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

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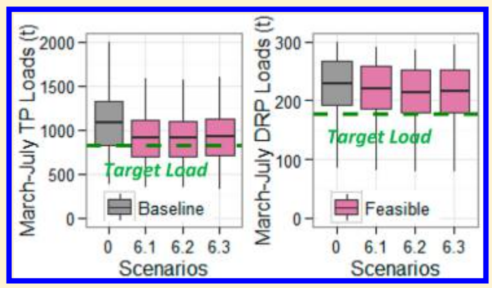
Supporting Information

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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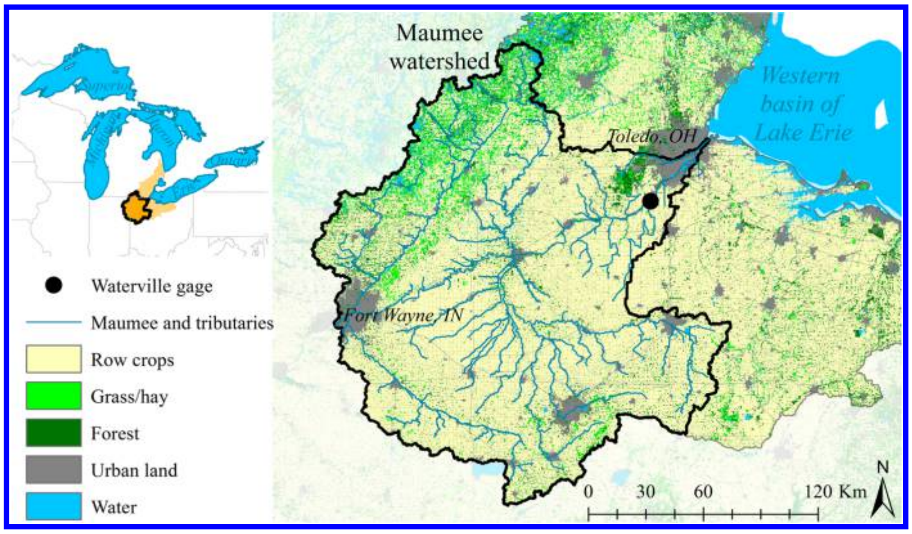

Figure 1. The Maumee River watershed was the focus of the stakeholder engagement and scenario development. This watershed is the main source of nutrients to western Lake Erie as it is large, intensively managed in row crop agriculture, and has prevalent artificial drainage of heavy clay soils.

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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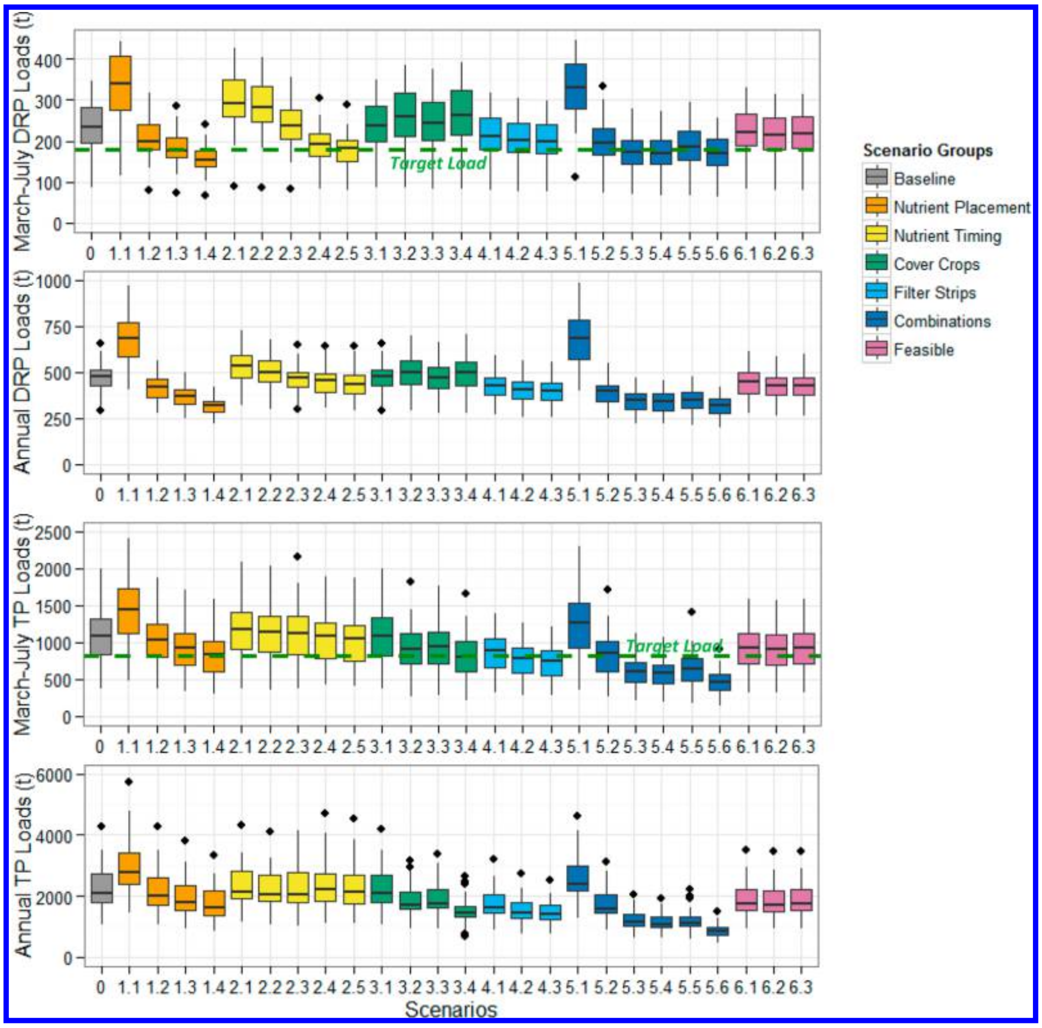

