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Less Agricultural Phosphorus Applied in 2019 Led to Less Dissolved Phosphorus Transported to Lake Erie

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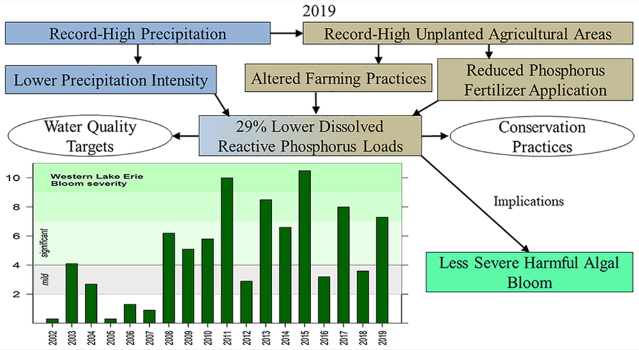
ABSTRACT: Extreme precipitation events affect water quantity and quality in various regions of the world. Heavy precipitation in 2019 resulted in a record high area of unplanted agricultural fields in the U.S. and especially in the Maumee River Watershed (MRW). March−July phosphorus (P) loads from the MRW drive harmful algal bloom (HAB) severity in Lake Erie; hence changes in management that influence P export can ultimately affect HAB severity. In this study, we found that the 2019 dissolved reactive P (DRP) load from March−July was 29% lower than predicted, while the particulate P (PP) load was similar to the predicted value. Furthermore, the reduced DRP load resulted in a less severe HAB than predicted based on discharge volume. The 29% reduction in DRP loss in the MRW occurred with a 62% reduction in applied P, emphasizing the strong influence of recently applied P and subsequent incidental P losses on watershed P loading. Other possible contributing factors to this reduced load include lower precipitation intensity, altered tillage practices, and effects of fallow soils, but more data is needed to assess their importance. We recommend conservation practices focusing on P application techniques and timing and improving resiliency against extreme precipitation events.



■ INTRODUCTION

Various climate models in previous studies have shown that heavy precipitation, especially during spring, and extreme precipitation events are likely to occur more frequently and affect streamflow discharge, nutrient exports, and water quality impairments in many regions around the globe.[1−7] Heavy precipitation and flooding across the U.S. Corn Belt in spring 2019 resulted in a record high 7.94 million hectares of unplanted crop. The unplanted area was approximately 12% of agricultural land in 12 Midwestern states (https://www.fsa.usda.gov/news-room/efoia/electronic-reading-room/frequently-requested-information/crop-acreage-data/index), including Ohio. Ohio had the second highest state total of unplanted areas with 633,686 ha, and 76% was located in counties that make up the Western Lake Erie Basin. These unplanted areas, commonly referred to as "prevented plant acres" in the agricultural industry, were expected to impact agricultural nutrient losses and subsequent riverine water quality.

Excessive phosphorus (P) exports, especially dissolved reactive P (DRP), from agricultural fields in the MRW have led to the recurrence of harmful algal blooms (HABs) in western Lake Erie.[8−13] More specifically, loads of P that enter Lake Erie from March 1 to July 31 (the nutrient loading season) in the MRW are the major driver of the severity of HABs[14] and form the basis of the HAB forecasts that are produced annually. In 2015, Annex 4 of the 2012 Great Lakes Water Quality Agreement set a target of a 40% reduction in total P (TP) and DRP loads from the Maumee River between March−July to achieve a bloom severity no worse than 2012 for 9 out of 10 years.[8−11,13]

Variation in DRP and particulate P (PP) loads since 2002 has been largely associated with variation in precipitation and subsequent discharge,[15] with little change in flow-weighted mean concentrations (FWMCs, total load over the time period divided by total streamflow discharge) of P over the past 15 years (Figure A1).[8] To date, no substantial reductions in DRP have been achieved despite investment in best management practices (BMPs) to help ameliorate P losses. Dissolved reactive P losses result from a complex interaction of recently applied nutrient, labile, and nonlabile soil P fractions and hydrologic characteristics. Changes in dissolved P losses from fields with high soil test P concentrations (STP) require many

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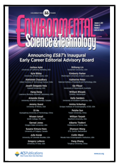

