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

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ABSTRACT. Widespread adoption of agricultural conservation measures in Lake Erie's Maumee River watershed may be required to reduce phosphorus loading which 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 and fall timing of phosphorus applications as the individual practices 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 total phosphorus (TP) loading. We found that practices effective for reducing TP and DRP load were not always mutually beneficial, culminating in tradeoffs 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 1970's the United States (US) and Canada set a Lake Erie target total P (TP) load of 11,000 metric tons/year (MT/y) through the Great Lakes Water Quality Agreement (GLWQA), [4] and while that annual target has generally been met since the early 1980's, algal blooms and hypoxia returned in the mid-1990s with increasing severity and toxicity.[5-6]

In response, the US and Canada reviewed and revised 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] new March-July loading 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]

[Figure 1]

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 sub-surface drained (e.g. tile-drained). The watershed is fairly flat with an 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, non-governmental organizations, researchers, and staff at state, federal, and international agencies active in nutrient management and agricultural conservation in western Lake Erie watersheds.

The online survey solicited stakeholder opinions about which conservation practices are the most relevant to evaluate their potential to reduce nutrient pollution. 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. Results also helped recruit participants and inform the stakeholder workshops. In total, 36 of 74 individuals responded to the survey for a 48% response rate; 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).

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), non-governmental organizations (3), 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.[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), non-governmental organizations (3), and business/farming (5).

Watershed Model Development and Calibration **-** The Soil and Water Assessment Tool (SWAT) is a semi-distributed, 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 4,000 ha stream threshold was used to approach subbasins 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 subbasin.[25]

While stakeholders provided some information on farm management operations, additional operational details 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 1997-2012,[30] manure nutrient content averages,[29] and recent estimates of crop rotations derived from overlaying datasets for the available years (2007-2012) of the National Agricultural Statistics Service Cropland Data Layer.[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. Inorganic fertilizers and 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 soil drainage using the newer tile drainage routine based on DRAINMOD equations (ITDRN=1).[32] Other existing practices, including non-wheat cover crops and filter strips, were not included in the baseline model because we lacked access to these data.

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 2006-2010, 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. With the publicly available dataset 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 one 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 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 Supplementary Information (SI) for details on the calibration and simulation of conservation practices.

Conservation Scenario Development and Implementation - Scenarios were developed and prioritized through the 2014 stakeholder engagement workshops, and then paired down to actions that the SWAT model would be able to simulate well. Those scenarios were refined and additional scenarios identified 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 subbasins, with a watershed area of 17,300 km^2. Thirty-two 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 under-estimated and DRP over-estimated because the model was built with management assumptions for 2000-2005 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 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.

[Table 1]

[Table 2]

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 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 usability 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 over-application of nutrients) would impact modeled results. As a result, modelers improved the calculation of manure and inorganic fertilizer application rates using multiple data sources (Table 1 in SI).

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 full distribution of soil P concentrations. 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. While 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. The results showing continuous no-tillage to be less effective than rotational no-tillage in this study were likely influenced by these limitations, and more field-verified parameterization of no-tillage practices would be beneficial for sorting through these concerns.

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 ($\bar{x}$=1.12, n=33), followed by soil erosion control practices (e.g., tillage 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 were technologically, economically, and socially feasible.

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 SWAT does not currently route subsurface tile drainage through wetlands.

Interpreting Conservation Scenarios – The final 25 scenarios spanned placement and timing of nutrient applications, winter 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 timescales, 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]

[Table 3]

The 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, except for 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. While 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) met the target DRP load in half of the years, and in all years for TP. However, when applied at what stakedholders consider feasible, this combination of practices (6.1-6.3) rarely met the target load for DRP and met it in only half the years for TP.

[Figure 2]

Seasonal dynamics of TP and DRP loading help explain less intiutive results such as load reductions from fall vs. spring P application and 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.

While 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 great improvement in March-July loading (the HAB relevant period) because much of the nutrient was exported during the season in which it was applied. Winter cover crops held back nutrient runoff during the winter months, and reduced TP loading considerably throughout most of the year (Figure 3c). However, it appears the 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 the timing of DRP loading was shifted from winter to spring and summer, the period most critical for HABs. Annual TP loading, which is critical for hypoxia formation in Lake Erie's central basin, was reduced by 15-32% with cover crops, while DRP, which is a relatively small (but variable) percentage of TP, increased slightly 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%.

