Evaluating the impact of legacy P and agricultural conservation practices on nutrient loads from the Maumee River Watershed

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ABSTRACT. The recent resurgence of hypoxia and harmful algal blooms in Lake Erie, driven substantially by phosphorus loads from agriculture, have led the U.S. and Canada to begin developing plans to meet new phosphorus load targets. To provide insight into which agricultural management options could help reach these targets, we tested alternative agricultural land use and land management scenarios on phosphorus loads to Lake Erie. These scenarios highlight certain constraints on phosphorus load reductions from changes in the Maumee River Watershed (MRW), which contributes roughly half of the phosphorus load to the lake's western basin. We evaluate the effects on phosphorus loads under nutrient management strategies, reduction of fertilizer applications, employing vegetative buffers, and implementing widespread cover crops and alternative cropping changes. Results indicate that even if fertilizer application ceased, it may take years to see desired decreases in phosphorus loads, especially if we experience greater spring precipitation or snowmelt. Scenarios also indicate that widespread conversions to perennial crops that may be used for biofuel production are capable of substantially reducing phosphorus loads. This work demonstrates that a combination of legacy phosphorus, land management, land use, and climate should all be considered when seeking phosphorus loading solutions.

INTRODUCTION

Recent resurgence of harmful algal blooms (HABs) in Lake Erie's western basin and depleted oxygen (hypoxia) in its central basin[1-2] threaten human and animal health as well as ecosystem integrity. While all loads to the western and central basins contribute to the evolution of hypoxia, the main HAB driver has been shown to be elevated phosphorus (P) loads coming from the watersheds that drain into the western basin[3], particularly from the Maumee River Watershed (MRW).[4-5] The 2012 Great Lakes Water Quality Agreement (GLWQA)[6] calls for revision of the 1978 Lake Erie P loading targets,[7] and the US and Canada have recently approved new March-to-July P loading targets[8] for the Maumee River Watershed of 186 metric tonnes (~0.109 kg/ha) of dissolved reactive phosphorus (DRP) and 860 metric tonnes (~0.506 kg/ha) of total phosphorus (TP).

Significant lake modeling effort was used to inform the target P loads for Lake Erie,[2,4,5,9-10] but less research has been done to identify policy and management actions needed to achieve them. Bosch et al.[12] suggested that extensive implementation of multiple conservation practices would be needed to address nutrient and sediment load problems in Lake Erie and Daloglu et al.[13] demonstrated the negative interactive effects of changes in conservation practices and recent changes in precipitation patterns on DRP loads. Knowledge and models of P transport within watersheds has continued to improve since these studies were published,[14-15] and there is a need to revisit and expand the potential strategies, especially in light of the new target loads.

The goal of the present work is to explore the potential outcomes of land management and land use changes in the MRW to determine the bounds of what might be expected from extensive changes in agricultural conservation practices. Our main objectives were to evaluate the impact of legacy P in the watershed and simulate the effects of hypothetical, rather extensive management strategies, including reducing farm fertilizer applications, employing vegetative buffers on all farm fields, and implementing winter cover crops and alternative cropping systems across all farm fields.

MATERIALS AND METHODS

Study Area & Model Development - We focused on the MRW (Figure 1) because it contributes the largest P load of any Lake Erie tributary and has been shown to be a primary driver of Lake Erie's HABs[4-5]. The watershed occupies over 17,000 km^2 and extends from northwest Ohio into Indiana and Michigan. Its land use is about 70% row crop agriculture, dominated by rotations of soybeans, corn, and winter wheat. The land is characterized by low slopes and heavy, clayey soils with poor natural drainage, with the majority of cropland artificially drained by subsurface tile drains. This watershed is also a perfect test bed for these analyses because the river P loads, measured near the outlet of the Maumee River, have been monitored daily for over 40 years by Heidelberg University's National Center for Water Quality Research (NCWQR),[16] thus providing stringent constraints on model performance.

[FIGURE 1]

We used the Soil and Water Assessment Tool (SWAT), a semi-distributed, hydrologic model that takes into account land use, land management, soils, slopes, and climate information to simulate watershed processes such as crop growth, streamflow, and nutrient and sediment dynamics across the landscape and in streams and rivers.[17] SWAT has been used for a variety of climates and land uses, and has been shown to work well in agricultural landscapes.[18-19] Our model was set up, calibrated, and validated for the MRW as described in Kalcic et al.[20] for streamflow and loadings of TP, DRP, sediment, and total nitrogen. The model's baseline cropping system consisted primarily of corn and soybean rotations, with 45% of cropland having some winter wheat in rotation. Fertilizer application rates were estimated based on fertilizer sales, manure applications were estimated based on numbers of animals, and tillage was estimated based on the Conservation Technology Innovation Center database. Tile flow accounted for 38-42% of the streamflow, and 42-48% of the DRP (8-10% of TP) loads to the river. The model performance for common evaluation criterion was deemed to be very good.[20,21] For more details of the SWAT model set-up, calibration, and validation see supporting information (SI) and Kalcic et al.[20]

In the next sections, we first evaluated the impact of legacy P (see "Legacy Phosphorus Impacts") and then significant implementation of agricultural conservation practices (see "Alternative Phosphorus Reduction Strategies"). All simulations are theoretical in nature, but provide insight on reaching target loads.