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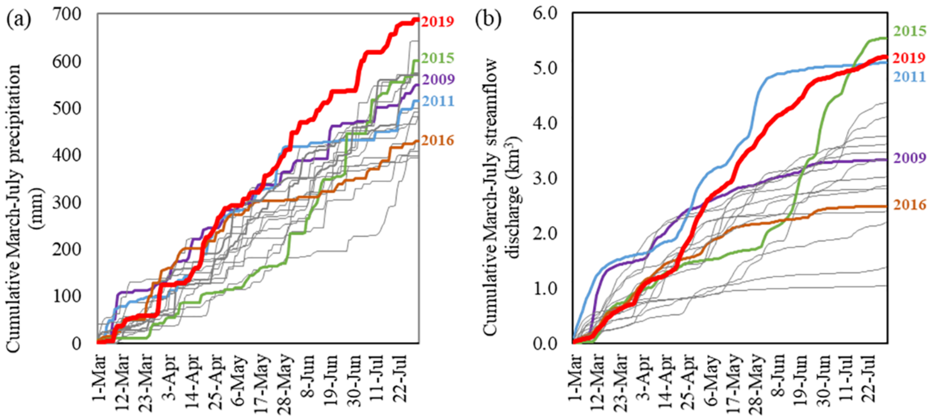

Figure 1. Cumulative March−July precipitation depth (a) and streamflow discharge volume (b) from 2002 to 2019 in the Maumee River Watershed (MRW). The heavy purple, blue, green, orange, and red lines represent 2009, 2011, 2015, 2016, and 2019, respectively. The light gray lines indicate the remaining years.

years to achieve via crop drawdown.[16] Also, despite the fact that watershed models indicate that a vast majority of the watershed must implement a multitude of practices to achieve the P reduction goal,[3] economically viable BMPs that can effectively reduce DRP have not been identified, and implementation of existing BMPs targeted to DRP has not been widespread. Finally, evidence suggests that there is a large pool of soil P that contributes to consistent DRP losses during storm events.[17,18] Hence, HAB severity in a given year is closely tied to precipitation rather than changes in agricultural practices.

The extremely high precipitation and the unusually high degree of unplanted area in the MRW during 2019 presented a unique opportunity to examine how changes in farming practices over a vast area of the watershed have altered and will change nutrient loads and HABs in western Lake Erie and other regions with water pollution issues. The results from 2019 may help us better anticipate and model how future climates will influence Lake Erie. We hypothesized that reduced P fertilization due to an increased percentage of unplanted areas was one of the major reasons for the reduction in DRP loads from the MRW during March−July 2019. The goals of this study were to 1) assess the 2019 DRP and PP loads in the MRW and HAB severity in western Lake Erie relative to past years, 2) investigate precipitation amounts and intensities, planting areas, and P fertilizer and manure application rates as explanatory variables for trends in March−July DRP loads, and 3) present the implications for BMPs, HAB severity, and responses to future climate scenarios.

■ MATERIALS AND METHODS

Study Area. The MRW covers over 17,000 km^2 in Ohio, Indiana, and Michigan and drains into the western basin of Lake Erie.[2,11,13,19,20] Approximately 70% of the MRW is row crop agriculture, mainly consisting of corn, soybean, and winter wheat.[2,11,13,19,20] The MRW is dominated by an especially flat topography (average slope less than 2%) and poorly drained silt loam, silty clay, and clay soils.[2,11,13,19,20] Extensive subsurface drainage systems have been installed in the MRW to lower the water table for agronomic purposes that ultimately boost crop yields.[2,11,13,19−22]

Precipitation, Unplanted Areas, and Fertilizer/Manure Application Data. Accumulated precipitation depth from March to July for 2002−2019 (Figure 1a) was calculated from daily precipitation depth data at the Toledo Express Airport station (GHCN ID: USW00094830, latitude, 41.59, longitude −83.81, elevation: 205 m) and downloaded from the Midwestern Regional Climate Center (https://mrcc.illinois.edu/). Trace precipitation comprised 14% of daily precipitation data, and the missing precipitation data was filled using the simple linear regression method.[23] The Richards path length, a streamflow flashiness index, was calculated for daily streamflow during March−July for each year from 2002 to 2019 to represent variation in streamflow in response to precipitation intensity.[19,20] Higher Richards path length values represent greater streamflow discharge flashiness or more rapid variation in daily streamflow discharge.[24,25]