Figure 2. Boxplots of simulated March–July and annual DRP and TP loading at the Waterville gage under conservation management scenarios. Target loads (dashed green lines) are at 96% of the Maumee target loads to weight to the watershed area above the Waterville gage. Diamonds are considered outliers 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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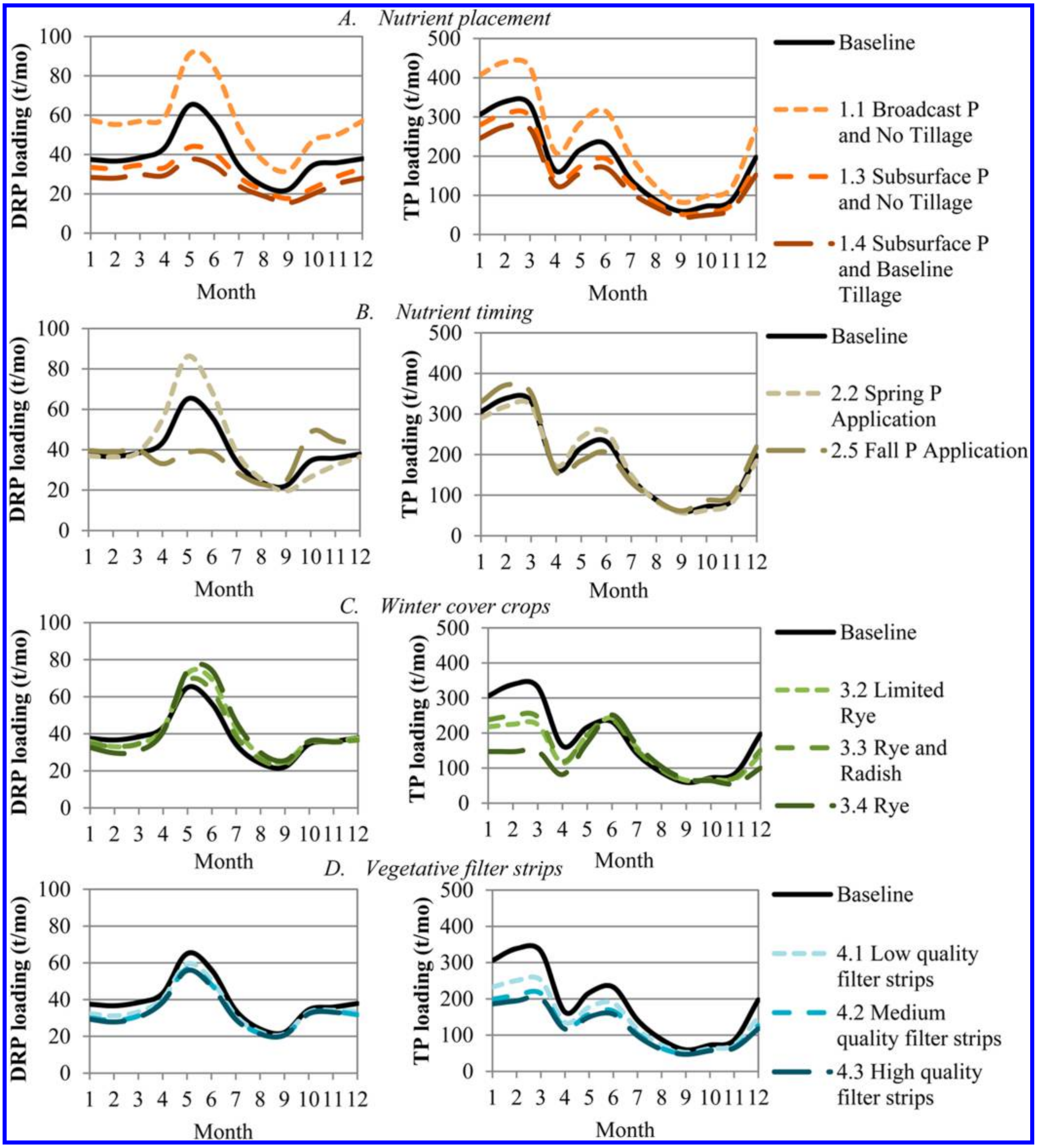

Figure 3. Seasonal dynamics of DRP and TP loading across conservation scenarios. (A) Nutrient placement influences DRP and TP loadings similarly throughout the year due to changes in stratification of P at the soil surface, with the greatest reductions from subsurface placement and rotational tillage. (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.; $\overline{x}$ = 1.15, n = 33), and practices that controlled flow from fields (e.g., filter strips, tiling, etc.; $\overline{x}$ = 1.15, n = 33). Respondents were least interested in evaluating the effectiveness of wind erosion control practices (e.g., hedgerow planting, windbreaks, etc.; $\overline{x}$ = 2.15, n = 33) or the effectiveness of putting lands in long-term conserving cover ($\overline{x}$ = 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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