Legacy Phosphorus Impacts - Before running agricultural conservation scenarios, we evaluated the watershed's response to eliminating fertilizer applications to assess the impact of legacy P. The baseline model was run for twelve years under observed climate and current management regimes as a warm up period, followed by eighty years of the same weather with one of four management scenarios:

(1) Business as usual (BAU): same fertilization and management used in baseline model

(2) No fertilizers (No Fert): ceasing all inorganic and organic nitrogen and P fertilizer applications

(3) No P fertilizers (No P Fert): ceasing all inorganic and organic P fertilizer applications

(4) No inorganic P fertilizers (No Inorganic P Fert): ceasing inorganic P fertilizer applications but continuing manure applications

For each case, we repeated a single year's temperature and precipitation patterns over the 80 year simulation to isolate the impact of legacy P. The other three weather variables used by SWAT (relative humidity, solar radiation, and wind speed) were generated within SWAT by the WXGEN weather generator which, combined with agricultural rotations, causes some year to year variability in outputs. Given that precipitation is a main driver of P losses via surface and subsurface pathways, we also wanted to consider the potential impacts of weather, so we selected average, wet, and dry years from the 1981-2010 record as follows. Because the target P loadings are based on spring (March-to-July) loads, we extracted precipitation, simulated streamflow, and P loads for each year (SI Figure S1) from the 1981-2010 simulation.[20] Two representative 'wet' years were selected for analyses: 1981, which had high spring precipitation, and 1982, which had high spring streamflow (driven, in this case, by snowmelt), because high rainfall and high streamflow can have different impacts on P loading. For example, the high rainfall year (1981) has greater simulated DRP load in the spring whereas the high streamflow spring (1982) had higher simulated TP loading. The year with the lowest overall values for all four variables (1988) was selected as the representative 'dry' year, and a year with values close to the average for all four variables (2004) was selected as the representative 'average' year.

Alternative Phosphorus Reduction Strategies - The baseline SWAT model was also used to test the impact of agricultural management and land use changes on P loads and crop yields under the observed 1981-2010 weather conditions. Table 1 briefly describes the scenarios run under these conditions; further details are provided in the SI. Two types of in-field strategies were tested: the reduction of P fertilizer application rates and addition of cereal rye winter cover crops. The rate of application was tested because this practice could be a cost-effective strategy to reduce P loads. While we tested a range of reductions, we want to emphasize that this study is watershed-scale; therefore, while the reductions were applied across all fields, the interpretation of the results would be that some farmers who are over-applying P would have larger reductions in rates, while others already applying correct amounts of P would have no change in rates. The addition of winter cover crops (cereal rye that is killed, not harvested, before cash crop plantings) was tested because they are commonly used in the Midwest and have been shown to provide multiple water quality benefits by providing ground cover for soil typically exposed during the winter months.[23-24] Recent surveys also suggest that there is currently little adoption of cover crops in the watershed, so there is great potential impact for addition of this practice.[22]

Vegetated filter strips were also implemented to test the impact of an edge-of-field practice on P loads. Vegetated filter strips can be planted alongside open waterways to intercept sediment and nutrients from adjacent farmland[25-26] and are a commonly recommended practice. In this watershed, around 31% of acres have an edge-of-field trapping practice;[22] therefore, there is still potential impact with further implementation. Filter strips were simulated with varying effectiveness using the newest filter strip routine in SWAT that is based on empirical relationships derived from simulations of the Vegetative Filter Strip MODel.[27] To vary the effectiveness of filter strips, the two parameters controlling filter strip effectiveness (FILTER_CH: the fraction of flow through the most heavily loaded 10% of filter strip which is fully channelized and FILTER_CON: the fraction of field drained by most heavily loaded 10% of filter strip) were changed along with the ratio of field area to filter strip area; see SI for more details.

Two agricultural land use changes were also evaluated: alternative row crops (sunflower and lentils) and cellulosic biofuel crops (switchgrass and miscanthus). Sunflowers and lentils are examples of row crops with potential to replace corn and soybeans in terms of ease of adopting existing equipment and providing similar food and feed products.[28-29] Although it is unlikely that they may be grown continuously or in rotation due to problems such as pests, these crops were simulated solely to test the impact of row crop variety on P loads. Switchgrass and miscanthus are two cellulosic biofuel crops capable of addressing the United States Energy Security and Independence Act of 2007 fuel mandates while potentially improving water quality.[30-32] These land use changes are examples of alternative farming pathways that allow farmers to produce crops; however, both options require policy, economic, and technological advances to be effective and feasible to producers.

[TABLE 1]

RESULTS AND DISCUSSION

Legacy P Impacts - When fertilizer applications were stopped under average weather conditions, spring DRP loads decreased to at or below the targets within 3-5 years, and continued to decline over time in contrast with the BAU scenario which remained steadily above the target (Figure 2; gray line). This highlights the potential importance of phosphorus applied in a given year. TP loads, however, took longer to reach the targets depending on weather, perhaps due to lower mobility of the particulate P fraction. When only inorganic P fertilizer was stopped and manure applications continued, DRP and TP loads hovered around the targets longer than in the no P fertilizer scenarios (Figures 2 & 3; gray lines). Such time lags in the watershed's response to cessation of fertilizer applications demonstrate how much legacy P may currently be in the MRW. This is discussed further below.

