NOAA-COCA Final Report: 1September13-31August 16

University of Michigan | University of Connecticut

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Project Title:

Enhancing manager and stakeholder awareness of & responses to changing climatic conditions & their impacts on Lake Erie

Project Team:

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Section 1: Introduction

This report summarizes the work accomplished under the "Enhancing manager and stakeholder awareness of & responses to changing climatic conditions & their impacts on Lake Erie" project from September 1, 2013 to August 31, 2016. Section 2 briefly describes team meetings, stakeholder workshops, and research while Sections 3-7 briefly summarize results and outreach efforts, and list all publications, presentations, and students/postdoctoral researchers funded on this project. Additional details about the research and work on this project can be found in the interim reports. Finally, we include relevant project publications including the final adaptation guidance document, and copies of published peer review papers.

Section 2: Meetings, Workshops, and Research Aims

2.1 Team Meetings

Routine communication via email, conference call, and in person meetings helped to advance the work and research. Specifically, team communication fostered collaboration on workshop planning, debriefs from the workshops, Stakeholder Advisory Group meetings and debriefs, scenario development and evaluation, fact sheet development and revision, adaptation guidance development and revision, coauthoring of peer reviewed publications based on this work, and writing of project progress reports.

2.2 Stakeholder Workshops Informed Scenario Modeling for Phosphorus Reduction

At its core, this project aims to foster an inclusive, collaborative approach by involving stakeholders more directly in the process of model development and in helping to direct what future scenarios are modeled. To achieve this aim, we designed a series of workshops to foster interaction, two-way learning, and to gather group-level input and feedback. We organized two sets of three stakeholder workshops in August 2014 and June 2015. Workshops were held at three different locations, the Ottawa National Wildlife Refuge (ONWR) in Oak Harbor, Ohio, the Old Woman Creek National Estuarine Research Reserve (OWCNERR) in Huron, Ohio, and the Graham Sustainability Institute on the campus of the University of Michigan in Ann Arbor, Michigan.

In total, 18 stakeholders took part in the 2014 workshops representing municipal or state governments (4), county soil and water conservation districts (3), federal government or international (3), non-governmental organizations (4), and business/farming (4). These workshops began with networking followed by interactive presentations about the climate and watershed modeling. Discussions were oriented towards making the modeling more transparent and, in so doing, providing stakeholders with an opportunity to suggest model improvements. The presentations were followed by facilitated brainstorming to determine which individual or suite of practices (hereafter called scenarios) stakeholders thought were the most important to include in the model and to discuss what each scenario might look like. Extensive notes capturing the full range of stakeholder comments were later consolidated into a report shared with stakeholders and used to guide the modeling efforts.

Twenty stakeholders took part in the 2015 workshops representing municipal or state governments (4), country soil and water conservation districts (3), federal government or international (4), non-governmental organizations (4), and business/farming (5). The second set of workshops focused on discussing modeling results, identifying additional high priority scenarios to include in the final modeling effort, and discussing research translation and strategies for reducing harmful algal blooms in Lake Erie. These discussions enabled stakeholders to ask questions and to provide feedback. A peer review paper by Kalcic et al. (2016) summarized stakeholder feedback and suggestions. An additional paper focused on the perspective of stakeholders engaged in the COCA project is in preparation by Arnott, Kirchhoff and Carroll.

2.3 Research: Generating Stakeholder-Relevant Information

2.3.1 SWAT Modeling

The 2014-2015 progress report and 2015-2016 progress report detail the SWAT modeling efforts including the suite of proposed and actual scenarios modeled in SWAT and efforts to incorporate iterative feedback and input from stakeholders including feedback regarding farm management assumptions and predicting both total and soluble phosphorus and input regarding what scenarios to model. Stakeholders also assisted in developing “feasible” scenarios, which were a set of practices considered effective and desirable at implementation rates considered by stakeholders to be “feasible” for the region.

2.3.2 Climate Modeling

The 2014-2015 progress report and 2015-2016 progress report detail the climate modeling efforts including work to evaluate a suite of global and regional models, select five models and prepare daily temperature and precipitation datasets for the SWAT analysis based on their performance in the historical time period (1981-1999).

2.3.3 Interviews/Surveys

The 2014-2015 and 2015-2016 progress reports describe in detail the survey and interviews conducted for this study. Three separate data collection efforts were undertaken for the project.

First, a survey in advance of the first set of workshops that gathered input about which conservation practices are the most relevant to evaluate from agricultural producers, policy-makers, county soil and water conservation specialists, agricultural advisors, non-governmental organizations, researchers, and staff at state, federal, and intergovernmental agencies active in nutrient management and agricultural conservation in western Lake Erie watersheds. While not representative of the entire watershed, responses helped identify the range of conservation practices of most interest to stakeholders in advance of the workshops and helped recruit participants for the workshops. In total, 36 of 74 individuals responded to the survey for a 48% response rate. Survey respondents represented agricultural producers (3), Soil and Water Conservation Districts or agricultural advisors (4), non-governmental organizations (9), academia (5), and city/state/federal/international agency staff (15). Second, nine interviews were conducted from among survey respondents to understand survey responses in more depth. Third, a second set of twelve interviews were conducted after the conclusion of the second workshop to better understand: 1.What motivates stakeholders to participate in coproduction research projects? 2. Do stakeholders perceive their input is valued by researchers? 3. Does stakeholder trust or perceived usefulness of a model improve through the process of interaction with researchers over the course of model development? 4. What ideas do stakeholders have to improve the design of more productive coproduction projects in the future?

Section 3: Results/Significance of the Work

3.1 SWAT Modeling

A full history of SWAT modeling undertaken for this project is detailed in 2014-2015 and 2015-2016 progress reports. The final set of conservation scenarios suggested by stakeholders is shown in Table 1, with results in Figures 1 and 2. Notable differences from the scenarios run prior to the second workshop include addition of nutrient timing scenarios, removal of increasing/decreasing tile drainage intensity scenarios, removal of scenarios with implementation rates less of 100% and inclusion of "feasible" scenarios with a combination practices at reduced implementation rates.

The "feasible" scenarios chosen by stakeholders integrate reduced tillage, which is promoted in the region for reasons of soil health, subsurface application of phosphorus fertilizers, which was the single most beneficial practice for preventing DRP losses according to the model, perennial cover crops such as cereal rye, which are also promoted in the region and show improvements for TP losses, and vegetated filter strips for preventing phosphorus losses in surface runoff.

Annual and seasonal TP and DRP loading at the watershed outlet are certainly influenced by conservation practices, as shown in Figures 1 and 2. The practices promoted in the region may not be, in all cases, the most helpful for reducing TP and DRP loading. This is most notable in the increased TP and DRP loads that come from no-tillage with broadcast phosphorus fertilizers (scenario 1.1), yet the model may not have realistically reproduced the improvement in soil health associated with no-tillage and cover cropping. Regardless, subsurface application of phosphorus fertilizers, which is rising in recognition in the region, can counteract much of this effect. The model suggests the "feasible" scenarios of combined practices at 25-33% adoption will not be able to reach the targets for harmful algal blooms recently approved by the United States and Canada.

Table 1: List and descriptions of conservation scenarios run through the Maumee SWAT model. All scenarios were run with temperature and precipitation forcing from the 30-year historical station record (1981-2010).

0. Baseline (calibrated model)	The baseline scenario had a mixture of no-tillage and conventional tillage based on historical management information. P and manure were broadcast and incorporated, and applied at rates consistent with historical data and estimations. Tile drainage was simulated on crop fields with poorly, very poorly, and somewhat poorly drained soils. 2, 3, and 7-year rotations were designed from overlaying the 2007-2012 Cropland Data Layer, and contained a mixture of corn, soybean, and winter wheat. Cover crops, filter strips, and additional conservation practices were not included in the baseline model because we lacked access to this data.
1. Nutrient placement	1.1 Continuous no-tillage with broadcast fertilizer and manure 1.2 Continuous no-tillage with subsurface-applied fertilizer and broadcast manure 1.3 Continuous no-tillage with subsurface-applied fertilizer and manure 1.4 Baseline tillage with subsurface-applied fertilizer and manure
2. Nutrient timing	2.1 Spring P applications with no fall tillage 2.2 Spring P applications with baseline fall tillage 2.3 Winter application of manure 2.4 Fall P applications with no spring tillage 2.5 Fall P applications with baseline spring tillage
3. Cover crops	3.1 Tillage radish after wheat in rotations 3.2 Cereal rye after soybeans and wheat in rotations 3.3 Cereal rye after soybeans and tillage radish after wheat in rotations 3.4 Cereal rye after corn, soybeans, and wheat in rotations
4. Vegetated filter strips	4.1 Application of poor-quality* filter strips throughout agricultural lands 4.2 Application of medium-quality* filter strips 4.3 Application of high-quality* filter strips ** Filter strip quality is based on the percentage*
5 Systems approach/ Combinations	5.1 Continuous no-tillage with broadcast fertilizer and manure and cereal rye after soybeans and tillage radish after wheat (1.1 + 3.3) 5.2 Continuous no-tillage with subsurface-applied fertilizer and manure and cereal rye after soybeans and tillage radish after wheat (1.3 + 3.3) 5.3 Continuous no-tillage with subsurface-applied fertilizer and manure, cereal rye after soybeans and tillage radish after wheat, and medium-quality filter strips (1.3 + 3.3 + 4.2) 5.4 Continuous no-tillage with subsurface-applied fertilizer and manure, cereal rye after soybeans and tillage radish after wheat, and high-quality filter strips (1.3 + 3.3 + 4.3) 5.5 Baseline tillage with subsurface-applied fertilizer and manure and cereal rye after corn, soybeans, and wheat (1.4 + 3.4) 5.6 Baseline tillage with subsurface-applied fertilizer and manure, cereal rye after corn, soybeans, and wheat, and high-quality filter strips (1.4 + 3.4 + 4.3)
6 Feasible scenarios	6.1 25% adoption* of continuous no-tillage with subsurface-applied fertilizer and broadcast manure, cereal rye after corn, soybeans, and wheat, and medium-quality filter strips (1.3 + 3.4 + 4.2) 6.2 25% adoption* of subsurface-applied fertilizer and broadcast manure, cereal rye after corn, soybeans, and wheat, and medium-quality filter strips (1.4 + 3.4 + 4.2) 6.3 33% adoption* of subsurface-applied fertilizer and broadcast manure, cereal rye after corn, soybeans, and wheat, and high-quality filter strips (1.4 + 3.4 + 4.3) ** All practices were adopted on the same, randomly-selected farm fields*

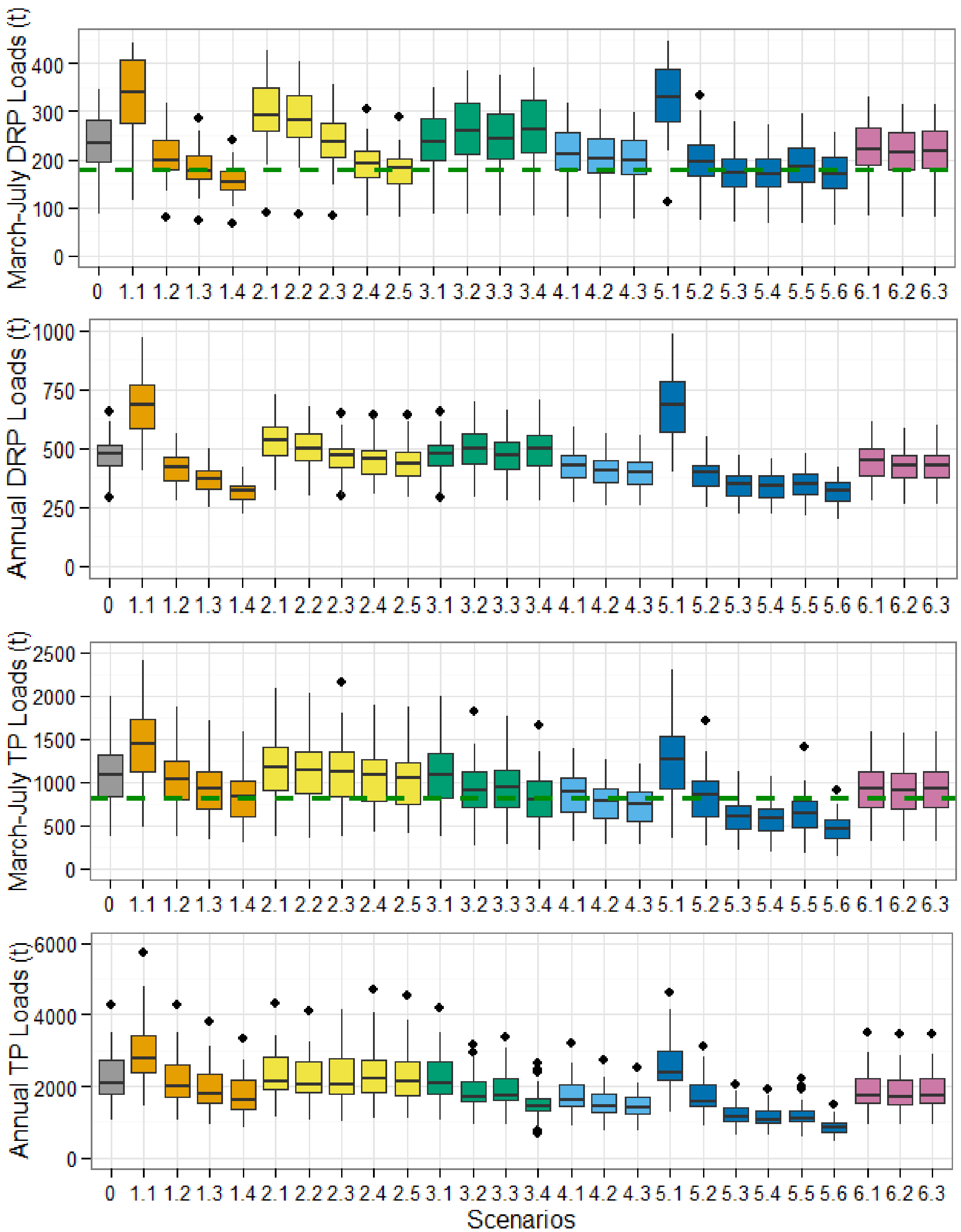
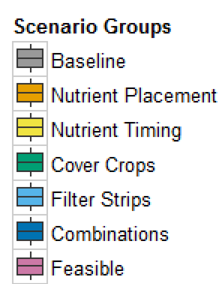


Figure 1: Boxplots of simulated March-July and annual DRP and TP loading at the Waterville gage under conservation management scenarios. Target loads (dashed green lines) are at 96% of the Maumee target loads to weight to the watershed area above the Waterville gage. Diamonds are considered outliers based on distance from the interquartile range (box). Consult Table 1 for scenario descriptions.



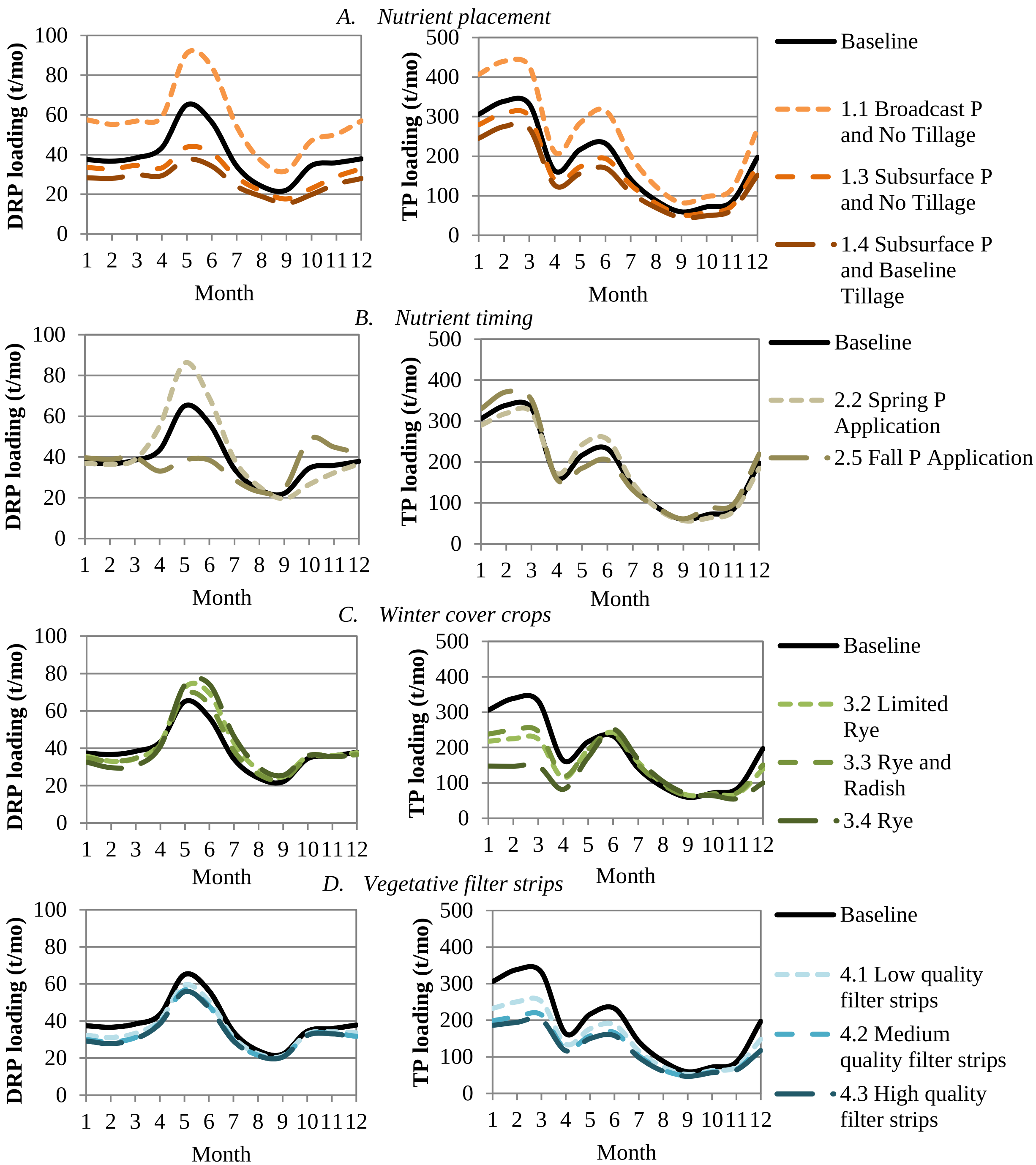


Figure 2: Seasonal dynamics of DRP and TP loading across conservation scenarios. *A:* Nutrient placement influences DRP and TP loadings similarly throughout the year due to changes in stratification of P at the soil surface, with the greatest reductions from subsurface placement and rotational tillage. *B:* Timing of P applications made little difference in annual DRP or TP loading, but was a strong driver in seasonal DRP loading, with fall applications yielding the greatest improvement in March-July loading responsible for the Lake Erie HABs. *C:* Winter cover crops held back nutrient runoff during the winter months, reducing TP loading considerably throughout most of the year, but shifting the timing of DRP from winter to spring-time and summer. *D:* Filter strips intercepted nutrients traveling in surface runoff similarly throughout the year, with greater reductions for TP than for DRP.

3.2 Climate Modeling

A full description of the climate modeling undertaken for this project is detailed in the 2014-2015 and 2015-2016 progress reports. Precipitation projections within the Western Lake Erie Basin (WLEB) were examined using climate model ensembles of varying resolutions to constrain and compare associated output uncertainties under high emission scenarios from the Climate Model Intercomparison Project (CMIP) experiments (CMIP3 and CMIP5). Daily probability distribution functions from three model ensembles reveal consistent increases in high precipitation events probabilities when compared to the observation period (1980 to 1999). For the WLEB, all three ensembles captured the range of daily intensity of historical events with an overestimation of intense events across all seasons, however this bias was improve for the autumn season across ensembles. While the high resolution RCM ensemble had a dry summer and autumn bias in intensity (and seasonality), the ensemble compared better with observations for winter events compared to the other two ensembles. Both regional ensembles had reduced intensity bias for the whole Great Lakes region compared with the global ensemble. Both CMIP5 and NARCCAP ensembles capture the annual GLB summer maxima, yet have a wet bias in the spring and winter, while the RCM3(HiRes) ensemble produced a dry bias for the spring and summer seasons but shows a similar wet winter peak. The overall consensus indicates an increase in monthly average precipitation across all seasons with higher amplitude changes in spring and winter across the GLB.

We selected five of these climate model simulations to provide daily temperature and precipitation input into SWAT. We used precipitation and temperature from models to drive SWAT and understand how phosphorus and nitrogen loading might change in the future. Figure 3 shows change in average temperature and precipitation while Figure 4 shows the change in spring* streamflow, total phosphorous (TP) and dissolved reactive phosphorus (DRP). Models showed a mixed response in TP loading, from a 50% increase to almost a 50% decrease. Interestingly, DRP loading was lower in the future models. There is considerable uncertainty in these predictions, derived from difference in the model and observations in the historical period, the future climate projections, and the SWAT model's response to climates outside the calibrated range. Additionally, we are comparing the future models to a historical time period that goes through only 1999, so current day DRP loading may be quite different.

Climate projections results were shared with stakeholders in the 2015-2016 workshop. Stakeholders expressed concern about the wide range of predictions, including many showing reduced phosphorus loading in the future, and were unsure how to use the results. .

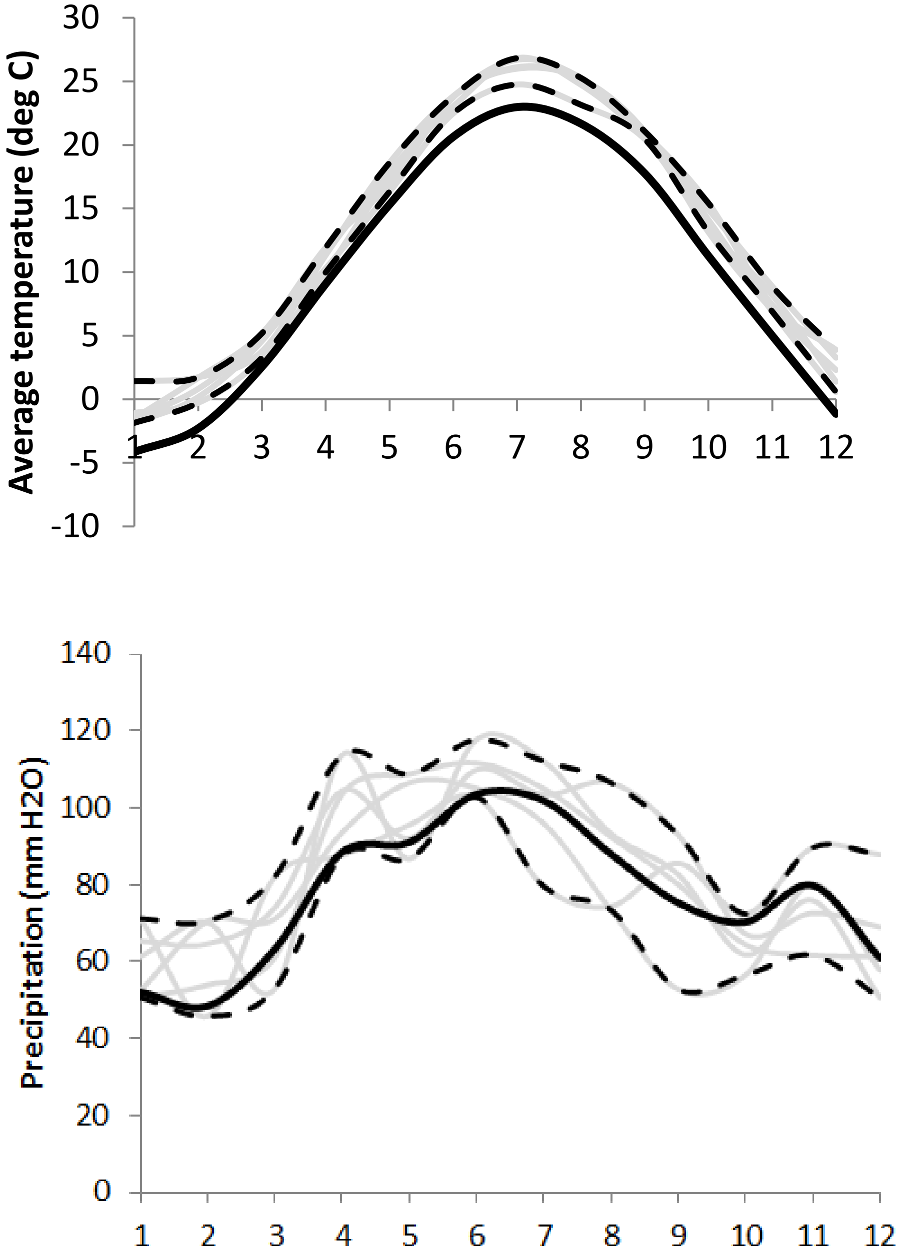


Figure 3: Projected (2046-2065) monthly temperature and precipitation under five climate models compared with the simulated historical data (1980-1999). The solid black line is the historical station data record (1980-1999), the grey lines are projected change from the five climate models multiplied by the historical record, and the dashed black lines show the envelope of projections. Temperatures are projected to increase considerably throughout the year, and in particular during the winter. Precipitation is projected to increase somewhat in the winter and spring.

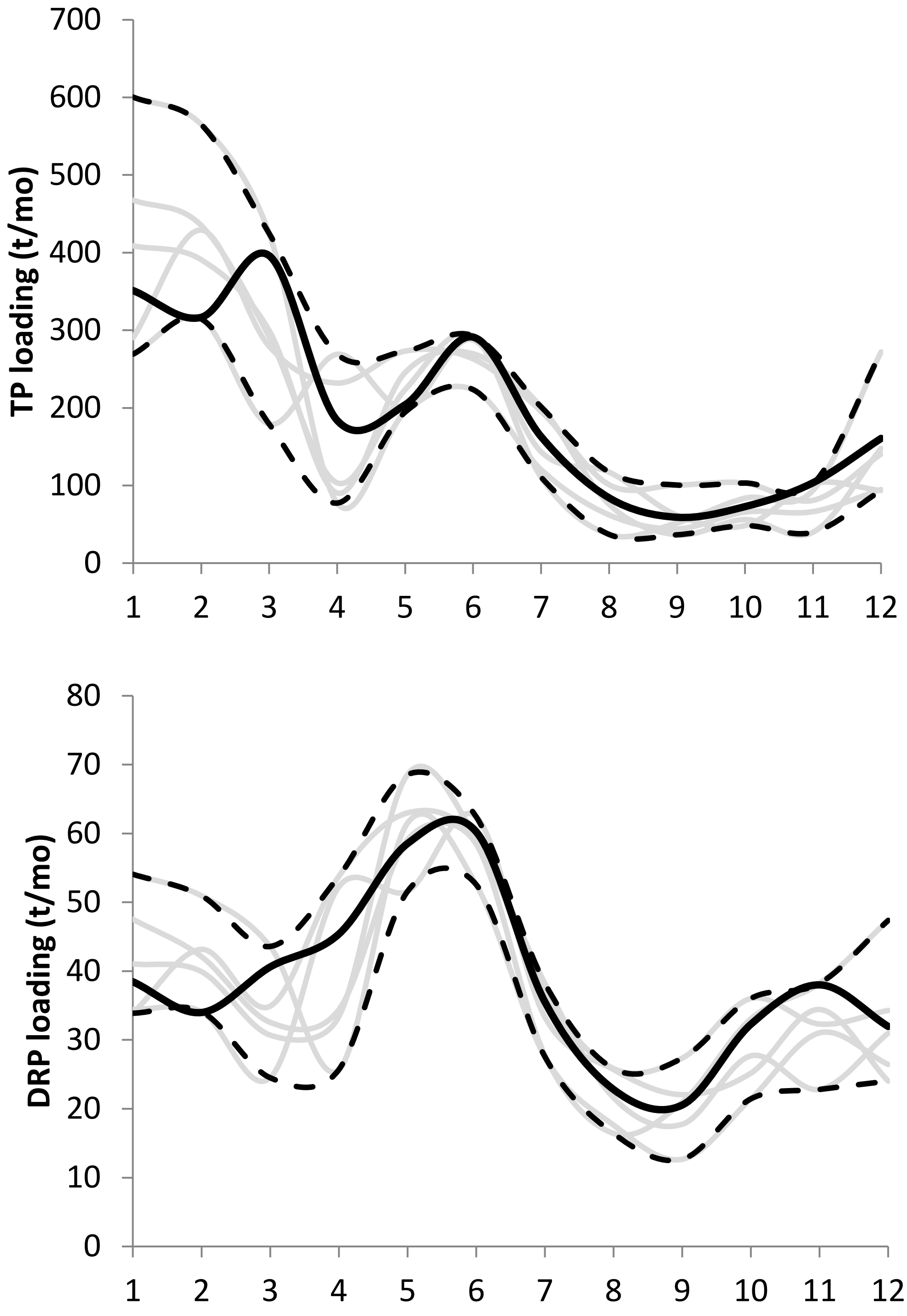


Figure 4: Projections of monthly TP and DRP loading from SWAT under baseline management driven by five climate models. The solid black line is SWAT results driven by the historical station data record (1980-1999), the grey lines are projected change from SWAT driven by the five climate models (between 1980-1999 and 2046-2065) multiplied by results from SWAT driven by the historical record, and the dashed black lines show the envelope of projections. Despite precipitation increases in the springtime, warmer winter and spring temperatures encourage greater infiltration and spring-time loading of TP and DRP is projected to decrease under many climate models.

3.3 Stakeholder Coproduction or Informed Research

We sought to capture the benefits of iterative and engaged research on improving the models and the policy-relevance of the results. By engaging stakeholders through surveys and in interactive workshops, we improved communication and mutual understanding between modelers and the stakeholders, illuminated and informed conservation practice model assumptions, solicited input that drove research questions, and increased the likelihood that the science produced would be policy-relevant. This was important because, while all modeling efforts make trade-offs among assumptions, decisions, and simplifications, to be useful for informing decisions models should be made transparent and results generated in collaboration with potential information users. Increasing this transparency benefits both the science by illuminating and "ground truthing" model assumptions, and its applicability by improving understanding, buy-in, and trust by potential users. Project team members published a manuscript in *Environmental Science & Technology* summarizing this effort entitled, "Engaging Stakeholders to Define Feasible and Desirable Agricultural Conservation in Western Lake Erie Watersheds."

We sought to better understand the perspectives of stakeholders who engage with scientists in coproduction, an area that is presently under studied in the literature. Specifically, we sought to answer five research questions: 1. What motivates stakeholders to participate in coproduction-oriented research projects? 2. What value do stakeholders gain from participation in collaborative research? 3. Do stakeholders believe the input and effort they contribute to coproduced research projects is valued by researchers (i.e. used to actually shape trajectory of research)? 4 Do stakeholders' trust in or perception of the usefulness of coproduced science (e.g., a model) increase as a result of coproduction? 5 What ideas do stakeholders have about opportunities for science-practice interaction that could inform the design of more productive partnerships in the future?

Data derived from interviews revealed a range of motivations for participating in coproduction, summarized in Box 1.

Box 1. Comprehensive list of motivations for participating in research project

- Fulfilling personal passion/curiosity
- Fulfilling professional obligations
- Obligation of public service, civic duty
- Serve as intermediary between research community and some end user
- Gaining new information, perspectives about their field to inform one's own work
- Making new or strengthening personal/professional connections (i.e. networking)
- Giving input to research (e.g., filling knowledge gaps, correcting inaccuracies)
- Gaining early access to research results
- Make sense of policy implications of research

Regarding our second and third research questions, interviews revealed stakeholders derived a range of benefits from participating in coproduction including interacting with scientist, being able to see the results of coproduction, and relevance to stakeholder's work while the majority of stakeholders interviewed felt their input was valued by scientists. Regarding trust in model and perceived model utility resulting from coproduction, some stakeholders felt interactions improved their trust in the model while others, the interaction and added transparency reduced their trust in the model and their perception of the model utility. Finally, stakeholders provided a range of suggestions for improving coproduction in the future including using different types of science-public-practice interactions; more carefully selecting participants to ensure that the each has relevant expertise and that one voice does not dominate the conversation; and conducting more follow up with the participants after the meeting. Some stakeholders were more critical of collaborative research itself both calling into question whether it is even appropriate to engage stakeholders in this kind of research and criticizing the design and execution of collaborative research projects. A manuscript summarizing this research entitled "What "they" think: perspectives of stakeholders on their participation in collaborative research" is in preparation by project by Arnott, Kirchhoff and Carroll.

Section 4: Guidance Document and Outreach

4.1 Guidance Document

A full description of the guidance document and outreach materials development is detailed in the summer 2016 progress report. A key output from this project is a guidance document, citation: **Murray, M.W., Kirchhoff, C., Kalcic, M.M., Steiner, A., Bosch, N., Lopez, F., Scavia, D. 2016.** Guidance addressing Lake Erie eutrophication in a changing climate based on a case study with agricultural and coastal managers.

The guidance document provides recommendations based on the results of this research for reducing phosphorus export from agricultural watersheds in the western basin to meet targets for Lake Erie and recommendations for future research with stakeholders to ensure policy and decision relevance. The key recommendations for reducing phosphorus export from agricultural watersheds in the western basin to meet targets for Lake Erie (in the current climate) are:

- Subsurface application of phosphorus fertilizer (or incorporation through tillage)
- Timing of fertilizer application is important, with simulation of fall application showing reduced March-July DRP loadings to the lake
- Consideration of trade-offs is important (e.g., some measures may contribute towards TP or DRP targets, but not necessarily both)
- To meet recently adopted targets for Lake Erie, will require relatively broad implementation of practices over a broader extent of agricultural land than what is considered "feasible" in this project

4.2 Website

A full description of the website development and contents is detailed in the summer 2016 progress report. The website, developed with expertise from a science communication doctoral student, provides a mechanism for interested parties to learn about and benefit from our work beyond the life of the project. The website includes both general information about algal blooms and Lake Erie, a video with the Project PI describing the project, contact information for the project team, a description of the collaborative process, and links to project outputs.

Section 5: Presentations at Conferences or Workshops

Basile, S.J., A.M Bryan, D. Brown and **A.L. Steiner**, Projected precipitation changes within the Great Lakes region: A multi-scale analysis of precipitation intensity and seasonality, presented at the American Meteorological Society Winter Meeting, Phoenix, AZ, 7 January 2015.

Basile, S.J., A.M Bryan, D. Brown and **A.L. Steiner**, Projected precipitation changes within the Great Lakes region: A multi-scale analysis of precipitation intensity and seasonality, Abstract GC33A-0479 presented at the Fall American Geophysical Union, San Francisco CA, 17 December 2014.

Kalcic, M. Building stakeholder-driven conservation scenarios to reduce farming impacts on Lake Erie. Invited presentation in the Mid-MEAC Land Use Lunch Series, Lansing, Michigan, February 6, 2015.

Kalcic, M. and R. Logsdon Muenich. U-M Water Center SWAT Model of Maumee River Watershed (MRW). Presented at Shaping Lake Erie Agriculture Nutrient Management through Scenario Development. Ann Arbor, Michigan, June 22-23, 2015.

Kalcic, M., Bosch, N., Muenich, R.**, Kirchhoff, C., Steiner, A., Murray, M., Lopez, F., and D. Scavia**. Bringing SWAT to stakeholders to explore conservation scenario development in the Western Lake Erie Basin. Oral presentation at the International SWAT Conference at Purdue University, October 12-16, 2015.

Kalcic, M., D. Scavia, and **N. Bosch**. Bringing SWAT to stakeholders for conservation scenario development. 21st Century Watershed Technology Conference and Workshop: Improving Water Quality and the Environment, presented at The University of Waikato, New Zealand, November 3 - 6, 2014.

Murray, M., CJ Kirchhoff, M. Kalcic, N Bosch, D Scavia, A Steiner, S Basile, F Lopez. Enhancing manager and stakeholder awareness of and responses to changing climatic conditions and their impacts on Lake Erie. Poster presented at the 2015 National Adaptation Forum. St. Louis, Missouri, May 11-14, 2015.

Section 6: Peer-Reviewed Publications and Theses

Arnott J, **Kirchhoff C,** Carroll A. What "they" think: Perspectives of stakeholders on their participation in a co-produced research project. In preparation.

Basile SL, Rauscher SA, **Steiner AL**. Projected precipitation changes within the Great Lakes and Western Lake Erie Basin: A multi-model analysis of intensity and seasonality, region: a 1 multi-scale analysis of intensity and seasonality. Submitted to the *International Journal of Climatology* on 27 May 2016.

Bossi J. 2015. Improving information use to prevent HAB's In Western Lake Erie. Unpublished undergraduate thesis. University of Connecticut.

Carroll A. 2016. The utility of scientific modeling through coproduction. Unpublished undergraduate thesis. University of Connecticut.