[Figure 3]

Water quality improvement that can be gained from single-practice and combinations at full adoption across the watershed reaches a 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 optimistic than the threshold of 25-30% from conservation scenarios run in the same watershed using a different model configuration, parameterization, and set of conservation practices in a previous study[56]. The new water quality targets 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. While 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 - While 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 conservation practices employed in this watershed, enabling the model to more realistically simulate them. 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 reached unless the right practices are included at a large extent.
- There may be tradeoffs 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 because each practice intercepts some nutrients and the next practice provides diminishing returns.
- Subsurface application of P or incorporation through tillage is the single most effective practice for reducing DRP loading, emphasizing the "right placement" in the 4R approach.[49]
- Timing of P applications strongly influences the timing of DRP loading, but perhaps not for the reasons being promoted in the region. We find the greatest DRP loading occurs during the season in which P is applied, and if reducing March-July loadings is a priority, fall P application may be preferable.
- Perennial cover crops are 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.
- 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.
- If practices are applied at levels stakeholders currently consider "feasible" (e.g., 25-33% adoption of generally desirable practices), the model suggests nutrient loading will not reach the new GLWQA loading targets, particularly for DRP. A more targeted

approach of encouraging the set of practices most effective for DRP loading in the critical DRP source areas may be needed.

While our focus was on the Maumee River watershed, the findings are likely transferable to other Midwestern watersheds where heavy clay soils and low slopes have been tile-drained to accommodate intensive row crop agriculture.

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Notes

ABBREVIATIONS

DRP, dissolved reactive phosphorus; HABs, harmful algal blooms; SWAT, Soil and Water Assessment Tool; TP, total phosphorus

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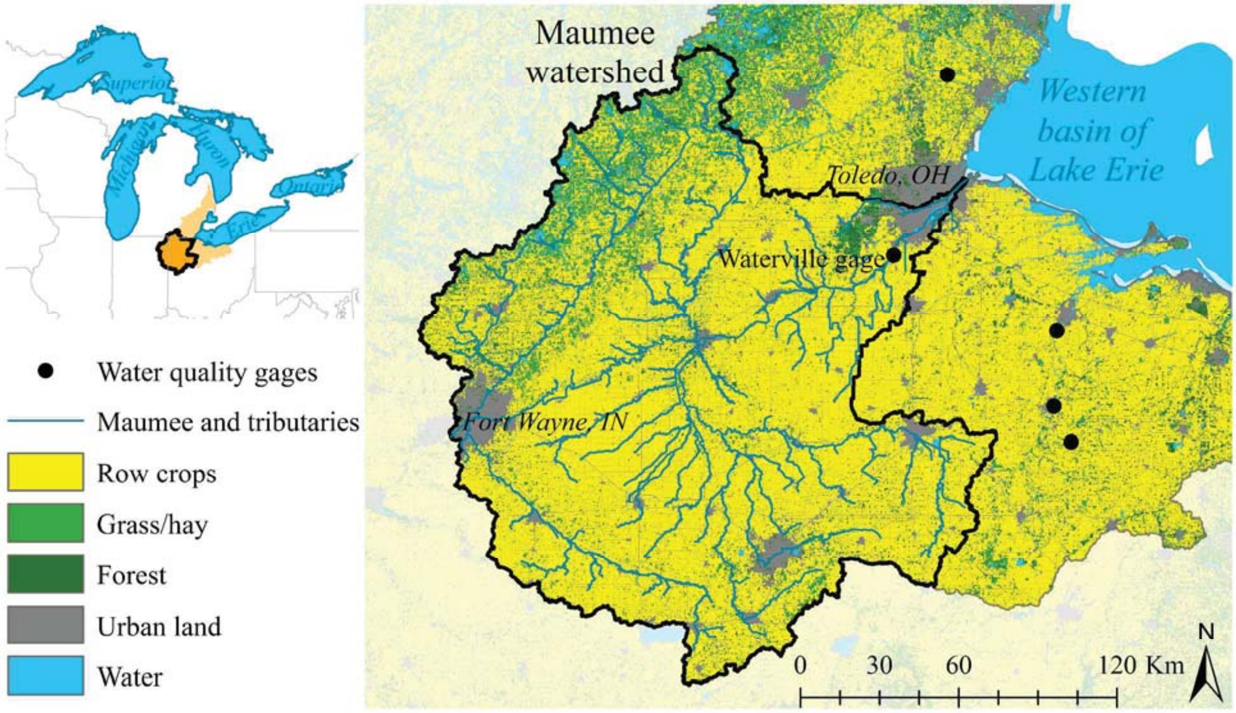