[FIGURE 2]

[FIGURE 3]

These results, similar to Daloglu et al.,[13] also show that weather variability can influence the timescale of the watershed's response. Under BAU management, the DRP targets are actually met in the driest years, but not in average or wet years (Figure 2) possibly due to the high mobility of dissolved phosphorus. However, that target was eventually met in every fertilizer reduction scenario under all weather conditions, *albeit* after 30-40 years in some cases. In years of high spring streamflow (and thus high runoff) and high spring precipitation it is unlikely that TP targets will be met, even under this extreme case of no fertilizer application (Figure 3). Under dry and average conditions, however, targets were met fairly quickly in the no fertilizer and no P fertilizer scenarios. However, when manure application continued, it added approximately ten years to the length of time to reach the target compared with the no P fertilizer scenario. While our approach begins to evaluate the impact of legacy P by putting "bounds" on the time it could take to reach target loads after cessation of P fertilizers, given varying weather conditions, in reality the time to reach targets would likely occur sometime between the results for dry and wet year simulations. Additionally, given that it is unreasonable to assume that all P fertilizer applications would cease, the legacy P in the soils and streams in the MRW along with continued applications could prolong reaching the targets unless other agricultural conservation practices are employed. This simulation also suggests that the legacy P in the watershed will need to be addressed along with other conservation practice implementation.

We also evaluated the response time of corn and soybean yields after eliminating all fertilizer applications under average weather conditions (Figure 4). As expected, the impacts on corn yields were seen almost immediately when both nitrogen and P applications were stopped. However, while eliminating only P applications decreased yield only slightly at first, significant declines did not occur for almost 25 years. Soybeans were not impacted by eliminating nitrogen fertilizer because they can fix nitrogen; however, they too saw significant impacts from cessation of P applications after 25 years.

This time lag between eliminating P applications and decreasing corn and soybean yields suggests significant excess or legacy P stored in the watershed's soils. Previous studies of intensively managed croplands have shown that legacy P in the soil can maintain crop growth for 8-20 years after P fertilizer applications cease.[33-35] The level of legacy P in soils may be substantial in the MRW. Soil test P is often used to guide application rates[36] because higher soil test P levels correspond to greater plant available P; higher soil test P can also lead to greater dissolved P in runoff.[37] Only 17% of fields surveyed in a nearby Lake Erie watershed had a Mehlich-3 Phosphorus (M3P) soil test P value of less than 21 ppm, whereas 48% had values between 21-43 ppm, 25% had values between 43-71 ppm, and 11% had values greater than 71 ppm.[38] The Tri-State Fertilizer Recommendations (for Michigan, Ohio, and Indiana)[39] suggest that a Bray-P1 soil test P value of 15 ppm (~ 27.7 ppm M3P)[40] is the critical P level for corn and soybeans, thus, in the soils reported[38], a large portion likely did not need additional P fertilizer. Yet, that study indicated that even for fields surveyed with greater than 71 ppm M3P soil test values, additional P fertilization was still being recommended for 75% of fields. Above the critical level, soil can supply P needed for the crop to grow, and below this level P will likely limit crop growth. For soil at critical soil test P levels, the Tri-State Recommendations are that no P fertilizer is required, yet they provide an estimate of P to apply as a means to "safeguard against sampling or analytical variation".[39] This safety factor built in to the recommendations may be one factor responsible for over-application of P in the Midwest.[41]

[FIGURE 4]

By modifying the SWAT code (see SI), we were able to report simulated values corresponding to the soil test P. In doing so, we found reducing SWAT's inorganic soil P initialization [42] to 1/5th of the default value resulted in a more reasonable range of soil test P (range: 10-145; median: 35) that corresponded well with existing data for soils tested in the Ohio Lake Erie Basin (range: 2.8-291; median: 35.8).[38] To further emphasize this point, we tested the effect of initializing SWAT at soil P levels higher than the calibrated value, and found that there is a "critical" SWAT soil test value of ~10 ppm below which corn and soybean production decline in the MRW model (see SI). In these tests, the soil could maintain critical levels for the duration of the entire simulation (>80 years) and thus maintain crop growth, which is unlikely even in this intensively managed system.

Response to Agricultural Conservation Practices - While the previous section focused on system responses to a theoretical elimination of fertilizer under average, wet, and dry weather, here we evaluate the impact of conservation practices driven by historical climate. The following conservation practice scenarios were simulated under observed 1981-2010 climate conditions and compared to the baseline model under those same conditions (Figure 5).

[FIGURE 5]

In-Field Practices - When inorganic P application rates were reduced to 75%, 50%, 25%, and 0% of the rates used in the baseline model, both DRP and TP loads decreased (Figure 5) with minimal impacts on crop yields (SI Figure S3). Even the 0% inorganic P scenario still exceeded the proposed TP and DRP target loads in some years with little impact on yields, indicating that manure applications, combined with legacy P, may be sufficient for plant growth for this 30 year period. This is consistent with the previous section's results that suggested at least 25 years may be required for decreased fertilization rates to impact corn and soybean yields under average weather conditions. Including a winter cover crop in rotations across all cropland reduced TP loads, but did not effectively decrease DRP (Figure 5). Winter cover crops reduce erosion and loss of sediment-bound P, while DRP concentrations in tile drainage flow remain unaffected. It should be noted that cereal rye modeled in this study is only one of many cover crops used by farmers, and while it is one of the best performing cover crops in poorly drained soils and establishes late in the fall, it may not be representative of some of the other common crops, particularly those that winter kill.