Kalcic M, Kirchhoff C, Bosch N, Muenich R, Gardner J, **Scavia D**. 2016. Engaging Stakeholders to Define Feasible and Desirable Agricultural Conservation in Western Lake Erie Watersheds. *Environmental Science & Technology* 50(15): 8135-8145. DOI: 10.1021/acs.est.6b01420

Section 7: Students/Postdocs Funded on this Project

1. Samantha Basile, completed MS in AOSS at the University of Michigan in 2015
2. Margaret Kalcic, Postdoctoral Researcher, University of Michigan
3. Jacob Gardner, undergraduate student at the University of Connecticut, funded spring/summer 2014
4. Yerina Ranjit, PhD student in Communications, University of Connecticut, funded fall 2015.
5. Berdakh Utemuratov, PhD student in Civil Engineering, University of Connecticut, funded summer 2016.

Attachments

Attachment 1: Guidance Document
Attachment 2: Kalcic et al. 2016

Attachment 1: Guidance Document

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

October 2016

Project Team

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Acknowledgments

We are grateful for the involvement of over 35 stakeholders from the agricultural, conservation agency, coastal management, academic, nongovernmental organization and intergovernmental communities for their time and thoughtful contributions to this project and for Old Woman Creek NERR, Ottawa National Wildlife Refuge, and the Graham Sustainability Institute (University of Michigan) which generously hosted our stakeholder workshops. We also appreciate the contributions of former project team members Melinda Koslow (formerly NWF) and Heather Elmer (formerly Old Woman Creek NERR). Finally, we thank the National Oceanic and Atmospheric Administration (NOAA) for funding the project under CPO grant #NA13OAR4310142. The content of this report is solely the responsibility of the authors, and does not represent the views of the funding agency.

Suggested citation: Murray, M.W., Kirchhoff, C., Kalcic, M.M., Steiner, A., Bosch, N., Lopez, F., Scavia, D. 2016. Guidance addressing Lake Erie eutrophication in a changing climate based on a case study with agricultural and coastal managers.

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)

*: Present affiliation: The Ohio State University

Contents

M. Murray

S. Davis, NRCS

NOAA

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]

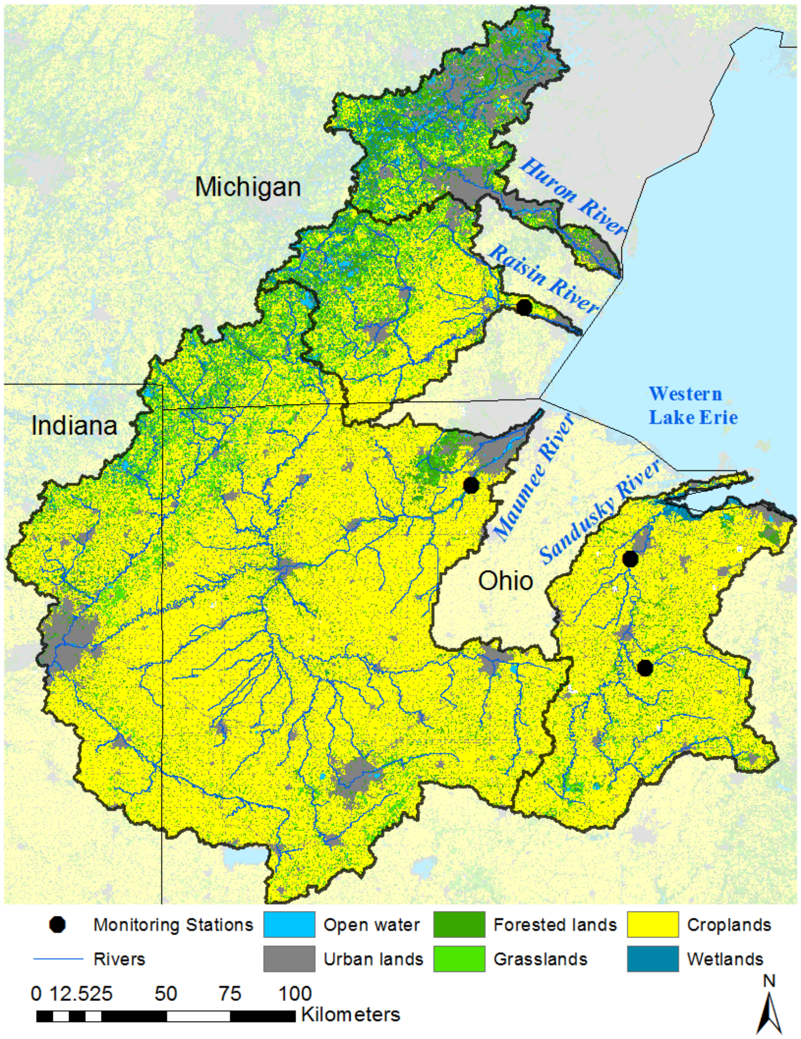

Figure 1. Map of four major western Lake Erie watersheds and land use. The major emphasis of this case study was the Maumee River watershed.

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]

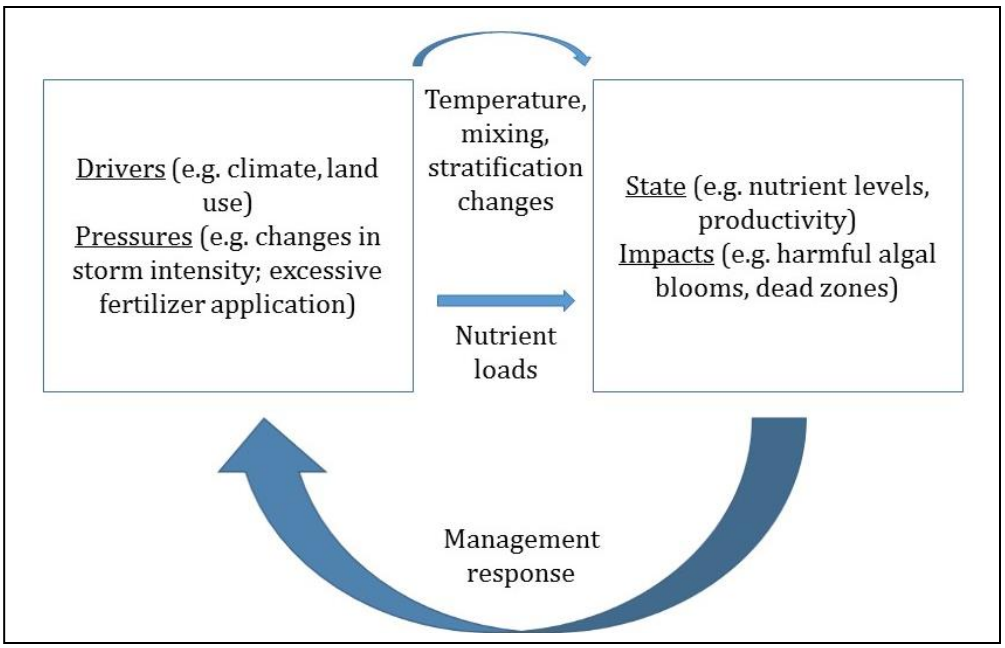

Figure 2. One potential approach to indicate relationships among various components in addressing Lake Erie eutrophication, following a Driver-Pressure-State-Impact-Response framework. In this simple formulation, the drivers and pressures are largely in the watershed, and the state and impacts of concern 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).

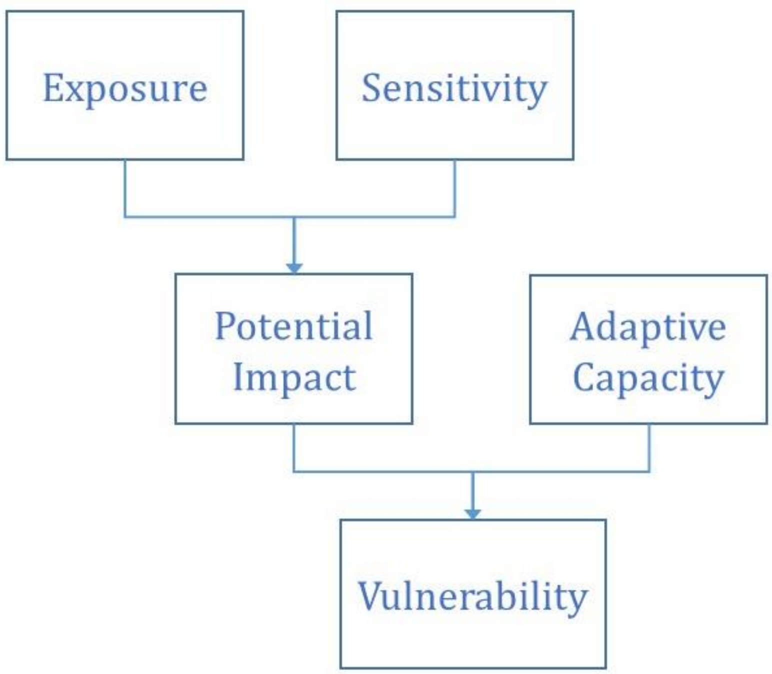

Figure 3. Schematic (redrawn from Glick et al. 2011 (reference 29)) showing climate change vulnerability components of exposure, sensitivity, and adaptive capacity. Reducing vulnerability can entail reducing the impacts (i.e., through addressing exposure or sensitivity) or increasing the adaptive capacity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

<u>Identification of BMP Scenarios</u>

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.

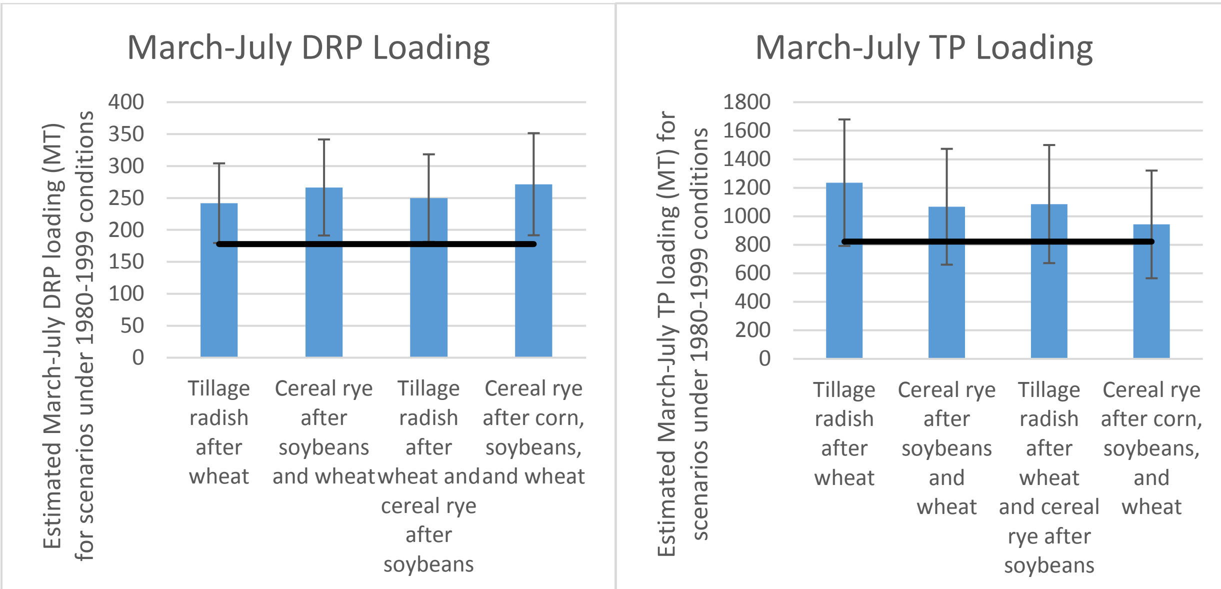


Figure 4. Simulated March-July DRP (left) and TP (right) loading (in metric tons (MT)) at Waterville (OH) for full implementation of four different uses of cover crops in crop rotations. The error bars give standard deviation of the years 1980-1999. Baseline simulations were 240 and 1238 MT for DRP and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

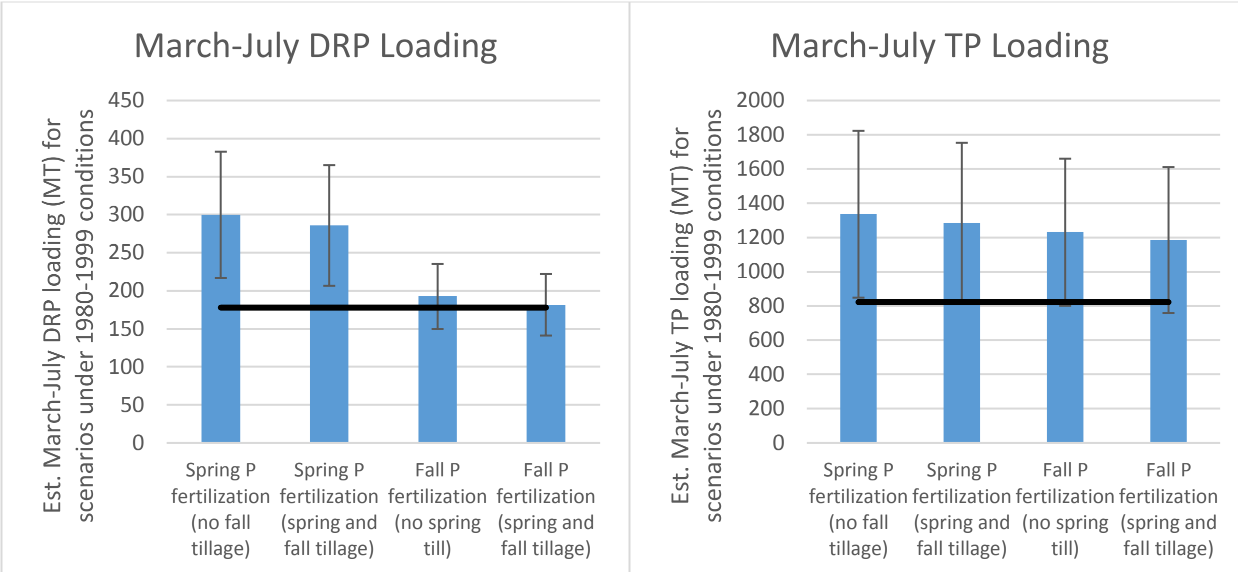


Figure 5. Simulated March-July DRP (left) and TP (right) loading (in metric tons (MT)) at Waterville (OH) when comparing spring vs. fall application of fertilizer. The error bars give standard deviation of the years 1980-1999. Baseline simulations were 240 and 1238 MT for DRP and TP, respectively, and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

<u>Climate Modeling Results and Stakeholder Discussions</u>

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.

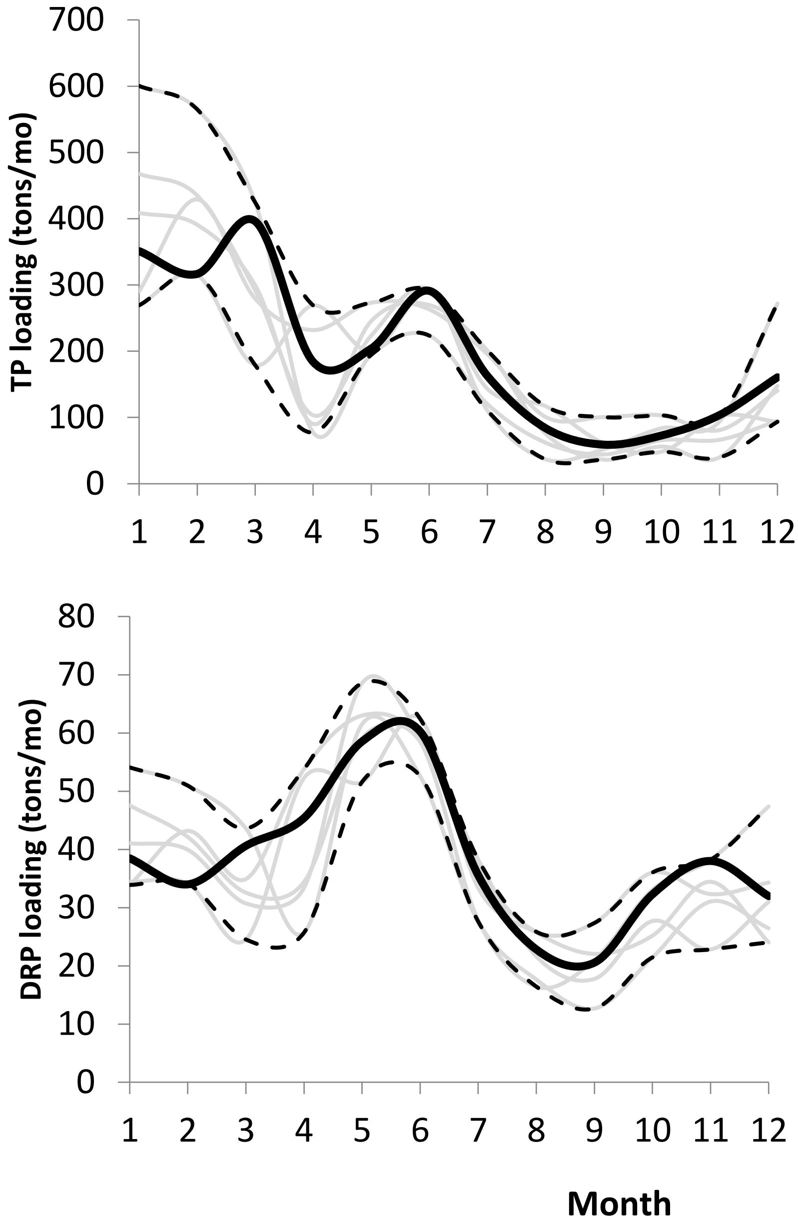


Figure 6. Projected mid-century (2041-2065) monthly total phosphorus loading (top) and dissolved reactive phosphorus loading (bottom) to Lake Erie from the Maumee River derived from SWAT model outputs. The SWAT model used five climate models (data indicated in light gray lines), with the baseline simulation (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.

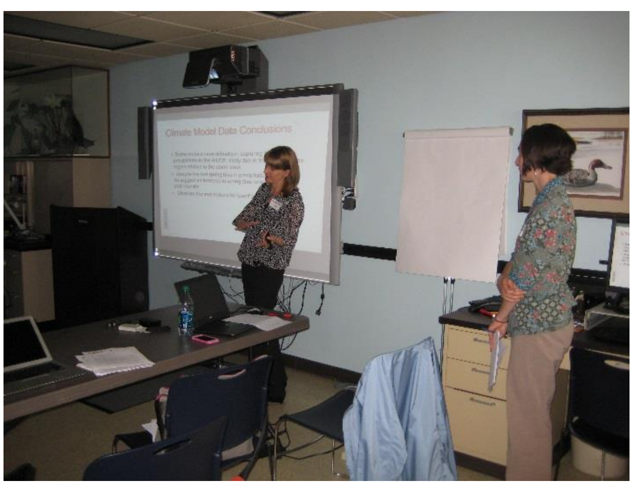
Strong stakeholder interest in exploring impacts of various BMPs on nutrient loads in the current climate, the plethora of BMP scenarios to consider, and the uncertainties in projected impacts of climate change on nutrient loads led to relatively limited stakeholder discussions on how management approaches 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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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/

Attachment 2: Kalcic et al. 2016

Environmental Science & Technology

Article

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Engaging Stakeholders To Define Feasible and Desirable Agricultural Conservation in Western Lake Erie Watersheds

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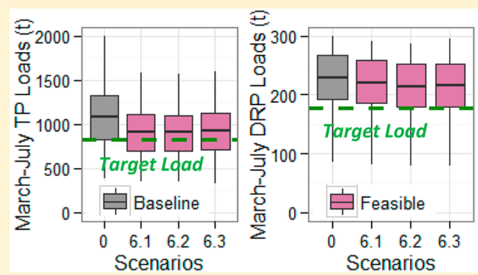
Supporting Information

ABSTRACT: Widespread adoption of agricultural conservation measures in Lake Erie's Maumee River watershed may be required to reduce phosphorus loading that drives harmful algal blooms and hypoxia. We engaged agricultural and conservation stakeholders through a survey and workshops to determine which conservation practices to evaluate. We investigated feasible and desirable conservation practices using the Soil and Water Assessment Tool calibrated for streamflow, sediment, and nutrient loading near the Maumee River outlet. We found subsurface placement of phosphorus applications to be the individual practice most influential on March−July dissolved reactive phosphorus (DRP) loading from row croplands. Perennial cover crops and vegetated filter strips were most effective for reducing seasonal total phosphorus (TP) loading. We found that practices effective for reducing TP and DRP load were not always mutually beneficial, culminating in trade-offs among multiple Lake Erie phosphorus management goals. 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.



INTRODUCTION

Anthropogenic nutrient loads produce harmful algal blooms (HABs) and hypoxia in lakes and seas worldwide.[1,2] Unlike saltwater environments where nitrogen is generally the limiting nutrient, phosphorus (P) is of greatest concern in freshwater environments.[3] In the 1970s, the United States (US) and Canada set a Lake Erie target total P (TP) load of 11 000 MT/y through the Great Lakes Water Quality Agreement (GLWQA),[4] and while that annual target has generally been met since the early 1980s, algal blooms and hypoxia returned in the mid-1990s with increasing severity and toxicity.[5,6]

In response, the US and Canada committed to reviewing and revising loading targets through the renegotiated GLWQA.[7] Because elevated P loading from intensively managed agricultural lands of the Maumee River watershed (Figure 1) is a primary driver of HABs in Lake Erie's western basin[8−10] and a major contributor to hypoxia in its central basin,[11] a new annual TP loading target reduction and March−July targets of 860 MT TP and 186 MT DRP for the Maumee were proposed as a 40% reduction from the 2008 loads,[12] and subsequently adopted by the US and Canada.[13]

Achieving these steep reductions from privately managed agricultural lands[14] will likely require significant investments in agricultural conservation practices. The challenge is to know where, how, and in what ways to invest limited resources in these voluntary programs. Modeling a range of conservation measures may help guide these investments. However, creating usable, policy-relevant knowledge requires making the scientific process more transparent to and iterative with potential information users.[15−18] Reducing P loading from the Maumee requires stakeholder engagement to determine feasible and desirable conservation efforts to be tested in models to quantify outcomes.[19] To that end, we engaged stakeholders in designing and modeling conservation scenarios to test what measures have the most potential to reduce P loading from the Maumee River.

MATERIALS AND METHODS

Study Area. The Maumee River watershed spans over 17 000 km^2 in northwest Ohio, northeast Indiana, and southeast Michigan (Figure 1), where soils are predominantly poorly drained,[20] and land use is over 70% row crops (corn, soybean, and wheat),[21] of which over 70% is estimated to be subsurface drained (e.g., tile-drained). The watershed is fairly flat with an

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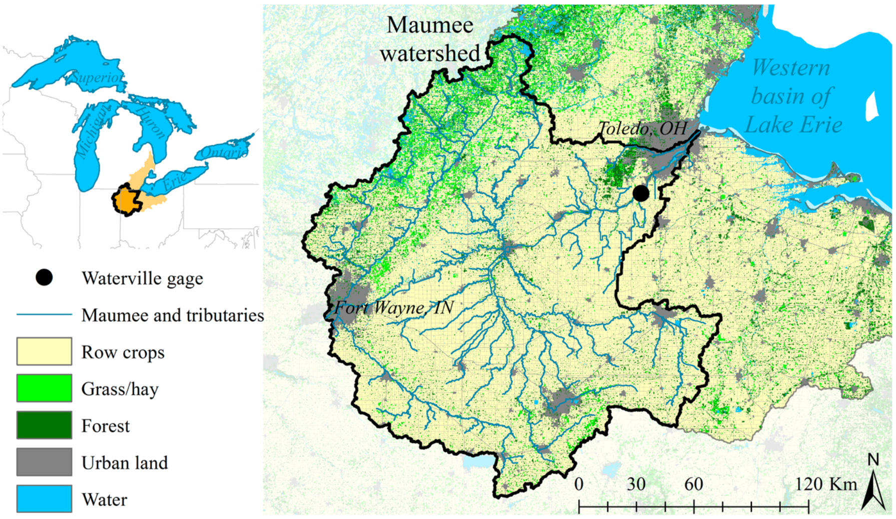

Figure 1. The Maumee River watershed was the focus of the stakeholder engagement and scenario development. This watershed is the main source of nutrients to western Lake Erie as it is large, intensively managed in row crop agriculture, and has prevalent artificial drainage of heavy clay soils.

average slope of 1.15%, with agricultural lands averaging 0.9% in slope.[22]

Surveys and Stakeholder Engagement. Through a survey and series of workshops, the team sought input from agricultural producers, policy-makers, county soil and water conservation specialists, agricultural advisors, nongovernmental organizations, researchers, and staff at state, federal, and intergovernmental agencies active in nutrient management and agricultural conservation in western Lake Erie watersheds.

The online survey administered in advance of the workshops solicited stakeholder opinions about which conservation practices are the most relevant to evaluate for their potential to reduce nutrient pollution in the Maumee watershed. Survey respondents selected the most important conservation measures among wind and soil erosion control practices, edge-of-field practices, nutrient management practices, drainage practices, wetlands and conservation lands, and practices that control concentrated flow using 1 for most important to 3 for less or not important. Although not representative of the entire watershed, responses helped identify the range of conservation practices of most interest to stakeholders in advance of the workshops and helped recruit participants for the workshops. In total, 36 of 74 individuals responded to the survey for a 48% response rate. Survey respondents represented agricultural producers (3), Soil and Water Conservation Districts or agricultural advisors (4), nongovernmental organizations (9), academia (5), and city/state/federal/international agency staff (15).

We organized two sets of three stakeholder workshops in August 2014 and June 2015. In total, 18 stakeholders took part in the 2014 workshops representing municipal or state governments (4), county soil and water conservation districts (3), federal government or international (3), nongovernmental organizations (4), and business/farming (4). These workshops began with networking followed by interactive presentations about the climate and watershed modeling. Discussions were oriented toward making the modeling more transparent and, in so doing, providing stakeholders with an opportunity to suggest model improvements. The presentations were followed by facilitated brainstorming to determine which individual or suite of practices (hereafter called scenarios) stakeholders thought were the most important to include in the model and to discuss what each scenario might look like. Extensive notes capturing the full range of stakeholder comments were later consolidated into a report shared with stakeholders and used to guide the modeling efforts.[23] The second set of workshops focused on discussing modeling results and identifying additional high priority scenarios to include in the final modeling effort. Twenty stakeholders took part in the 2015 workshops representing municipal or state governments (4), country soil and water conservation districts (3), federal government or international (4), nongovernmental organizations (4), and business/farming (5).

Watershed Model Development and Calibration. The Soil and Water Assessment Tool (SWAT) is a semidistributed, physically based watershed model frequently used to simulate hydrology and water quality in agriculturally dominated landscapes.[24] SWAT permits the user to input detailed management operations and a large set of conservation practices, making it ideal for testing conservation scenarios.

A baseline SWAT model was set up for the Maumee watershed using medium-resolution streams,[25] elevation data,[22] land use data,[21] soils data,[20] and climate data.[26] A 4000 ha stream threshold was used to approach sub-basins the size of 12-digit hydrologic unit codes (HUCs), and HUC-12 outlets were added for subbasin delineation. Hydrologic response units (HRUs) were defined by a single slope class and a 10% threshold in lumping of soils. Point sources were based on National Pollution Discharge Elimination System (NPDES) permits,[27] and wetlands and reservoirs were based on NHD waterbody coverage in each sub-basin.[25]

Although stakeholders provided some information on farm management operations, additional management operations were estimated from a 2006 tillage survey,[28] county-level fertilizer application rates from fertilizer sales reported in 1987−2001 from the US Geological Survey,[29] county-level manure production from 1997 to 2012,[30] manure nutrient content averages,[29] and recent estimates of crop rotations derived from overlaying data sets for the available years (2007−2012) of the National Agricultural Statistics Service Cropland Data Layer (Tables S1 and S2, Figure S1).[31] Five crop rotations of corn and soybeans were applied at random throughout the watershed, while seven rotations containing winter wheat were concentrated on very poorly drained lands to approximate an observed spatial pattern (Figure S2). Inorganic fertilizers and

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Table 1. Maumee SWAT Model Calibration Parameters

parameter	initial value	range	calibrated value	description
ANION_EXCL	0.5	0−1	0.1	fraction of soil pore space from which anions are excluded; affects how long it takes nitrogen to travel in the soil
BC1	0.55	0.1−1	0.1	biological oxidation of NH_4 to NO_2 in the reach (1/d)
BC3	0.21	0.2−0.4	0.02	hydrolysis rate of organic N to NH_4 in the reach (1/d)
BC4	0.35	0.01−0.7	0.01	mineralization rate of organic P to DRP in the reach (1/d)
BIOMIX	0.2	NA	0.3	biological mixing efficiency; essentially tillage on Dec. 31
CH_COV1	0	0−1	0.5	channel cover factor 1; a fairly erodible channel
CH_COV2	0	0−1	0.5	channel cover factor 2; a fairly erodible channel
CH_N1	0.014	0−0.15	0.025	Manning's roughness for tributary channels
CH_N2	0.014	0−0.15	0.035	Manning's roughness for the main channel
DDRAIN	0	NA	1000[a]	depth to subsurface tile drain (mm)
DEP_IMP	6000	NA	1500[a]	depth to the impervious layer in the soil (mm)
DRAIN_CO	NA	18902	25	daily drainage coefficient (mm/day); set to ~1 in./d
ESCO	0.95	0.01−1	1	soil evaporation factor; limited in lower layers
ITDRN	0	0 or 1	1	tile drainage equations flag; newer DRAINMOD routine
IWTDN	0	0 or 1	1	newer water table algorithm flag
LATKSATF	NA	0.01−4	1	lateral soil hydraulic conductivity in tile-drained fields as multiple of original soil conductivity value
NPERCO	0.2	0.01−1	0.4	nitrate percolation coefficient; higher value permits greater nitrate loading in surface runoff.
R2ADJ	1	0−3	8[a]	curve number adjustment for increasing infiltration in nondraining soils; used optimal value from another study[59]
RS2	0.05	NA	0.01	benthic source rate for DRP in the reach (mg $P/m^2/d$)
RS3	0.05	NA	1	benthic source for NH_4 in the reach ($mgNH_4{-}N/m^2/d$)
RS4	0.05	0.001−0.1	0.001	organic N settling rate in the reach (1/d)
RS5	0.05	0.001−0.1	0.05	organic P settling rate in the reach (1/d)
SDRAIN	NA	7600−30,000	15000	tile drain spacing (mm)
SFTMP	1	−10	−2	snowfall temperature (°C); value means precipitation will fall as snow if the average daily temp is below −2 °C
SMFMN	4.5	1.4−6.9	2	minimum snowmelt factor (mm H_2O/d)
SMFMX	4.5	1.4−6.9	2	maximum snowmelt factor (mm H_2O/d)
SMTMP	0.5	−10	−2	base snowmelt temperature; melts if daily temp. >−2 °C
SOL_CRK	0.5	0−1	0.45	maximum soil crack volume; drives DRP loss through tiles
SOL_P_MODEL	0	0 or 1	0	soil phosphorus subroutine; 0 = newer model
SOL_SOLP	5	NA	1	initial labile P in the soil layer (mg labile P/kg soil)
SPCON	0.0001	0.01	0.000273	parameter drives maximum sediment concentration the river can route; lower value for soils with high clay content
SURLAG	4	NA	1	surface runoff lag coefficient; for smoother hydrograph
TIMP	1	0.01−1	0.05	snow pack temperature lag
VCRIT	5	NA	1	critical velocity at which a river will resuspend sediments

[a]Indicates parameter was changed only for tile-drained lands, and NA indicates no stated range in the SWAT documentation.

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Table 2. Maumee SWAT Model Calibration and Validation Results[a]

	statistic	aim	calibration (2001–2005) daily	calibration (2001–2005) monthly	validation (2006–2010) daily	validation (2006–2010) monthly	back-validation (1981–2000) daily	back-validation (1981–2000) monthly
flow	R^2	>0.6	0.82	0.87	0.86	0.90	0.78	0.84
	NSE	>0.5	0.80	0.87	0.84	0.88	0.77	0.83
	PBIAS	<±10	−1	−2	7	7	2	2
sediment	R^2	>0.4	0.69	0.77	0.75	0.87	0.48	0.55
	NSE	>0.4	0.69	0.77	0.75	0.87	0.37*	0.46
	PBIAS	<±25	−1	−3	6	6	−35*	−34*
TP	R^2	>0.4	0.65	0.67	0.66	0.68	0.57	0.61
	NSE	>0.4	0.64	0.67	0.66	0.66	0.56	0.61
	PBIAS	<±25	−2	2	3	2	−4	−4
DRP	R^2	>0.4	0.47	0.62	0.45	0.46	0.36*	0.42
	NSE	>0.4	0.46	0.61	0.44	0.42	0.04*	0.07*
	PBIAS	<±25	−1	1	−12	−13	59*	61*
TN	R^2	>0.4	0.75	0.82	0.63	0.73	0.69	0.75
	NSE	>0.4	0.73	0.75	0.60	0.67	0.69	0.73
	PBIAS	<±25	−1	0	10	8	−4	−4
NO_3	R^2	>0.4	0.70	0.75	0.54	0.61	0.61	0.66
	NSE	>0.4	0.60	0.54	0.36*	0.36*	0.58	0.59
	PBIAS	<±25	0	1	15	13	−3	−4

[a]In calibration and validation periods, the model had exceptional daily and monthly performance of nearly all constituents by all measures. Nitrate (NO_3) loading was low for the validation period, and sediment and DRP did not meet aims for the back-validation of 1981–2000, likely due to historical changing of agricultural practices throughout that time period[42] that were not incorporated in the model. Results outside of the desired range are depicted with *.

manures were applied at the average estimated rate in proportion to crop needs across the watershed. Tile drainage was simulated on row cropland with very poorly, poorly, and somewhat poorly drained soils (Figure S3) using the newer tile drainage routine based on DRAINMOD equations (ITDRN = 1).[32] Other existing practices, including nonwheat cover crops and filter strips, were not included in the baseline model because we lacked access to these data. The Supporting Information also provides detailed cropland management by rotation in Tables S3–S5.

We modified the SWAT 2012 Revision 635 source code to correct a bug preventing soluble P (a proxy for DRP) from flowing through tile drains. After running a preliminary sensitivity analysis in SWAT-Cup,[33] we conducted a detailed daily and monthly manual calibration for 2001–2005, with validation from 2006 to 2010, such that flow and loading of sediments, TP, DRP, total nitrogen, and nitrate were well estimated near the watershed outlet at the Waterville gaging station (Figure 1). With the publicly available data set for this gage containing daily flow and water quality data,[34] we were able to calculate statistical and graphical criteria at numerous time scales. Daily climate inputs[26] were lagged by 1 day to assist with daily calibration and account for the difference in timing of climate measurements and riverine measurements. We used the coefficient of determination (R^2), the Nash-Sutcliffe Efficiency (NSE), and percent bias (PBIAS) with more stringent constraints than the recommended ranges for flow and water quality,[35,36] due to the prevalence of water quality data at the Waterville gage. We ensured crop yields were consistent with observations and that considerable flow and DRP were routed through tile drains in the model. This latter consideration originated in part through the stakeholder engagement process wherein stakeholders revealed considerable interest in predicting both TP and DRP, which required more realistically simulating P flows through tile drains. Consult the Supporting Information for details on the source code change, model calibration, and simulation of conservation practices (Table S6).

Conservation Scenario Development and Implementation. Scenarios were developed and prioritized through the 2014 stakeholder engagement workshops, and then prioritized to actions that the SWAT model would be able to simulate. Many of the desired scenarios that we were not able to simulate focused on soil health, linking soil tests to manure applications, in-stream practices such as two-stage ditches and wetlands, or innovative practices such as bioreactors and saturated buffers that are not yet options in the SWAT model. The prioritized scenarios were refined in the 2015 workshops. All scenarios were forced with temperature and precipitation from the 30 year historical station record of 1981–2010.[26]

■ RESULTS AND DISCUSSION

Model Calibration. The final SWAT model had 10 266 HRUs and 358 sub-basins, with a watershed area of 17 300 km^2. Thirty-four parameters were changed in calibration or set as model inputs to simulate cropland management (Table 1). Calibration and validation were judged as very good by common metrics[35,36] for all constituents at both daily and monthly comparison (Table 2). In the back-validation period (1981–2000), sediment was underestimated and DRP overestimated because the model was built with management assumptions for 2001–2005 and therefore unable to capture the long-term loading trends due to changing practices over the decades. The model was also verified for crop yields[37] averaging 9.6–9.9 t/ha for corn and 2.2–2.4 kg/ha for soybeans in calibration and validation, which are reasonable for this region. Partitioning of streamflow between surface runoff and tile drainage is important for this watershed. During calibration and validation, tile flow accounted for 38–42% of streamflow—somewhat lower than rates observed in watersheds dominated by tile flow.[38,39] Tiles carried 42–48% of DRP yield to the river (and 8–10% of TP), which is within the range of field observations.[40] Perhaps due to reduced tile flow,[41] it was difficult to achieve greater loading without particulate P transfer through tiles or simulating soil

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Table 3. List and Descriptions of Conservation Scenarios Run through the Maumee SWAT Model[a]

Type	Scenarios
0. Baseline (calibrated model)	The baseline scenario had a mixture of no-tillage and conventional tillage based on historical management information.[28] P and manure were broadcast and incorporated, and applied at rates consistent with historical data and estimations.[29] Tile drainage was simulated on crop fields with poorly, very poorly, and somewhat poorly drained soils.[22] 2, 3, and 7-year rotations were designed from overlaying the 2007-2012 Cropland Data Layer,[32] and contained a mixture of corn, soybean, and winter wheat. Cover crops, filter strips, and additional conservation practices were not included in the baseline model because we lacked access to this data.
1. Nutrient placement	1.1 Continuous no-tillage with broadcast fertilizer and manure 1.2 Continuous no-tillage with subsurface-applied fertilizer and broadcast manure 1.3 Continuous no-tillage with subsurface-applied fertilizer and manure 1.4 Baseline tillage with subsurface-applied fertilizer and manure
2. Nutrient timing	2.1 Spring P applications with no fall tillage 2.2 Spring P applications with baseline fall tillage 2.3 Winter application of manure 2.4 Fall P applications with no spring tillage 2.5 Fall P applications with baseline spring tillage
3. Cover crops	3.1 Tillage radish after wheat in rotations 3.2 Cereal rye after soybeans and wheat in rotations 3.3 Cereal rye after soybeans and tillage radish after wheat in rotations 3.4 Cereal rye after corn, soybeans, and wheat in rotations
4. Vegetated filter strips	4.1 Application of poor-quality* filter strips throughout agricultural lands 4.2 Application of medium-quality* filter strips 4.3 Application of high-quality* filter strips ** Filter strip quality is based on the percentage*
5 Systems approach/ Combinations	5.1 Continuous no-tillage with broadcast fertilizer and manure and cereal rye after soybeans and tillage radish after wheat (1.1 + 3.3) 5.2 Continuous no-tillage with subsurface-applied fertilizer and manure and cereal rye after soybeans and tillage radish after wheat (1.3 + 3.3) 5.3 Continuous no-tillage with subsurface-applied fertilizer and manure, cereal rye after soybeans and tillage radish after wheat, and medium-quality filter strips (1.3 + 3.3 + 4.2) 5.4 Continuous no-tillage with subsurface-applied fertilizer and manure, cereal rye after soybeans and tillage radish after wheat, and high-quality filter strips (1.3 + 3.3 + 4.3) 5.5 Baseline tillage with subsurface-applied fertilizer and manure and cereal rye after corn, soybeans, and wheat (1.4 + 3.4) 5.6 Baseline tillage with subsurface-applied fertilizer and manure, cereal rye after corn, soybeans, and wheat, and high-quality filter strips (1.4 + 3.4 + 4.3)
6 Feasible scenarios	6.1 25% adoption* of continuous no-tillage with subsurface-applied fertilizer and broadcast manure, cereal rye after corn, soybeans, and wheat, and medium-quality filter strips (1.3 + 3.4 + 4.2) 6.2 25% adoption* of subsurface-applied fertilizer and broadcast manure, cereal rye after corn, soybeans, and wheat, and medium-quality filter strips (1.4 + 3.4 + 4.2) 6.3 33% adoption* of subsurface-applied fertilizer and broadcast manure, cereal rye after corn, soybeans, and wheat, and high-quality filter strips (1.4 + 3.4 + 4.3) ** All practices were adopted on the same, randomly-selected farm fields*

[a]All scenarios were run with temperature and precipitation forcing from the 30 year historical station record (1981−2010).

macropore flow in the model, and these routines are still under development. However, tiles contributed 81−85% of nitrate (61−67% of total nitrogen), which is at the top of the range reported in another study.[39] Overall, model outputs were reasonable and the model was able to simulate daily and monthly flow and water quality quite well.

Selecting and Interpreting Scenarios. We sought to capture the benefits of iterative and engaged research on improving the models and the policy-relevance of the results.[15−18] By engaging stakeholders in interactive workshops, we improved communication and mutual understanding between modelers and the stakeholders, illuminated and informed conservation practice model assumptions, solicited input that drove research questions, and increased the likelihood that the science produced would be policy-relevant. This was important because, while all modeling efforts make trade-offs

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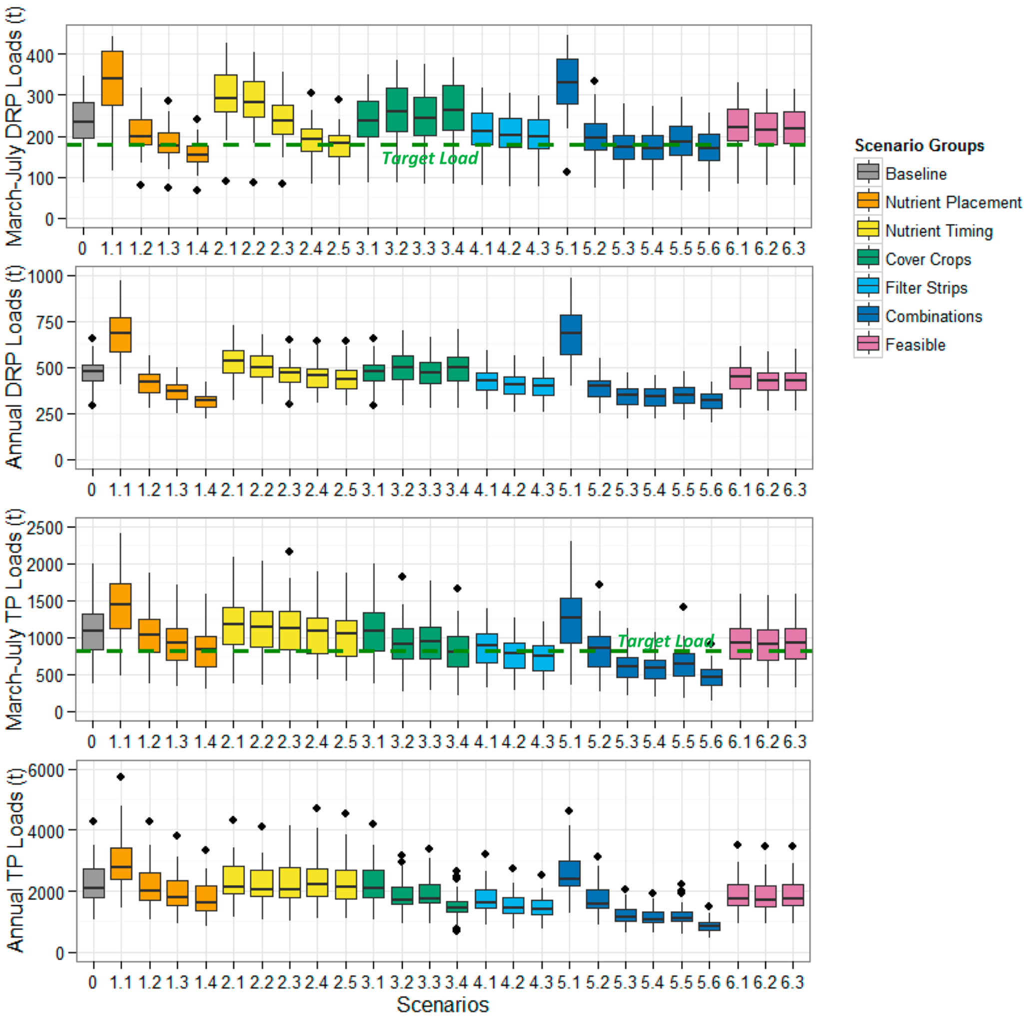

Figure 2. Boxplots of simulated March–July and annual DRP and TP loading at the Waterville gage under conservation management scenarios. Target loads (dashed green lines) are at 96% of the Maumee target loads to weight to the watershed area above the Waterville gage. Diamonds are considered outliers based on distance from the interquartile range (box). Consult Table 3 for scenario descriptions.

among assumptions, decisions, and simplifications, to be useful for informing decisions models should be made transparent and results generated in collaboration with potential information users.[16−18] Increasing this transparency benefits both the science by illuminating and "ground truthing" model assumptions, and its applicability by improving understanding, buy-in, and trust by potential users.[15−19,43−48]

Illuminating and "Ground Truthing" of the Watershed Model. The modeling team was open with stakeholders about assumptions used, such as what crops were grown in what rotations, dates for planting and harvesting, amount, type, and timing of fertilizer application, and types and levels of adoption of conservation practices. Stakeholders agreed with some assumptions, suggested fine-tuning of others, and raised concerns about how others might influence results. For example, stakeholders expressed concern about how decisions about the amount, type, and timing of fertilizer application (e.g., winter application of manure and overapplication of nutrients) would impact modeled results. As a result, modelers attempted to improve estimates of manure and inorganic fertilizer application rates using multiple data sources (Table S1).

Modelers and stakeholders also discussed how the model captured real-world conditions, which helped stakeholders better understand the relationship between how SWAT initializes soil P and the more familiar soil test P measures use to determine where and how much P is needed to maintain optimal crop yields. Simultaneously, the conversation helped modelers understand stakeholder concerns regarding the model's ability to simulate the range of variability and distribution of soil P concentrations, particularly field-by-field soil test P levels and fertilizer and manure applications. By directly addressing stakeholder concerns and discussing how the model simulates soil P and fertilizer application rates, stakeholders gained a better appreciation for the value of the results for showing how typical farm management in aggregate influences nutrient loading at the watershed scale.

Finally, stakeholders provided feedback on whether the model produced reasonable results for each simulated conservation practice. Although most agreed the results were reasonable, stakeholders were concerned that the model's approach to "no-tillage" scenarios that simply removes tillage operations did not take into account improved soil tilth, including higher organic matter, and greater infiltration potential. In fact, cover crops may also improve soil tilth, yet soil health improvements are not yet simulated in the model. Therefore, results showing continuous no-tillage to be less effective for reducing P loading than rotational no-tillage were likely influenced by these model

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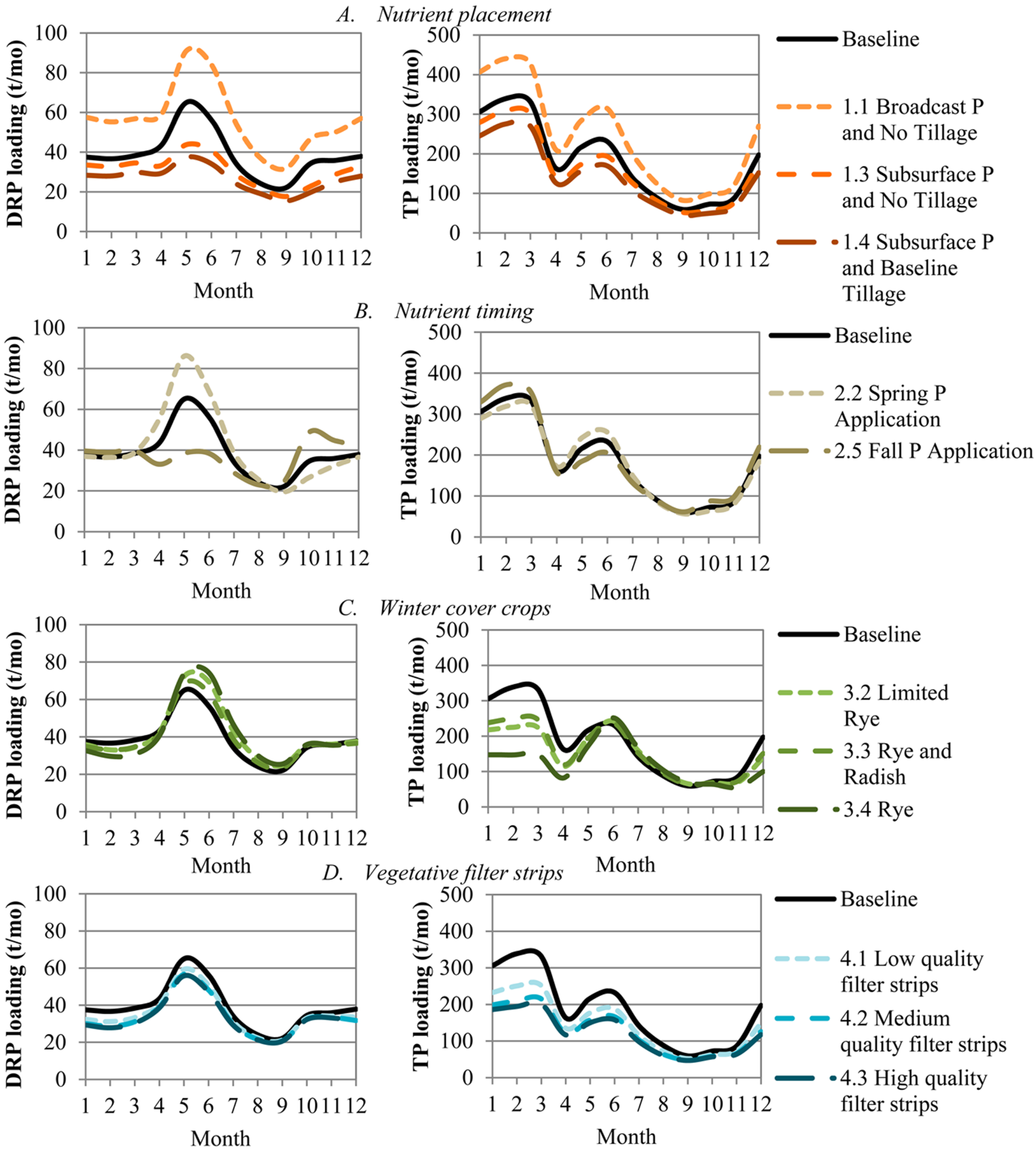

Figure 3. Seasonal dynamics of DRP and TP loading across conservation scenarios. (A) Nutrient placement influences DRP and TP loadings similarly throughout the year due to changes in stratification of P at the soil surface, with the greatest reductions from subsurface placement and rotational tillage. (B) Timing of P applications made little difference in annual DRP or TP loading, but was a strong driver in seasonal DRP loading, with fall applications yielding the greatest improvement in March–July loading responsible for the Lake Erie HABs. (C) Winter cover crops held back nutrient runoff during the winter months, reducing TP loading considerably throughout most of the year, but shifting the timing of DRP from winter to spring-time and summer. (D) Filter strips intercepted nutrients traveling in surface runoff similarly throughout the year, with greater reductions for TP than for DRP.

limitations, and which suggests a need to improve the model's ability to simulate soil health.

Scenario Development and Prioritization. Survey respondents were asked opinions about which practices are the most important to evaluate for reducing nutrient pollution in western Lake Erie. Results indicated greatest interest in evaluating nutrient management practices such as the 4Rs—"right source, right rate, rate time, and right place"—of nutrient management,[49,50] conservation tillage, and manure application ($\overline{x}$ = 1.12, n = 33), followed by soil erosion control practices (e.g., tillage

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management, cover crops, etc.; $\bar{x}$ = 1.15, n = 33), and practices that controlled flow from fields (e.g., filter strips, tiling, etc.; $\bar{x}$ = 1.15, n = 33). Respondents were least interested in evaluating the effectiveness of wind erosion control practices (e.g., hedgerow planting, windbreaks, etc.; $\bar{x}$ = 2.15, n = 33) or the effectiveness of putting lands in long-term conserving cover ($\bar{x}$ = 1.83, n = 30).

Facilitated discussions helped shape the scenarios in three ways: (1) emphasize export of P, particularly DRP, from the Maumee watershed; (2) explore multiple rather than single-practice options, including in-field, edge-of-field, and in-stream practices because TP and DRP management may require different strategies and not all practices are relevant to all farms or farming practices, and (3) consider costs assumed by the farmers. Thus, the modeling effort focused on suites of conservation practices that were both capable of achieving P load reductions, and which stakeholders considered desirable and technologically, economically, and socially feasible in the region.

Further iteration with stakeholders helped prioritize specific practices (or suites of practices) for evaluation among in-field, edge-of-field, and in-stream practices. Discussions about in-field management practices centered on tillage, nutrient and manure management, and cover crops. For example, inorganic fertilizer and manure application methods, and their placement in the soil, or at the soil surface, were discussed in relation to tillage operations. Specifically, stakeholders wanted to know more about the potential effects on P export of placement of P fertilizer deeper in the soil versus at the soil surface. Edge-of-field management discussions focused primarily on understanding the effect of drainage systems on DRP loading and how filter strip size and location influenced P reduction performance. For example, stakeholders noted that a common assumption of wider filter strips being more effective is an oversimplification and that adjacent tillage practices could build up a berm such that surface flow is rerouted alongside a filter strip. Thus, stakeholders felt that a more nuanced understanding of filter strip performance would be important for phosphorus management efforts. Finally, stakeholders expressed interest in better understanding how to evaluate in-stream practices such as wetland placement. However, further conversations tempered expectations for this exploration because of limitations in modeling wetlands in SWAT, including their inability to receive subsurface tile drainage flows.

Interpreting Conservation Scenarios. The final 25 scenarios spanned placement and timing of nutrient applications, perennial (cereal rye) and annual (tillage radish) cover crops, filter strips of various quality, and combinations of those practices (Table 3). We focused on DRP and TP loading at both annual and March–July time scales, the period most strongly related to the extent of algae bloom in the western basin and the period identified in the GLWQA targets.[8,10]

Boxplots (Figure 2) show the distribution of results across 30 years of historical climate, and the March–July loading plots include the GLWQA target load. Nearly all scenarios reduced DRP and TP loads, with the notable exception of no-tillage with broadcast fertilizers (1.1 and 5.1), which increased P concentration in the soil surface making it susceptible to runoff, consistent with other studies.[51,52] Subsurface-placement of P was the most effective single practice for DRP, followed by fall timing of P applications. Cereal rye cover was also effective for reducing TP as expected,[53] as well as filter strips.[54] Both cover crops and filter strips were less effective for DRP because dissolved P not only travels with the water and is less readily taken up in filter strips, but much of it travels through tile drains which bypass edge-of-field conservation altogether. Although greater reductions could be met with combinations of practices, most of the benefit was derived from a single practice (subsurface-placement of P); adding more practices achieves modest and diminishing returns on conservation investment. The most effective combination of practices (5.6) was slightly less effective for March–July DRP losses than the most effective single practice, subsurface application of P (1.4), even though this scenario is included in 5.6, because the cereal rye cover crop (3.4) increased seasonal DRP loading due to a shift in timing of nutrient load, as explained further below. The combination of practices (5.6) met the target DRP load in half of the years, and in all years for TP. However, when this combination of practices was applied at rates stakeholders considered feasible (6.1–6.3), they rarely met the target load for DRP and met it in only half the years for TP.

Seasonal dynamics of TP and DRP loading help explain less intuitive results such as load reductions from fall vs spring P application and the potential for winter cover crops to increase March–July DRP loading (Figure 3). Nutrient placement (Figure 3a) influenced both DRP and TP loading throughout the year. Stratification of P at the soil surface from broadcast applications without incorporation by tillage resulted in 33% greater TP and 46% greater DRP loading annually. Subsurface P applications reduced TP and DRP loading under no-tillage by 12% and 20% and under rotational tillage by 22% and 32%, respectively.

Although the timing of P applications made little difference in annual P loading, it was a strong driver in seasonal loading, particularly for DRP (Figure 3b). Fall applications yielded improvement in March–July loading (the HAB relevant period) because much of the nutrient was exported during the season in which it was applied. However, winter soil conditions may not be captured fully in the SWAT model. Although the model captures snowmelt runoff well, the model does not restrict fertilizer applications to the soil surface and subsurface such as during frozen or saturated ground conditions. Winter cover crops held back nutrient runoff during the winter months, and reduced TP loading considerably throughout most of the year (Figure 3c). However, nutrients stored in the cover crop were released after the crop was killed in the spring, providing higher P at the soil surface available for export in the late spring and summer. Thus, DRP loading was further increased in spring and summer, the period most critical for HABs. The model does not account for some of the benefits of cover crops—improvements in soil organic matter and corresponding infiltration capacity—and over time those benefits may reduce P loading from treated ground. Even without considering these benefits, annual TP loading, which is critical for hypoxia formation in Lake Erie's Central Basin, was reduced by 15–32% with cover crops, whereas DRP slightly increased by 1–6%. Filter strips intercepted nutrients throughout the year, with greater reductions for TP than for DRP (Figure 3d). Annual TP loading was reduced by 21–35%, which is in the lower end of the reported range,[55] and DRP by 9–15%.

Water quality improvement that can be gained from single-practice and combinations at full adoption across the watershed reaches a percent reduction threshold of 32% for annual DRP, 41% for March–July DRP, 61% for annual TP, and 57% for March–July TP. This nutrient reduction threshold is similar and somewhat more optimiztic than the threshold of 25–30% from conservation scenarios run in the same watershed using a different model configuration, parametrization, and set of

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conservation practices in a previous study.[56] The new water quality targets under the GLWQA call for March−July TP and DRP reductions of 40% from the year 2008, which is equivalent to an average reduction of 32% reduction for TP and 34% for DRP from the 1981−2010 period. According to our model results, the targets may be achievable in most years given greater implementation of fairly common practices.

An important consideration in interpreting these findings is the extent to which existing practices were incorporated in the baseline model. Although many practices were included in the baseline model, cover crops and filter strips were not present due to lack of access to data on the location and extent of these practices, and yet a recent study estimates that 35% of farmers in the Maumee have implemented filter strips on at least one field and at least 8% grow winter cover crops.[57] This means that results for cover crops and filter strips may somewhat overestimate the improvements that can be gained. The best interpretation is that the required implementation extent for the feasible scenarios (e.g., 25% implementation of filter strips) is needed beyond what is currently happening in the watershed.

Recommendations for Agricultural Conservation and Future Modeling Efforts. Although models help quantify the environmental impacts of potential conservation actions, engaging stakeholders helps to both improve the model and increase the likelihood that results will be feasible and policy-relevant. Iterative engagement with stakeholders provided critical insights into and details about agricultural and conservation practices employed in this watershed, enabling more realistic simulations. Moreover, engagement helped focus and prioritize modeling of conservation scenarios including which scenarios to evaluate and how to evaluate them using a systems approach that takes feasibility into account. Ultimately, this approach resulted in the production and evaluation of feasible and desirable scenarios.

Our findings should help guide key implementation decisions as the region strives to reach the nutrient targets for western Lake Erie. Main findings include:

- Lake Erie P targets will not be met unless the right practices are implemented to a large extent across the watershed. The exact location of needed practices is not identified by this model, which is at a watershed scale and assumes similar cropland management throughout the watershed. As such, findings from this work should be complemented by on-the-ground knowledge of in-field application and impacts of specific practices.
- There may be trade-offs in meeting multiple targets. Practices that are favorable for March−July targets for reducing HABs may not benefit annual targets for managing hypoxia. Additionally, practices may provide benefits in DRP but not TP loading, and vice versa.
- Applying a combination of conservation practices is not additive, and additional practices may provide diminishing water quality returns.
- Subsurface application of P or incorporation through tillage was the single most effective practice tested for reducing DRP loading, emphasizing the “right placement” in the 4R approach.[49]
- Timing of P applications influences the timing of DRP loading whereas timing made little difference for meeting the annual TP target for hypoxia. If reducing March−July loadings is a priority, fall P application may be preferable to spring-time. These findings should be field verified as the model does not fully capture fertilizer applications on frozen or saturated ground.
- Perennial cover crops, such as cereal rye, may be effective for reducing sediment-bound P loading, and have the capacity to hold dissolved nutrients over the winter months. However, if the focus is on March−July DRP export, the delay in nutrient availability may exacerbate DRP loading in this critical time. These results may underestimate cover crop effectiveness due to model limitations including not incorporating the beneficial effect of the practice on soil organic matter and corresponding water holding capacity.
- Applying filter strips along all waterways in the basin would help greatly for TP, but because they are less effective at trapping DRP the target may not be reachable using filter strips alone.
- Results suggest that practices applied at levels stakeholders currently consider feasible (e.g., 25−33% adoption of generally desirable practices) will not reach the new GLWQA loading targets, particularly for DRP. Significantly higher adoption rates and a more targeted approach of encouraging the set of practices most effective for DRP loading in the critical DRP source areas may be needed.[58] Successful targeting will likely require availability of field-level information such as soil test phosphorus results and conservation and farm management practices to prioritize BMP adoption on farm fields most susceptible to phosphorus export.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.6b01420.

Detailed explanations of cropland management assumptions, simulation of conservation practices in SWAT, changes to the SWAT source code, and model calibration and validation (PDF).

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Notes

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■ ABBREVIATIONS

DRP dissolved reactive phosphorus
HABs harmful algal blooms

SWAT Soil and Water Assessment Tool
TP total phosphorus

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