Figure 1: The Maumee River watershed was the focus of the stakeholder engagement and scenario development. The Maumee River watershed is the main source of nutrients to western Lake Erie as it is large, intensively managed in row crop agriculture, and has prevalent artificial drainage of heavy clay soils.

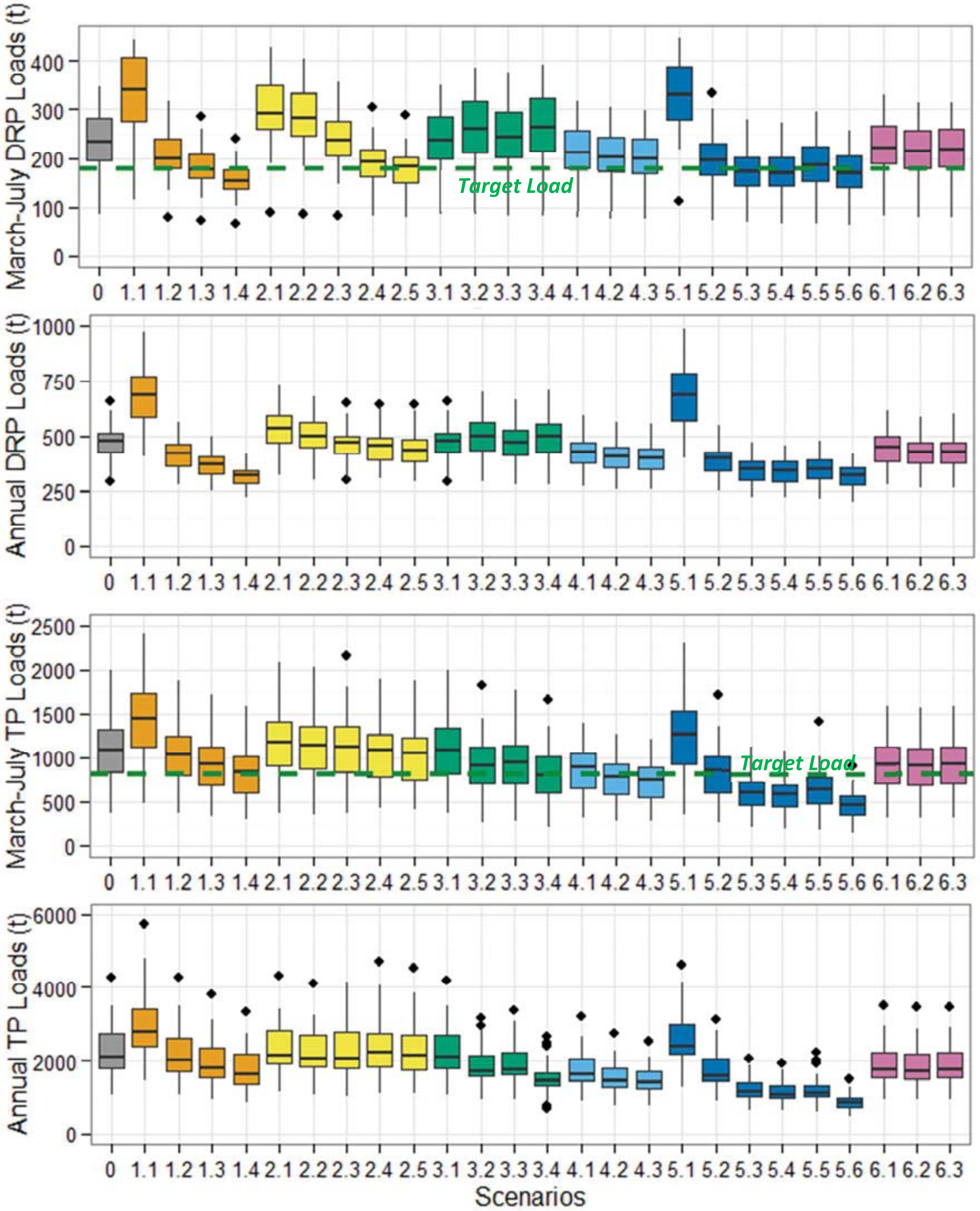
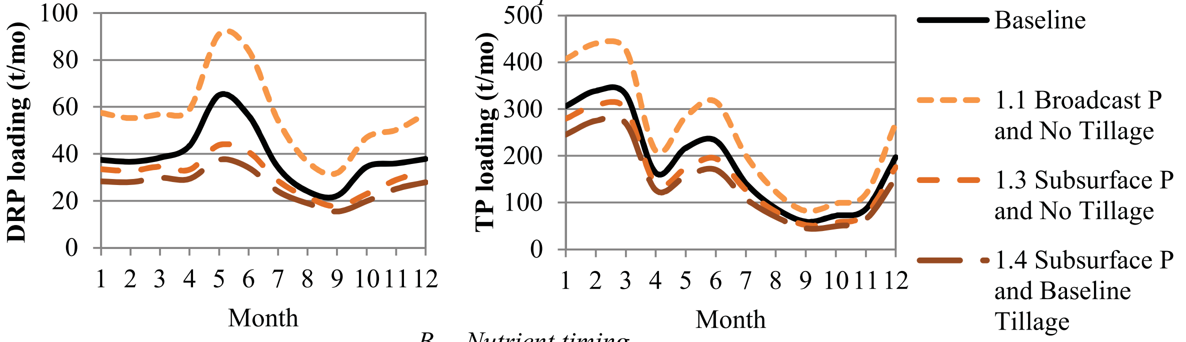
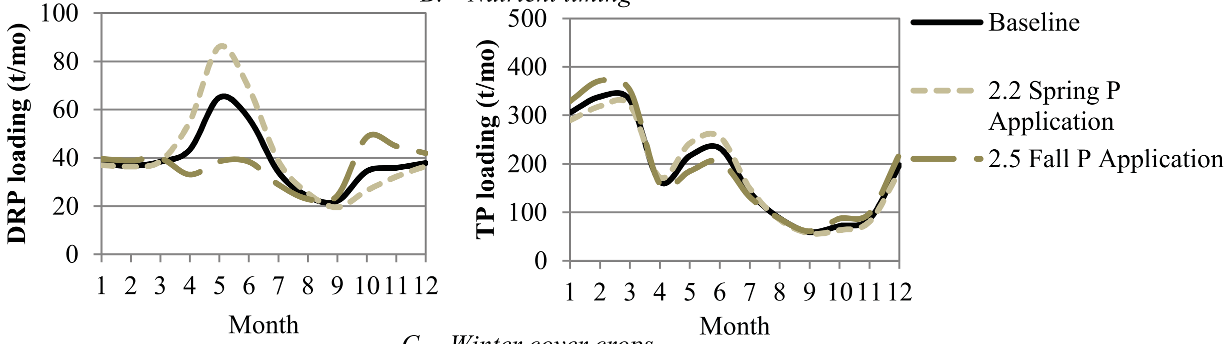