Edge-of-Field Practice - Simulated vegetated buffer strips varied in their ability to intercept TP and DRP (Figure 5). With higher quality filter strips placed along every agricultural waterway, the loading target could often be met for TP. However, this average masks weather-related inter-annual variability, and it is likely filter strips would not prevent wetter-than-average years from exceeding the targets (SI Figure S4). DRP load was reduced with filter strips because some portion of DRP moves with surface runoff, but it did not meet targets on average, even at full watershed implementation. One of the reasons is that approximately 40% of DRP is delivered through tile drains in our model (a value in the range reported in King et al.[14]) and those drains empty directly to ditches and streams, bypassing filter strips. While this percent of DRP through tiles was calibrated to match the reported range of field values, further improvements in the modeling of P transport through tiles could influence the results of this scenario, especially with respect to DRP loads. Additionally, filter strips are given no spatial area of converted land in the model, and while surface runoff from farm fields passes through before reaching the stream, they do not treat streamflow when waters rise above stream banks. Future improvements to the mechanics of filter strips in SWAT could also influence prediction of P intercepted by filter strips.

Alternative Land-Use Strategies – The impacts of changing all agricultural land to alternative row crop rotations (continuous sunflower, continuous lentil, or sunflower-lentil rotations) varied as a function of how much P was applied (Figure 5). In the high P application scenarios (roughly equivalent to current corn/soybean application rates), the alternative row crops generally had higher DRP loads and very similar TP loads to the baseline model. In general, the alternative row crops performed similarly to the baseline, suggesting that the amount of P applied to row crops was more important than the type of crop planted, especially as modeled by SWAT. However, when comparing the recommended P fertilizer rates from the Tri-State Standard for corn and soybean to growth handbooks for sunflowers and lentils,[43-44] under similar soil P levels, these alternative crops require less P. Alternative crops could have a greater impact on P losses to the extent that they have require lower P applications.

Changing the entire MRW from conventional row crop agriculture to perennial biofuel grasses would have a significant impact on P loads (Figure 5). These crops were fertilized with nitrogen at rates required for their growth,[45-48] and with no inorganic P. Thus, each biofuel scenario was run with and without manure application for better comparison to the baseline model. Compared to the baseline, if all agricultural lands produced either switchgrass or miscanthus, DRP and TP loads would diminish greatly. Continuing manure applications prevented achieving targets for DRP in some years, whereas these grasses grown without manure additions met targets every year. Their impact on TP loads is much greater because these crops are grown in stands (not rows), don't winter kill, and develop deeper and larger root systems. This allows these crops to trap sediment and runoff more easily, tap into legacy nutrients within the soil profile, and provide cover for soil in the winter to prevent erosion. For these reasons the TP targets were met under all scenarios and variations. Biofuel crop yields remained relatively constant throughout the time period (SI Figure S5), and were similar to previously reported values for a similar climate.[47]

Policy Implications

Our results highlight information which should help those responsible for developing action plans to reduce P loads to Lake Erie from agricultural sources. First, our results support conclusions from Bosch et al.[12] that it will take more than one agricultural conservation practice with widespread implementation to see consistent P load reductions because no single practice could achieve the target loads every year. Second, the alternative biofuel crops did show significant reductions in both TP and DRP. Although these were also implemented across the entire MRW, partial and perhaps targeted conversion of marginal croplands back to grassland has the potential to decrease P loads, and using biofuel crops could allow farms to remain economically viable given the right policy incentives. Third, our results demonstrate the importance of P stored within the soil and its long-term impact on restoring water quality. For example, in our simulations, crop growth continued for ~25 years and it took as much as 30-40 years to reach P load targets even after fertilization was stopped, depending on climatic conditions. This suggests a large amount of legacy P exists in the MRW soil and this legacy will need to be addressed in agricultural conservation. These same runs also demonstrated that DRP loads could drop relatively quickly under average weather conditions, highlighting the importance of current P fertilizer applications in driving a given year's loads. From this it is clear that conservation strategies will need target losses due to current fertilizer applications, as well as losses due to legacy P in the system. Lastly, this work highlights the importance of climatic impacts on P given the stark differences between TP and DRP loads under wet, dry, and average weather conditions. Therefore, it will be crucial for policymakers to understand how climate change, or even inter-annual variability, may impact proposed management solutions. For example, previous work in the Maumee has shown that precipitation may decrease in May-to-October, but increase in the rest of the year[45] so targeting conservation strategies temporally will be important. Overall, this work demonstrates that significant changes in agricultural land management in the Western Lake Erie Basin are needed to reach target P loads in order to prevent or mitigate future harmful algal blooms.

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ABBREVIATIONS

BAU, business as usual; DRP, dissolved reactive phosphorus; GLWQA, Great Lakes Water Quality Agreement; HABs, harmful algal blooms; M3P, Mehlich-3 Phosphorus; MRW, Maumee River watershed; NCWQR, National Center for Water Quality Research ; No Fert, no fertilizers; No inorganic P Fert, no inorganic phosphorus fertilizers; No P Fert, no phosphorus fertilizers; P, phosphorus; SI, supporting information; SWAT, Soil and Water Assessment Tool; TP, total phosphorus.