To quantify the annual unplanted areas in the MRW, we compiled information from the U.S. Department of Agriculture Farm Service Agency (USDA FSA) and satellite remote sensing based on the Normalized Difference Vegetation Index (NDVI). "Prevented plant acres" (unplanted areas) in the MRW (Figure 2) were calculated based on weighted averaged values at a state level for Ohio, Indiana, and Michigan during 2007 and 2019 from USDA FSA (https://www.fsa.usda.gov/). The NDVI is a vegetation index ranging from 0 to 1, where high values indicate dense vegetation coverage, and low values indicate low or no vegetation coverage (Figure 3).[26] The NDVI in this study was obtained from the National Aeronautics and Space Administration (NASA) Moderate Resolution Imaging Spectroradiometer (MODIS) product, Terra 16-Day Global Vegetation Indices at 500m. To calculate

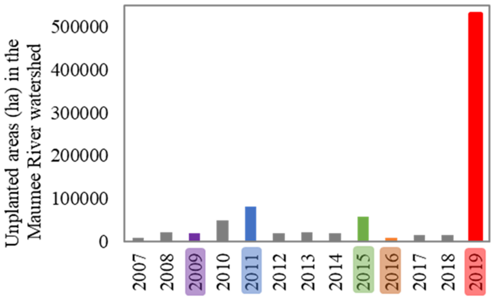

Figure 2. Calculated unplanted areas in the MRW from 2007 to 2019 based on claimed state-level "prevented plant acres" from the U.S. Department of Agriculture's Farm Service Agency (USDA's FSA). Colors correspond to the years shown in Figure 1.

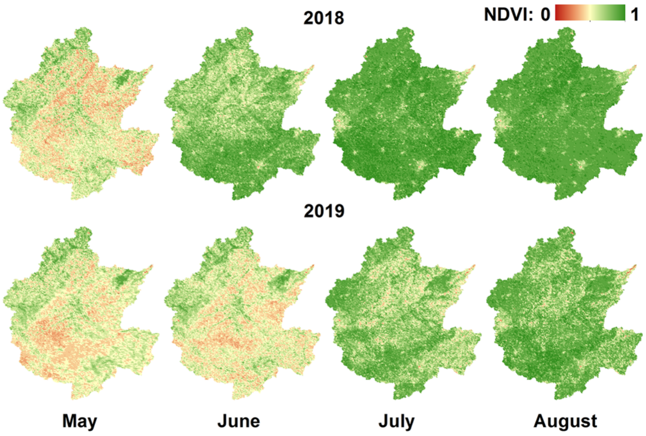

Figure 3. Normalized Difference Vegetation Index (NDVI) for the Maumee watershed from May to August (during the growing season), for 2018 and 2019. The value of NDVI ranged from 0 to 1 in the study area, where high values (green regions on the map) indicate high vegetation coverage, and low values (yellow and red regions on the map) indicate low vegetation coverage.

the unplanted areas, MODIS Land Cover Type, MCD12Q1.051 Yearly Global 500m, was used to split crop landcover from other landcover types. The threshold NDVI value to distinguish planted and unplanted areas was set as 0.5, which was based on the average range of MODIS derived NDVI values during the growing season of agricultural land in the Midwest.[27−30] Within the crop landcover, the area with low NDVI values (less than 0.5) in 2018 and 2019 was considered to be unplanted areas without vegetation (Figure 3).

The amount of P fertilizer sold from 2006 to 2018 was determined from tonnage data of the fertilizer delivered between November 1 and October 31 of the previous year reported to the Ohio Department of Agriculture by licensed fertilizer dealers.[31] Fall 2018 and spring 2019 P fertilizer application amounts in the Western Lake Erie Basin were collected through surveys with local agribusiness representatives, conducted by the College of Food, Agricultural, and Environmental Sciences at the Ohio State University.[31,32] These agribusiness representatives were members of the Ohio AgriBusiness Association, providing retail/wholesale fertilizer services in northern Ohio.[31,32] Manure application data was collected through phone interviews with commercial manure applicators whose primary service area is located in northwestern Ohio.[31,32]

Maumee River Water Quality and Streamflow Data. The National Center for Water Quality Research (https://ncwqr.org/) at Heidelberg University has been monitoring sediment and nutrient concentrations from the Maumee River near Waterville, Ohio, on a subdaily basis since 1974.[8,12,14] Streamflow data was provided by the U.S. Geological Survey (USGS) gauging station (04193500), also at Waterville, Ohio.[8,12,14] Nutrient loads (mass) were calculated as streamflow discharge (volume) multiplied by nutrient concentrations. Missing nutrient concentration data (<3% of the time) was interpolated from previous days using the linear regression method.[33]

A linear model was used to examine the relationship between DRP load and streamflow discharge volume during 2002−2018: $y = 100.00x - 60.61$, where x is discharge volume in km^3, and DRP load is in units of Mg, with the proportion of the variance captured by the model, $R^2 = 0.83$, and the model errors as captured by a confidence interval of two mean standard errors (95%) of 57 Mg. The relationship between PP load and streamflow discharge volume during 2002−2018 was described by the linear regression model: $y = 343.45x - 151.64$ ($R^2 = 0.90$, 95% confidence interval = 197 Mg). Further descriptions of statistical metrics of models and the validation and selection of models are shown in Data A1 and Table A1.

■ RESULTS

Precipitation and Streamflow Discharge in the MRW. Cumulative precipitation depth for the period of March−July 2019 in the MRW was the largest since 2002 (Figure 1a), and streamflow discharge volume (Figure 1b) was the second largest. Moreover, cumulative streamflow discharge volume during the 2019 water year (October 1, 2018 to September 30, 2019) was the highest (8.86 km^3) since 2002. However, the precipitation intensity and subsequent responses in streamflow from March−July 2019 were low, as the Richards path length of daily streamflow discharge in March−July 2019 (0.32) was the second lowest since 2002 and was lower than that in March−July 2009, 2011, 2015, 2016, and 2018 (Richards path

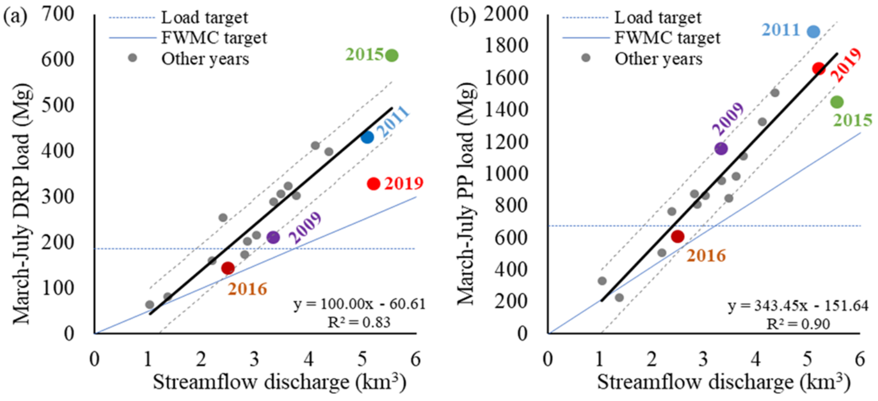

Figure 4. Dissolved reactive phosphorus (DRP) load (a) and particulate phosphorus (PP) load (b) as a function of streamflow discharge volume during March−July from 2002 to 2019. The purple, blue, green, orange, and red dots are for 2009, 2011, 2015, 2016, and 2019, respectively. The gray dots are for all remaining years. The dashed blue line indicates the water quality target for DRP load. The blue line represents the water quality target for DRP flow-weighted mean concentration (FWMC). The heavy black line represents the linear regression between load and discharge. Two light gray dashed lines around the heavy black line represent the 95% confidence intervals.

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length: 0.44−0.58) (Figure A2). Moreover, there were few rapid increases in the accumulated March−July streamflow volume plot for 2019 (Figure 1b), consistent with the Richards path length values (Figure A2).

Unplanted Areas in the MRW. The unplanted area in the MRW in 2019 was the highest since USDA FSA began to release the report in 2007 (Figure 2). Aside from 2019, 2011 and 2015 also had appreciable unplanted areas (Figure 2) due to heavy rainfall, although far less than 2019. These results were reflected in the 2019 vegetation coverage from May to August in the MRW, which were much lower than those in 2018 based on the NDVI image (Figure 3). Based on the NDVI, about 41% of agricultural land in the MRW was unplanted in 2019, while only about 5% of agricultural land was unplanted in 2018 (Figure 3). This was consistent with the "prevented plant acres" claimed by landowners, as reported by USDA FSA (Figure 2).

