforts in general were gained through this project:

- For development of information most useful to stakeholders, the modeling efforts should be as transparent as possible and the information generation process should involve information users to the maximum extent possible. These efforts recognize that co-production is more than just bringing together two different but internally similar communities (e.g., "scientists" and "stakeholders"); rather, it should be a process for facilitating the integration of numerous sets of knowledge and expertise.[79] Components of this project were designed to optimize both of these objectives, through the combination of the survey, interviews, and workshops.
- Additional findings related to stakeholder perspectives included recognition of a diversity of perspectives and motivations for individual involvement in scientist-stakeholder collaborative research; the potential for stakeholder fatigue; and a diversity of thinking concerning the scope of concerns of individuals, including ranging across potential elements over which individuals have control. In particular, because stakeholders are not homogenous, strategies for engaging with them on knowledge production potentially need more nuance and adjustment than previously thought.[80]

In summary, this project involving a collaborative effort between a diverse group of stakeholders and a multi-institution project team yielded a number of useful insights concerning the challenges of addressing ongoing eutrophication of Lake Erie. This report briefly highlights a few of the many factors involved in addressing agricultural practices potentially relevant to nutrient loads to Lake Erie, the potential for a watershed model to calculate loads for different scenarios, what is more certain and less certain concerning potential future climate conditions in the region, and the importance of strong involvement of stakeholders in multiple aspects of this project, including developing scenarios and communicating results. While multiple science questions remain – including on components of future regional climate, nutrient behavior in the watershed, and strengths and limitations of the watershed model – future involvement of stakeholders in similar collaborative processes will help ensure that results produced are as policy- and practitioner-relevant as possible.

VII. Endnotes

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VIII. Selected Climate Adaptation Resources

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General Adaptation Guidance Reports

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Selected Online Climate Adaptation Resources

EcoAdapt, Climate Adaptation Knowledge Exchange (CAKE)
http://ecoadapt.org/programs/cake

National Oceanic and Atmospheric Administration, Climate Adapted Planning Resources
http://www.regions.noaa.gov/great-lakes/index.php/project/climate-change-adaptation-resources/

National Oceanic and Atmospheric Administration, Great Lakes Coastal Resilience Planning Guide
http://greatlakesresilience.org/

Ontario Centre for Climate Impacts and Adaptation Resources
http://www.climateontario.ca/

University of Michigan, Michigan State University, Great Lakes Integrated Sciences and Assessments
http://glisa.umich.edu/

University of Notre Dame/National Science Foundation, Collaboratory for Adaptation to Climate Change
https://adapt.nd.edu/