SUPPORTING INFORMATION. Includes additional information on the SWAT model set-up, details for year selection in legacy phosphorus runs, details for management scenario runs, additional results, and description of methods used to evaluate soil test phosphorus in SWAT.

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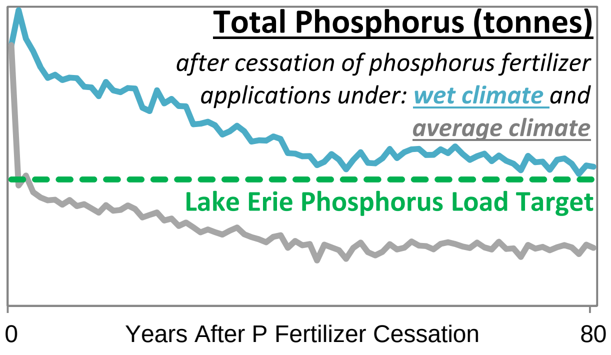
TABLE OF CONTENTS GRAPHIC AND SYNOPSIS



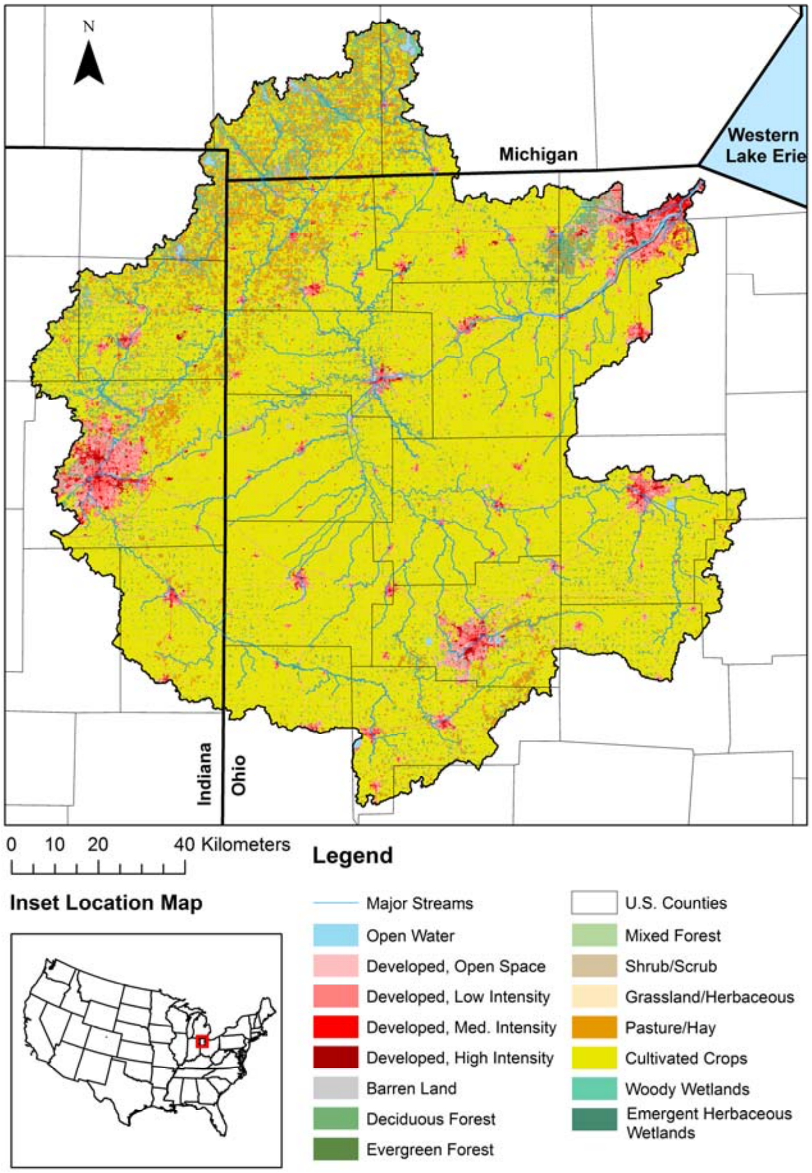


Figure 1. Location and land-use (from the USGS 2006 National Land Cover Dataset) of the Maumee River Watershed. The Maumee River Watershed Soil and Water Assessment Tool model was developed using a combination of the National Land Cover Dataset and the National Agricultural Statistics Service Cropland Data Layer, extracted for multiple years[20].

Table 1. Alternative P reduction strategy scenarios run under historical climatic conditions. Further details for scenario implementations in SWAT are provided in the SI.

Type	Scenarios	Further variations
Rate of P applications	1. Baseline with 75% inorganic P fertilizer 2. Baseline with 50% inorganic P fertilizer 3. Baseline with 25% inorganic P fertilizer 4. Baseline with 0% inorganic P fertilizer	None
Filter Strips	5. 25% of agricultural lands with filter 6. 50% of agricultural lands with filter 7. 75% of agricultural lands with filter 8. 100% of agricultural lands with filter	Filter strip condition: poor to good
Cover crops	9. Cover crops over 25% of ag. lands 10. Cover crops over 50% of ag. lands 11. Cover crops over 75% of ag. lands 12. Cover crops over 100% of ag. lands	None
Alt. Row Crops	13. High P application 14. Medium P application 15. Zero P application	Three rotations: continuous sunflower, continuous lentil, and sunflower-lentil rotation
Biofuels	16. Manure applied (not incorporated) 17. No manure applied	Two varieties: Shawnee switchgrass (*Panicum vigratum*) and *Miscanthus x giganteus*

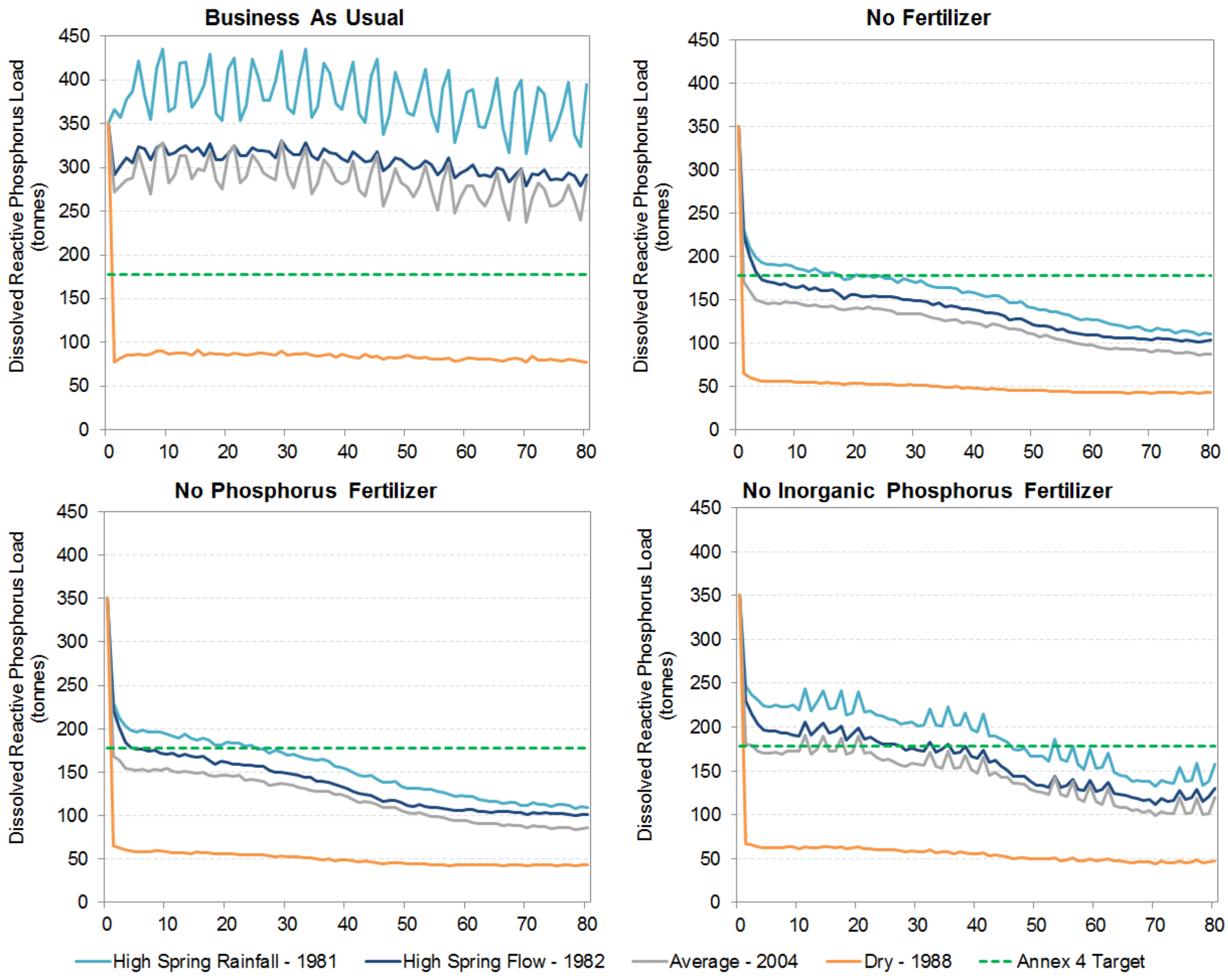


Figure 2. March-to-July dissolved reactive phosphorus loads under each fertilizer application cessation scenario for each type of climate condition across 80 years of simulation. The light blue line represents high spring rainfall conditions (1981), the dark blue line represents high spring streamflow conditions (1982), the gray line represents average climate conditions (2004), the orange line represents dry climate conditions (1988) and the dashed green line represents the GLWQA targets area-weighted to the Heidelberg water quality station near Waterville, Ohio.

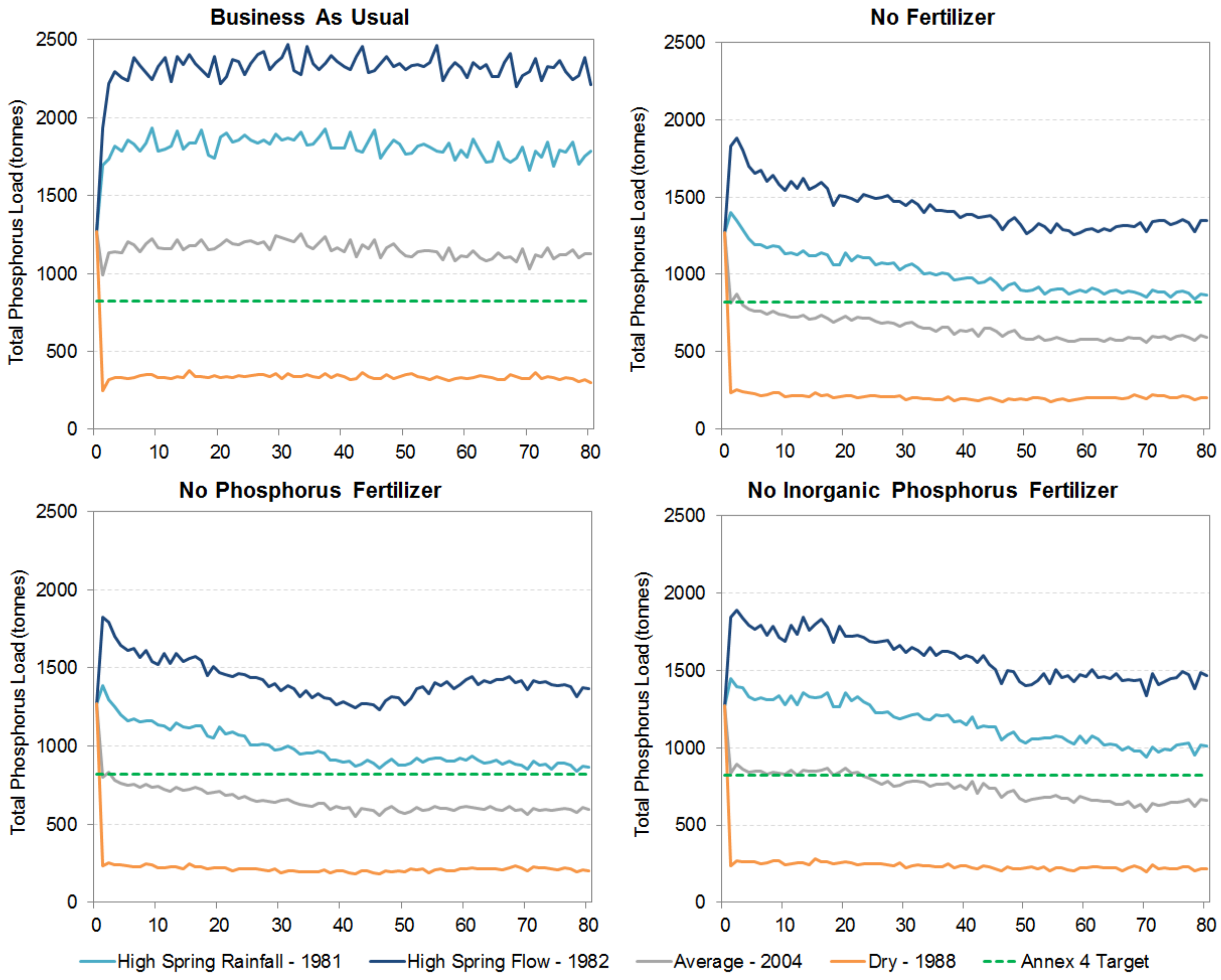


Figure 3. March-to-July total phosphorus loads under each fertilizer application cessation scenario for each type of climate condition across 80 years of simulation. The light blue line represents high spring rainfall conditions (1981), the dark blue line represents high spring streamflow conditions (1982), the gray line represents average climate conditions (2004), the orange line represents dry climate conditions (1988) and the dashed green line represents the GLWQA targets area-weighted to the Heidelberg water quality station near Waterville, Ohio.

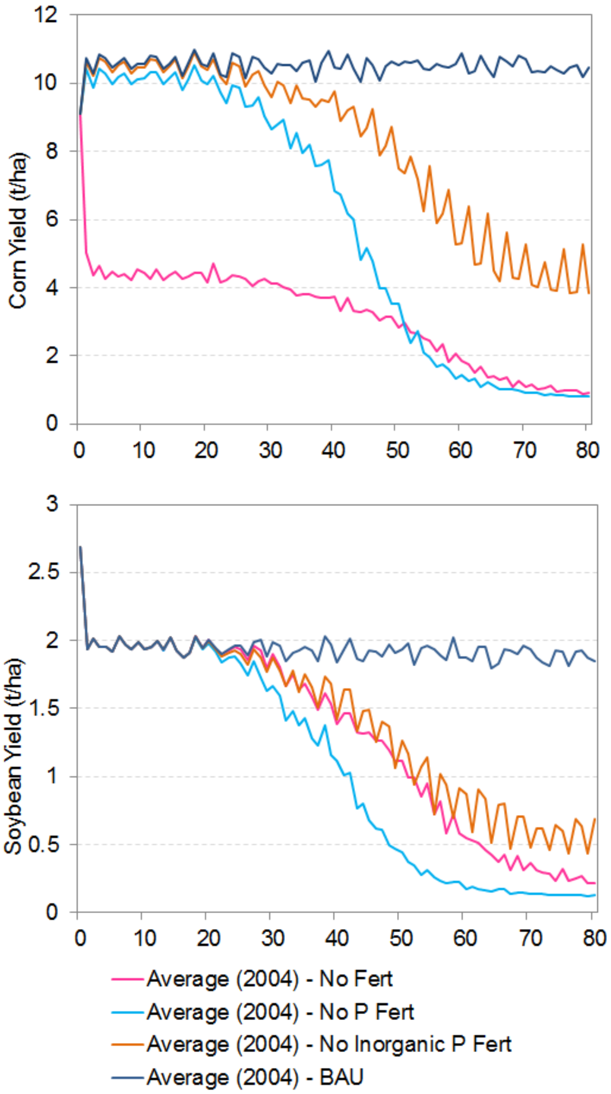


Figure 4. Average MRW yields (t/ha) of corn (top) and soybean (bottom) under average (2004) weather conditions across 80 years of simulation.

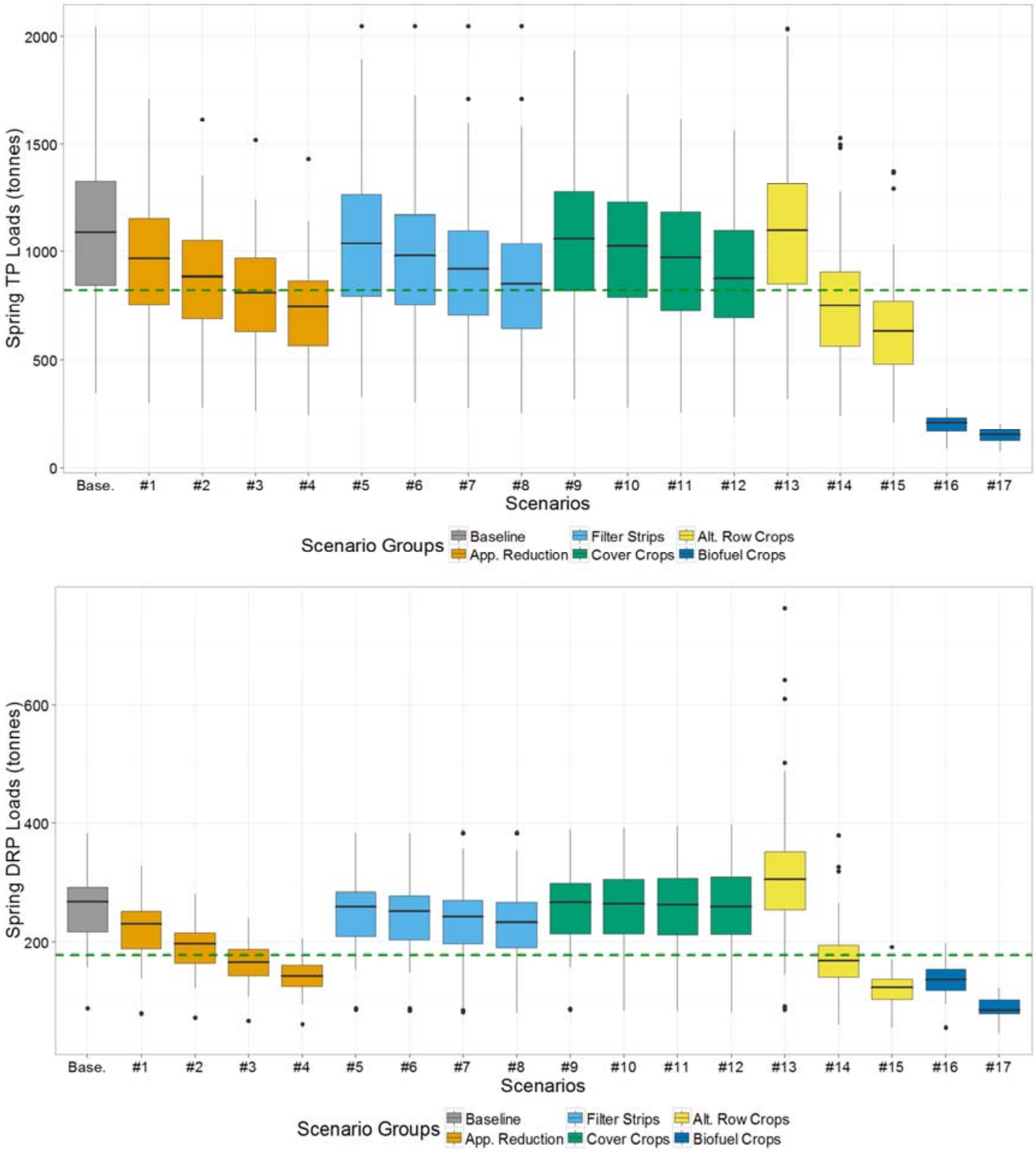


Figure 5. Scenario results under 1981-2010 climate for springtime (March-to-July) TP (top) and DRP (bottom) loads grouped by scenario types. Colored boxes contain results from 75% of the years in the multi-year simulations. Solid black line represents the median value. The thin vertical lines represent the range of the results, and the dots show extreme outliers. The GLWQA targets are shown with the dashed line. Observed DRP loading differs more from the baseline because the model was calibrated for a period with higher DRP concentrations.