Commercial fertilizer (P_2O_5) delivered to agricultural producers within the Lake Erie watershed from November 2018 to May 2019 (7878 Mg) was reduced by 54% over that from November 2017 to May 2018, based on fertilizer delivery data reported by agricultural retailers through web surveys.[32] Moreover, manure application from April to June in 2019 (75,708 m^3) was 85% lower than over the same period in 2018, based on phone survey-interviews with ten out of 20 total commercial applicators in Northwestern Ohio.[32] Manure application was shifted from spring 2019 to summer and fall in 2019.[32] However, manure applied later in the growing season in 2019 could not affect nutrient losses during March−July. Annual P fertilizer delivered to the region has been declining at an estimated 392 Mg annually from 2006 to 2019.[31,32] Due to heavy rainfall or high fertilizer prices, fertilizer usage in 2009, 2011, and 2016 (19731−24824 Mg P_2O_5 fertilizer sold) was less than years without excess rainfall (average P_2O_5 fertilizer sold: 29,903 Mg).[31]

March−July DRP and Particulate P (PP) Loads in 2019. The March−July DRP load in 2019 (red dot on Figure 4a) was 29% lower than expected based on the historical relationship between DRP load and streamflow discharge (i.e., 460 Mg expected vs observed load of 328 Mg). Although the March−July DRP load in 2019 was 18% lower than the lower bound of the 95% confidence interval (402 Mg), it still exceeded the March−July DRP load target (186 Mg) (Figure 4a). On the contrary, the observed March−July DRP load was 23% higher than the expected value in 2015 (Figure 4a), which also had high precipitation (Figure 1a). Moreover, the March−July DRP FWMC in 2019 was 0.065 mg L^{-1} (Figure A1), lower than expected based on the historical relationship (0.095 mg L^{-1}). Similarly, the March−July DRP load in 2009 (211 Mg) and in 2016 (144 Mg) was lower than expected (Figure 4a). Differences between expected and observed March−July DRP loads in 2009 and 2016 (62 and 44 Mg, respectively) were lower than in 2019 (132 Mg). In general, higher precipitation led to increased streamflow discharge and DRP and PP loads (Figures 1a, 1b, 4a, and 4b), which was largely because FWMCs have been fairly consistent from 2002−2018 (Figure A1).[14] However, the impacts of discharge on DRP load and PP load were inconsistent in March−July 2009, 2011, 2015, and 2019 (Figures 4a and 4b). Notice that unlike DRP, PP load for 2019 was similar to the value predicted based on discharge.

In addition to cumulative March−July precipitation, the impact of cumulative fall (September-November) precipitation from the previous year on March−July DRP loads was also considered. March−July DRP loads across years were compared with fall precipitation from the previous year (Figure A3), due to the potential impact of antecedent soil moisture conditions. No correlation between March−July DRP loads and cumulative fall precipitation in the previous year was found (Figure A4, R^2 = 0.14).

■ DISCUSSION

Nonpoint source losses of DRP to surface water can be reduced to two categories: (i) acute losses of P from recently applied highly soluble fertilizer and manure that has not yet equilibrated appreciably with the soil (aka "incidental loss")[34,35] or (ii) chronic losses from soils that have little to no unreacted P from recent applications. The latter scenario is prevalent among soils that have STP values far beyond agronomic optimum (20−40 mg kg^{-1} Mehlich-3 P in Ohio, Indiana, and Michigan) and is referred to as "legacy P" soil.[36−39] Losses of DRP from legacy P soils are of low magnitude but high frequency, while incidental losses from recent applications are less frequent but of greater magnitude.[40−46]

The 29% reduction (relative to expected) in DRP load during March−July 2019 at the outlet of the MRW was likely due to reduced P fertilizer and manure applications. Such applications were minimal in 2019 because of a reduction in crop establishment (Figures 2 and 3) due to the excessively wet conditions (Figures 1a and 1b). Phosphorus fertilization was reduced during fall 2018 and spring 2019 as both seasons had unusually high precipitation (Figures 1a and A3), making it difficult or illegal to apply under Ohio Fertilizer Application Rules for the region. The lack of abnormally high reports of violations to Ohio Department of Agriculture's manure application regulatory entities indicated that manure storage discharges or direct discharges from land application did not occur at an elevated rate in fall 2018 and spring 2019.[32] Although decreased P fertilization was likely responsible for unusually low (i.e., less than predicted) DRP loads, we could not determine whether P fertilization in spring 2019 or in fall 2018 had higher impacts on DRP loads.[31,32] An interesting comparison to 2019 is 2015, since it also received a large amount of precipitation (Figure 1a), produced similar discharge (Figure 1b), and also experienced an appreciable unplanted area (Figure 2). Yet 2015 did not produce a lesser than expected DRP load based on total discharge (Figure 4a), which is likely because of the drastic differences in unplanted areas (Figure 2) and P fertilization amounts.[31,32]

Other Potential Reasons for Lower DRP Loads in March−July 2019. *Soil Test P (STP).* Concentrations of dissolved P in runoff and leaching are related to STP concentration (in this case, Mehlich-3), where higher STP leads to higher dissolved P concentrations.[47] Typically, such studies include a wide range of soil concentrations, often exceeding 300 mg kg^{-1} Mehlich-3. The optimum agronomic range for STP in Ohio, Indiana, and Michigan is 20−40 mg kg^{-1} Mehlich-3 P. At such low levels, little DRP is lost. For example, according to the relationship between STP and DRP concentration established in Ohio,[48] a Mehlich-3 value of 30 mg kg^{-1} would produce DRP concentrations of only 0.048 mg L^{-1}. Based on a long-term soil database of STP results from the Western Lake Erie Basin within Ohio, Dayton et al.[49] showed that 50% of soils possessed Mehlich-3 P values less than about 35 mg kg^{-1}. A single annual application of P that would increase STP values from 30 mg kg^{-1} to a concentration where soils become an appreciable legacy P source, considered to be 100 to 150 mg kg^{-1} by several states,[50] would require a very large and expensive P application rate that is improbable and far beyond standard agricultural practices.[51] For example, Penn et al.[43] needed to apply around 440 kg P ha^{-1} to a typical MRW soil in order to increase Mehlich-3 P from 15 to 100 mg kg^{-1}. Typical fertilizer applications are only 30−60 kg P ha^{-1}. It is more likely, because of the P buffering capacity of soils, that many years of excessive P applications would need to occur to increase STP levels to the degree of becoming a "legacy P" soil and high risk for DRP losses.

Not only does soil P buffering prevent STP from dramatically increasing with routine P applications, but also it prevents STP from appreciably decreasing with crop uptake after cessation of P applications. For example, long-term field experiments indicate that depending on soil type and crop, Mehlich-3 P is only decreased 1 to 5 mg kg^{-1} per year, due to crop uptake.[52−54] This suggested that reductions in DRP losses in 2019 could not have resulted from changes in STP associated with a lack of P fertilizer application. Therefore, it appeared reasonable that the decrease in DRP load was associated with a decrease in "incidental loss" of recently applied unreacted P, rather than equilibrated soil P.

Precipitation Amount and Intensity. Moreover, the accumulated March−July streamflow volume plot in 2019 possessed fewer sharp changes in slope compared to other wet years (2009, 2011, and 2015), indicating steadier and less intense precipitation and discharge (Figure 1b). The flashiness index of daily streamflow discharge in March−July 2019 (0.32) was lower than that during 2002−2009 and 2011−2018 (0.35−0.99) (Figure A2). Less intense precipitation events in March−July 2019 could be a contributor to the reduced DRP load. Fewer extreme storms in March−July 2019 could result in more water leaving the agricultural fields through subsurface drainage systems relative to surface runoff.[55] As P-rich water originating from the surface soil layer leaches through subsoil, which typically contains little to no soluble P, the subsoil is able to naturally filter dissolved P before reaching a tile drain.[56] As expected, previous research has shown for this region that tile drainage water produces lower DRP concentrations compared to surface runoff at equal STP levels due to increased contact between low-P subsoil and DRP before entering a tile drain.[55,57] Similarly, events with the greatest discharge intensity deliver not only the highest DRP loads but also concentrations.[17,46]

Tillage Practices. Besides fertilization rates and precipitation intensity, tillage practices can also impact the DRP load.[44] The lack of tillage in 2019 was expected to result in lower losses of sediment due to erosion and therefore PP. However, Figure 4b illustrated that PP loss in March−July 2019 was similar to expected. This suggests that either conservation tillage has less influence on PP losses than expected or that perhaps a significant portion of PP loading from the MRW is from eroding streambanks and movement of sediment within the contributing ditches and streams, rather than upland soils. A study from Wilson et al.[58] conducted in the MRW showed that more than 50% of the fine sediment originated from streambanks and the riverine bed among six of eight subwatersheds. Moreover, the P release of crop residue and the retention of released P in fields can be affected by tillage practices.[59−62]

Implications for DRP and TP Targets and HAB Severity. Our results further support the need to prioritize DRP load reductions through the establishment of P load targets based on total bioavailability of P (the sum of bioavailability P from both DRP and PP).[14] Current watershed modeling efforts indicate that the DRP load reduction target is more challenging to achieve than the TP reduction target, as the majority of current conservation practices is effective at controlling soil losses and intercept PP instead of reducing incidental and chronic losses of DRP.[3]

The responses of HAB severity index and magnitude to high precipitation and streamflow discharge volume in 2019 were different from those in 2011 and 2015 (Figure 5), which also experienced an appreciable unplanted area and discharge (Figures 1 and 2). The HAB severity index shown in Figure 5 is a normalized log transform of the average of the three highest HAB magnitudes over 10-day periods.[63] The HAB severity has been well predicted using estimates of total bioavailable P based on DRP and PP loads (DRP + PP * 0.26 *0.30), as described by Stumpf et al.[33] Using the HAB severity model based on total bioavailable P load predicted from the historical relationship between discharge and DRP and PP (Figure 4),[33] the Lake Erie HAB severity index in 2019 was predicted as 9.9 (blue bar, Figure 5), which was as severe as those in 2011 and 2015 (10 and 10.5, Figure 5). On the contrary, predicted HAB severity determined with total bioavailable P from measured DRP and PP loads in 2019 was predicted as 7.5, similar to the measured value of 7.3 (Figure 5).[33,64] Moreover, the highest HAB magnitude over 10-day periods in 2019 (8.6 × 10^{20} cells) was only about 29% and 30% of that in 2011 and 2015, and the average of the three highest HAB magnitudes over 10-day periods in 2019 (7.6 × 10^{20} cells) was 46% and 30% of that in 2011 and 2015, respectively.[33,64] This was due to a lower bioavailable P load in streamflow discharge in March−July 2019, as it carried lower DRP loads than expected.

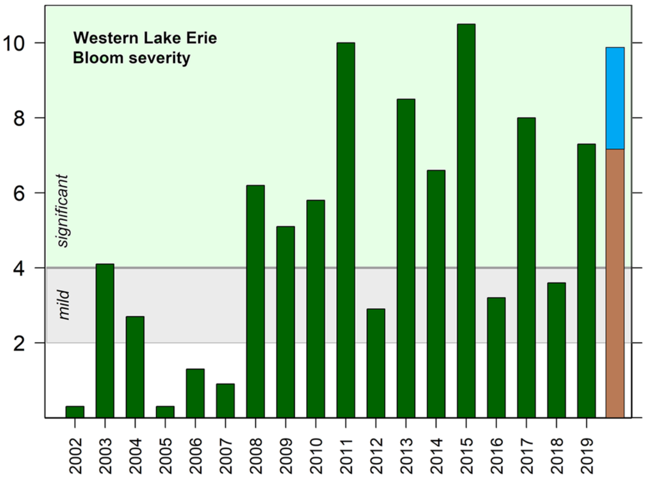

Figure 5. Lake Erie Harmful Algal Bloom (HAB) severity index for 2002−2019 (green bars). The blue and brown bars represent the 2019 HAB severity index forecasted by a model based on total bioavailable phosphorus. The blue bar used dissolved reactive phosphorus and particulate phosphorus as estimated by the historical relationship with discharge (Figure 4), and the brown bar used measured 2019 values.

Nutrient Transport under Changing Climates. It is essential to improve our understanding of P mobilization and transport in order to adapt to changing climates.[1,2,65] Our results indicated that besides the direct impacts of extreme precipitation on nutrient losses, more complicated indirect impacts might result and interact with each other. Such indirect impacts include changes in crop area planted; degree, method, and timing of P applications; tillage practices; and length of the growing season. For example, this study showed that the responses of PP and DRP loads to changing precipitation and streamflow discharge were inconsistent over several years in the MRW (Figures 4a and 4b).

The diversity in precipitation and conditions among the data presented strongly suggests that their direct and indirect effects may control the degree of certain P loss pathways and the dominant P source for those pathways, such as runoff vs tile drainage, preferential flow vs matrix flow, and legacy soil P sources vs incidental fertilizer/manure P sources. Knowing the degree of contribution from these P sources and pathways is critical to choosing proper BMPs. Contrasting data from 2019 to other years strongly suggested that a larger than expected portion of DRP delivered to the Maumee River is from incidental fertilizer/manure P applications. We can estimate the approximate range of dissolved P lost from incidental sources knowing that there was a 29% load reduction, that 54% less fertilizer was sold and 85% less manure applied, and that 25−30% of the P applied to the MRW is through manure.[66−69] This last point is important since it allows the percent decrease in P application to be properly weighted for each source. Specifically, a 54% and 85% decrease in fertilizer and manure applied, respectively, translates to approximately 39% and 23% reduction in P input to the watershed from fertilizer and manure. This combined 62% decrease in P input in the MRW resulted in a 29% decrease in dissolved P in 2019. This indicates that efforts to improve the application rate, timing, and placement of P in the MRW should have a substantial influence on dissolved P that enters Lake Erie and subsequently bloom severity.

More details about the effects of changing future climates on water pollution and nutrient mobilization can be found in Data A2. Please find recommendations on the identification and implementation of BMPs to adapt to the direct and indirect effects of future climate changes in Data A3.

Future Research Opportunities. For future research on the selection and implementation of conservation practices, there is a need to consider the following: specific soil, climate, and cropping characteristics; farming patterns and practices; potential P pathways (e.g., plant uptake, accumulation within soils, surface and subsurface hydrologic pathways, and transport via rivers);[70−72] economic impacts; and water quality targets in each region. Overall, this study found that a nearly watershed-wide change in fertilizer application had measurable effects at the watershed outlet. One of the barriers to widespread adoption of conservation practices is that stakeholders often question their effectiveness at reducing nutrient loads.[73,74] The more confidence producers have about the effectiveness of conservation practices, the more likely adoption will occur.[73] Due to a high degree of variability and often confounding influence of multiple factors, there is a need for experimental watersheds at a small scale to help test the effectiveness of conservation practices at various magnitudes. Re-examination of previous studies on links between fertilization amounts and DRP loads could provide useful insights.[75] These studies need to be ongoing to help support adaptive management efforts at improving the health of watersheds.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.0c03495.

> Figures of DRP flow-weighted mean concentrations and flashiness index daily streamflow discharge during March−July from 2002 to 2019, cumulative precipitation depth during September−November from 2001 to 2018, and DRP loads during March−July from 2002 to 2019 as a function of precipitation depth during September−November from 2001 to 2018 in the Maumee River Watershed; statistical metrics of models and the validation and selection of models that represented relationships between March−July DRP loads and streamflow discharge and PP loads and streamflow discharge; and more descriptions of water pollution and nutrient mobilization and transport under changing climates and recommendations on conservation practices (PDF)

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Author Contributions

The manuscript was written through the contributions of all authors. All authors have given approval to the final version of the manuscript.

Notes

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■ ABBREVIATIONS

MRW, Maumee River Watershed; P, phosphorus; DRP, dissolved reactive phosphorus; HABs, harmful algal blooms; TP, total phosphorus; FWMC, flow-weighted mean concentration; BMPs, best management practices; STP, soil test P; USDA FSA, U.S. Department of Agriculture Farm Service Agency; NDVI, Normalized Difference Vegetation Index; NASA, National Aeronautics and Space Administration; MODIS, Moderate Resolution Imaging Spectroradiometer; USGS, U.S. Geological Survey; PP, particulate phosphorus

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