Figure 2: Boxplots of simulated March-July and annual DRP and TP loading at the Waterville gage under conservation management scenarios. Target loads (dashed green lines) are at 96% of the Maumee target loads to weight to the watershed area above the Waterville gage. Consult Table 3 for scenario descriptions.

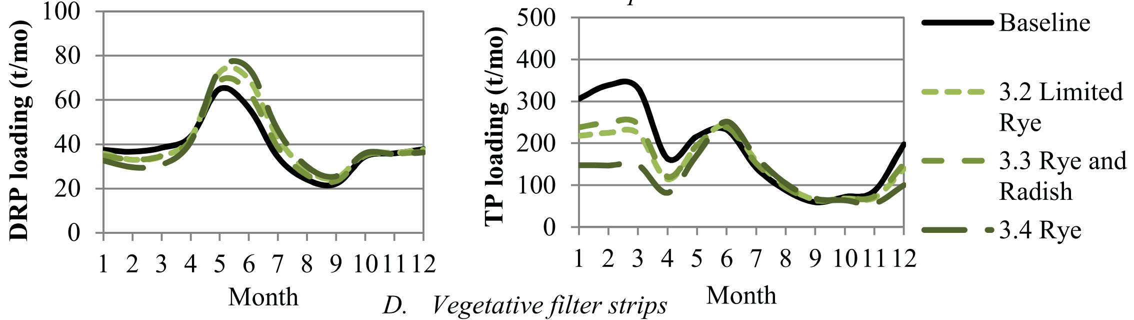
A. Nutrient placement



B. Nutrient timing



C. Winter cover crops



D. Vegetative filter strips

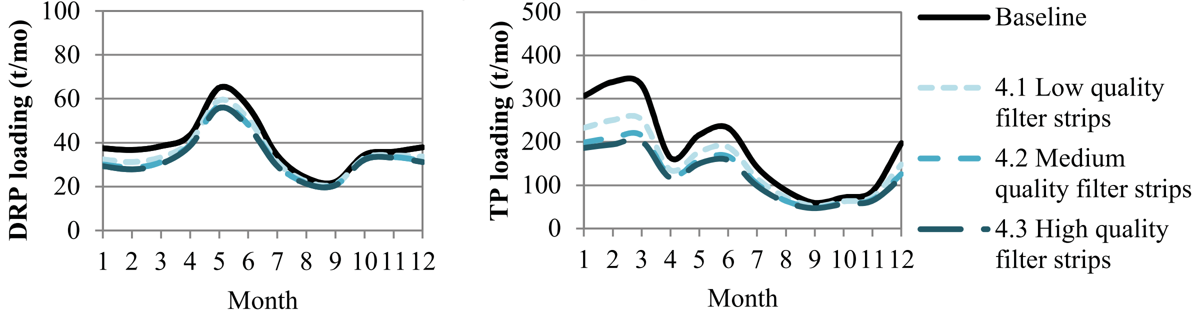


Figure 3: Seasonal dynamics of DRP and TP loading across conservation scenarios. *A:* Nutrient placement influences DRP and TP loadings similarly throughout the year due to changes in stratification of P at the soil surface, with the greatest reductions from subsurface placement and rotational tillage. *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.

Table 1: Maumee SWAT model calibration parameters. ** Indicates parameter was changed only for tile-drained lands.*

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	1,000 *	Depth to subsurface tile drain (mm)
DEP_IMP	6000	NA	1,500 *	Depth to the impervious layer in the soil (mm)
DRAIN_CO	NA	18902	25	Daily drainage coefficient (mm/day); set to ~1 inch/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 *	Curve number adjustment for increasing infiltration in non-draining soils; used optimal value from another study[58]
RS2	0.05	NA	0.01	Benthic source rate for DRP in the reach (mg P/m2/d)
RS3	0.05	NA	1	Benthic source for NH_4 in the reach (mgNH_4-N/m2/d)
RS4	0.05	0.001-0.1	0.001	Organic N settling rate in the reach (1/day)
RS5	0.05	0.001-0.1	0.05	Organic P settling rate in the reach (1/day)
SDRAIN	NA	7600-30,000	15000	Tile drain spacing (mm)
SFTMP	1	-10	-2	Snowfall temperature (deg C); value means precipitation will fall as snow if the average daily temp is below -2 deg C
SMFMN	4.5	1.4-6.9	2	Minimum snow melt factor (mm H2O/day)
SMFMX	4.5	1.4-6.9	2	Maximum snow melt factor (mm H2O/day)
SMTMP	0.5	-10	-2	Base snow melt temperature; melts if daily temp. >-2 deg 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 sub-routine; 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

Table 2: Maumee SWAT model calibration and validation results. 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 *.

			Calibration	(2001-2005)	Validation	(2006-2010)	Back-validation	(1981-2000)
	Statistic	Aim	Daily	Monthly	Daily	Monthly	Daily	Monthly
Flow	R2	>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
Sed.	R2	>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	R2	>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	R2	>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	R2	>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
NO3	R2	>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

Table 3: 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).

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*

Abstract Art: