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Commentary: Achieving phosphorus reduction targets for Lake Erie

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ABSTRACT

Harmful Algal Blooms (HABs), which were largely absent from Lake Erie from the 1980s until the mid-late 1990s, have been growing steadily worse in intensity. While much of the phosphorus loading into the lake prior to 1972 was caused by point-source pollution, approximately 88% to 93% of current loading comes from nonpoint sources, of which agriculture is the dominant land use. A reduction target of 860 metric tons, or 40% of the total phosphorus spring loading in 2008, has been set with the expectation that such a reduction could limit the size and associated impact of HABs in 9 out of every 10 years. We review the effectiveness of recommended practices aimed at reducing phosphorus loss in agriculture and pair this knowledge with behavioral data on likely adoption to identify how best to achieve the reduction target. The data suggests that the target is feasible as a majority of the farming population is willing to consider many of the recommended practices. However, increases in adoption over time have been minimal, and farmers will need better cost-benefit information, site-specific decision support tools, and technical assistance in order to more rapidly adopt and execute the placement of recommended practices. A combination of voluntary and mandatory approaches may be needed, but policies and programs promoting voluntary adoption should be designed to better target known barriers and maximize voluntary program effectiveness.

Introduction

Harmful Algal Blooms (HABs), which were largely absent from Lake Erie from the 1980s until the mid to late 1990s, have been growing steadily worse in intensity (i.e., density and surface area), with the five worst blooms on record all occurring since 2011 (Kane et al., 2014; NOAA, 2017). With the return of eutrophication to the lake, scientists, policymakers and stakeholders have been seeking methods to reduce annual HABs. The Ohio Phosphorus Task Force, convened in both 2007 and 2013, recommended a 40% reduction in phosphorus loading from the Maumee River and Western Basin tributaries to address HABs in the Western Basin. In October 2013, the International Joint Commission endorsed this recommendation and called for additional reductions to address hypoxia, i.e. dissolved oxygen levels below 2.0 mg/L, in the Central Basin (International Joint Commission, 2014). Two years later in May 2015, the Objectives and Targets Task Team (hereafter, the Task Team) of Annex 4 of the Great Lakes Water Quality Agreement (GLWQA) conducted a separate analysis and issued their final report calling for a 40% reduction from 2008 loads in spring (March 1 to July 31) total phosphorus (TP) and dissolved reactive phosphorus (DRP) loading to the Western Basin to address HABs (USEPA and Environment and Climate Change Canada, 2015). In addition, the Task Team suggested a 40% reduction in Western and Central Basin annual TP loading to address hypoxia (USEPA and Environment and Climate Change Canada, 2015).

The TP spring loading goal from the Annex 4 Report for the Maumee River is 860 metric tons or less corresponding to a flow-weighted mean concentration (FWMC) of 0.23 mg/L. The DRP loading goal is 186 metric tons or less corresponding to a FWMC of 0.05 mg/L, representing a 40% reduction from the 2008 loads. The Task Team selected 2008 as the base year because, among other things, it was a relatively wet year, and the spring discharge from the Maumee River in 2008 was only exceeded twice in the previous 20 years. The rationale being, if the target loads are achieved during wet years, then the TP and DRP loads will be less than the targets during years with lower rainfall (i.e., the long-term average load will need to be less than the targets under current climatic conditions). These reductions are designed to

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reduce the size and extent of HABs, resulting in HABs similar to or smaller than blooms observed in 2004 and 2012 (Fig. 1), 9 years out of 10, or 90% of the time. The reductions are also designed to raise the average dissolved oxygen concentration in the hypolimnion of the Central Basin to above 2.0 mg/L. The United States (US) and Canadian Governments approved the recommendations in February 2016. On June 13, 2015, the governors of Ohio and Michigan and the Premier of Ontario signed a collaborative agreement to reach the 40% reduction target by 2025 and set an aspirational goal of a 20% reduction by 2020.

While the Lake Erie Basin contains some of the most productive farmland in the world and is critical for current and future global food production, 11 million people also rely on Lake Erie for clean drinking water. Thus the goal is to support agricultural production while improving water quality and maintaining the ecosystem services provided across the watershed. Reaching this goal requires identification of effective practices and strategies to reduce the phosphorus load, as well as policies or programs that will most effectively promote these solutions to critical decision makers (e.g., farmers and other agricultural stakeholders). The goal of this article is to succinctly summarize current scientific understanding about HABs in Lake Erie, while highlighting what pathways show the most promise at decreasing the nutrient loading driving such events. In addition, we hope these insights will aid elected officials, managers, and decision makers in moving toward phosphorus reduction targets.

Background

Past HABs and response

HABs caused by excessive nutrient loading to the lake were common in the 1960s and 1970s, resulting in large blooms of blue-green algae, or cyanobacteria, and areas with hypoxic conditions (De Pinto et al., 1986). The cyanobacteria observed, both historically and presently, in Lake Erie are native to the lake. These native species prefer water that is above 60 °F with eutrophic nutrient concentrations. Lake Erie, specifically the Western Basin, is the southernmost, shallowest, warmest, and most nutrient enriched of the Great Lakes (Ludsin et al., 2001). The suspended and floating phytoplankton algae in Lake Erie are the base of the food web, and the phytoplankton community in the lake is normally very diverse. However, during HABs, phytoplankton diversity is greatly reduced, and the community is dominated by cyanobacteria, which are of very little value to the food web (Ludsin et al., 2001).

The GLWQA of 1972 identified excessive phosphorus as the cause of eutrophication, nuisance algal blooms, and oxygen depletion in Lake Erie at that time and noted that 70% of the phosphorus was coming from point sources (International Joint Commission, 1972). The GLWQA of 1978 set an 11,000 metric ton annual (MTA) target load of TP for the whole lake and a concentration limit for TP leaving sewage treatment plants in the Great Lakes watershed of 1.0 mg/L (International Joint Commission, 1978). The 11,000 MTA load was approximately a 60% reduction (International Joint Commission, 1978). The TP target included both particulate phosphorus (PP) and dissolved reactive phosphorus (DRP). PP is approximately 26% bioavailable and usable by plants and algae, while DRP is almost 100% bioavailable (Baker et al., 2014a; Ellison and Brett, 2006). However, it is important to note that most phosphorus leaving sewage treatment plants is DRP, so the 60% reduction in TP loading during the 1970s, which focused primarily on sewage treatment plants, constituted a very large reduction in DRP loading. In Ohio, sewage treatment plants outside of the Lake Erie watershed were not required to reach the target discharge concentrations.

Through this set of regulations and targets, as well as shifts to conservation tillage in agriculture, the desired phosphorus level of

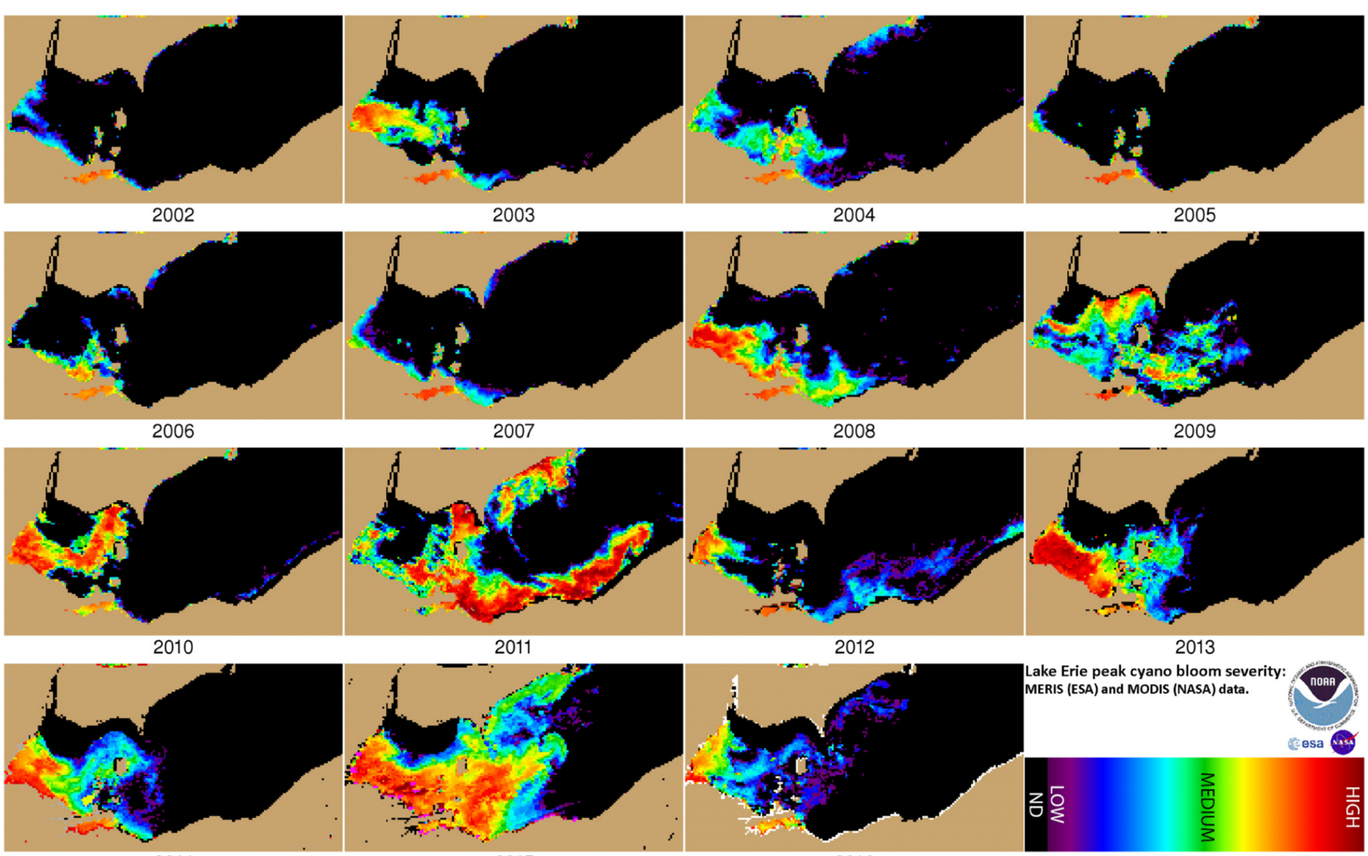

Fig. 1. Maximum bloom each year as determined from satellite imagery. These images from MERIS (medium resolution imaging spectrometer) and MODIS (moderate resolution imaging spectroradiometer) show the extent and concentration of cyanobacteria at the peak of the bloom. Updated from Stumpf et al., 2016. Figure Credit: Richard Stumpf, NOAA.

11,000 metric tons was reached in 1981 (De Pinto et al., 1986; Scavia et al., 2014). As a result, lake conditions improved dramatically, phytoplankton biomass in all three basins was reduced 52 to 89% from 1970 to the mid-1980s, and the southwestern shore of Lake Erie became a premier destination for sport fisherman looking to capitalize on the bountiful walleye population (Makarewicz, 1993; Munawar and Munawar, 1976). Additionally, coastal economic development and tourism grew rapidly. Today, tourism in the eight Ohio counties that border Lake Erie supports almost 124,000 jobs and has an annual economic value in excess of $14 billion (Tourism Economics LLC, 2018).

Current HABs and new issues

Elevated numbers of cyanobacteria in the WLEB began to reappear in the mid-to-late 1990s and have grown rapidly since 2002, with the worst blooms occurring in 2011 and 2015 (Fig. 1 and Kane et al., 2014; Stumpf et al., 2016). However, if phosphorus loading is reduced, recovery of the lake from HABs is likely to occur rapidly, largely because the retention time for water in the Western Basin is only 20–50 days (USEPA and Environment and Climate Change Canada, 2015). This is evidenced by the reduction in bloom size between 2011 and 2012 and again in 2015 and 2016 (Fig. 1), where 2011 and 2015 were very wet springs with larger phosphorus loads, and 2012 and 2016 were very dry springs with smaller phosphorus loads. Recent research also indicates that internal loading of phosphorus from lake sediments is approximately 3–7% of the total load (Matisoff et al., 2016), which would be insufficient to maintain a bloom once loads have decreased to target levels.

To reduce the intensity and extent of HABs, strategies should focus on bioavailable phosphorus (i.e., DRP plus 26% of PP), as it is the primary driver of HAB biomass. In addition, unlike PP, which has declined slightly, DRP loading increased by 132% from the mid-1990s to the mid-2010s (Bullerjahn et al., 2016; USEPA and Environment and Climate Change Canada, 2015). Although total nitrogen flow-weighted mean concentration and loads have decreased since the early 2000s, further reducing nitrogen loading is also important, as it sometimes limits HAB growth and the algal toxins are approximately 14% nitrogen by weight (Chaffin et al., 2018; USEPA and Environment and Climate Change Canada, 2015). However, focusing only on nitrogen is not the solution as some of the cyanobacteria that produce toxins are nitrogen fixers (able to get the nitrogen they need from the air; e.g., *Dolichospermum spp*., *Aphanizomenon spp.*).

Causes of the current situation

Although much of the phosphorus loading into the lake prior to 1972 was caused by point-source pollution (De Pinto et al., 1986), improvements in sewage treatment significantly reduced the impact of these sources (Scavia et al., 2014). For example, point sources of phosphorus from sewage treatment plants decreased by about 75% in the 1970s and 1980s due to actions under the Clean Water Act. Permitted facilities, including combined sewer overflows (CSOs) associated with wastewater treatment plants, now contribute <8% of the phosphorus in the Maumee River Basin (Ohio Environmental Protection Agency, 2016, 2018). Another phosphorus source, home sewage treatment systems, contributes only 4% of the total phosphorus load annually in the Maumee River (Ohio Environmental Protection Agency, 2016, 2018). CSOs have been reduced since the mid-1990s and more improvements are underway. Almost all CSO communities in the Lake Erie Basin in the U.S. have Long-Term Control Plans that must be implemented by permit requirements or court orders. By 2020, 40 of 62 Ohio communities in the Lake Erie Basin plan to have completed all the projects required by their Long-Term Control Plans (Ohio Department of Agriculture et al., 2013). In addition, as of January 2013, Scott's Miracle-Gro removed phosphorus from its lawn care products, and it is estimated that 95% of the lawn care fertilizer market followed Scott's lead, thereby reducing the potential loss of phosphorus from residential landscapes (Ohio Department of Agriculture et al., 2013).

The Maumee and Sandusky Rivers contribute the largest tributary loads of phosphorus to Lake Erie and the Great Lakes. Approximately 88% to 93% of the phosphorus loads from these two rivers come from nonpoint sources, of which agriculture is the dominant land use (i.e., over 70% of the watershed) (Ohio Environmental Protection Agency, 2016, 2018). These tributaries do not typically deliver nutrient loads at a continuous rate throughout the season, but instead as pulses during storm events. For example, between 2002 and 2013, 70–90% of the phosphorus and nitrogen loads discharged from the Maumee River occurred during the highest 20% of the flows from the river (Baker et al., 2014b). Mean TP concentrations in the Maumee and Sandusky Rivers are about 30 times greater than in the Detroit River (0.42 mg/L versus 0.014 mg/L), and the Detroit River concentration is not high enough to cause a HAB. Further, the Detroit River actually introduces low phosphorus concentrations that have the potential to dilute Maumee and Sandusky River phosphorus loads if weather conditions are right (e.g., wind speed, river flow rates, lake mixing, etc.). The Maumee River contributed over 3800 tons of TP to Lake Erie in 2008 and is the major driver of HABs in the Western Basin (USEPA and Environment and Climate Change Canada, 2015; Bertani et al., 2016; Verhamme et al., 2016); the majority of the loading driving the HABs comes during the spring season (Stumpf et al., 2016). The Sandusky River contributed over 1100 tons of TP in 2008 and is a contributor to HABs in Sandusky Bay (USEPA and Environment and Climate Change Canada, 2015). While the Detroit River is not a major driver for Western Basin HABs, the Task Team identified it as one of their 14 priority tributaries to Lake Erie, and its ~2500 ton load is a contributor to Central Basin hypoxia.

Agricultural nutrient losses contributing to P runoff

Amending the soil with fertilizer is common in agriculture to supplement soil available nutrients and replace nutrients removed through grain and fiber harvest. From the 1970s to the mid-1980s, phosphorus was applied at 4.4 to 17.4 lbs (1.0 lb = 2.2 kg) of elemental phosphorus above crop removal rates (or 10–40 lbs P_2O_5 phosphate), resulting in an accumulation of phosphorus in the soils of the region (Mullen, 2013; Powers et al., 2016). Since the mid-1990s, reports indicate that current application rates are near crop removal rates (Mullen, 2013; Natural Resources Conservation Service, 2016), with 58% of fields having phosphorus applied at or below crop removal rates (Natural Resources Conservation Service, 2016). In addition, the Natural Resources Conservation Service (NRCS) (2016) found that 42% of the acres assessed accounted for 78% of the total P runoff and 80% of the sediment loss. This suggests that a minority of acres may be contributing to the majority of TP runoff.

Widespread use of soil testing has increased our understanding of soil nutrient levels and informs farmers as to the amount of fertilizer needed to meet optimum crop yields (Vitosh et al., 1995). When Soil Test Phosphorus (STP) is below 50 ppm Bray P1, event median DRP concentrations in drain tiles generally meet Annex 4 guidelines (0.05 mg/L, the target flow-weighted mean concentration for DRP for the Maumee River). As STP levels increase above 50 ppm, DRP concentrations in tiles tend to increase (Duncan et al., 2017). Eighty percent of the soil test samples in the Maumee watershed have STP levels <50 ppm Bray P1, approximately 15% of the samples have STP levels between 50 and 100 ppm, and 5% of the samples have STP levels above 100 ppm (Herman, 2011; International Plant Nutrition Institute, 2017). The Tri-State Fertilizer recommendations, which are used to provide nutrient application guidance to Ohio, Indiana and Michigan, recommend not adding phosphorus when STP levels are above 50 ppm Bray P1 (Vitosh et al., 1995). An excessive build-up of STP is often the result of past manure application practices that occurred prior to environmental concerns about phosphorus, such as using a nitrogen-limited criteria to set manure application rates, resulting in over-application of phosphorus. These fields with excessive build-up are often termed "legacy phosphorus fields" and may disproportionately contribute to P loading, although there is no agreed upon definition for the specific ppm threshold for this classification.

Current guidelines for manure applications do not recommend applications when STP levels in fields exceed 150 ppm (Natural Resources Conservation Service, 2013). Between 40 and 150 ppm, the NRCS 590 Standards allow a phosphorus application rate equal to the crop phosphorus needs of the rotation for 1 or more years, with recommendations for increased ground cover and setbacks from sensitive areas and incorporation of applied P and N (NRCS, 2013). While STP measurements are a good initial screening tool for risk of phosphorus loss (Duncan et al., 2017), other site characteristics that affect transport such as slope, soil type, timing of phosphorus application and phosphorus leaching potential will also impact phosphorus losses from a field (Williams et al., 2017).

Fertilizer application practices can also contribute to phosphorus loading in waterways. Vertical phosphorus soil stratification is a recognized occurrence even under a rotational tillage management system where soils are chiseled or disked as a way to incorporate broadcast fertilizer (Baker et al., 2017). Highly P-stratified soils are found most commonly under conditions of no-till and broadcast application of fertilizer, and result in higher P concentrations near the surface (Baker et al., 2017). Soil fissures and macropores from desiccation cracking, biological activity, geological forces, or human activity can connect elevated phosphorus at the surface to subsurface drainage and increase DRP losses through tile drainage (Baker et al., 2017; King et al., 2015).

Next steps

An increased focus on managing agricultural nutrient loss is needed to address the high phosphorus loading from nonpoint sources in the Western Basin. There are two primary strategies to deploy. First, it is essential to identify the most effective on-farm best management practices (BMPs). Using this knowledge to carefully identify and place the most appropriate BMPs across the landscape is critically important in the WLEB where agriculture is the dominant land use. Second, these BMPs will only be effective if adopted by farmers, requiring a better understanding of the unique set of concerns and barriers that influence on-farm decision making. These insights on BMP effectiveness and farmer decision making must then be combined to develop more effective policy and outreach efforts that target practices to the fields and farms at the greatest risk.

Identifying effective best management practices

The 4R's of Nutrient Stewardship (i.e., right rate, source, time and placement) are one set of recommendations designed for optimal on-farm nutrient use and to minimize agriculture's environmental footprint (Johnston and Bruulsema, 2014). Of particular importance to reducing phosphorus contributions in the Maumee Basin is phosphorus application at the appropriate rate based on soil testing and subsurface placement of fertilizer. It is important that soil testing occurs with sufficient frequency and density to accurately inform application rates. This includes testing at a scale that is appropriate, corresponds to the topography and hydrology of the field, and occurs once in the crop rotation, at a minimum, following the NRCS 590 Standards. Soil test-informed rates match application to crop need and reduce nutrient over-application that may further contribute to water quality issues. Placement of fertilizer beneath the surface can also reduce both DRP and TP at the field level (King et al., 2015; Williams et al., 2016). Watershed modeling analyses have found that subsurface placement could result in significant DRP reductions (Scavia et al., 2017): up to 46% of DRP annually and 42% in spring assuming 100% adoption across the watershed, with reductions of TP of 29% annually and 27% in spring (Gildow et al., 2016).

In addition to increased precision in the rate and method of nutrient application, BMPs designed to improve water retention capability and soil quality are necessary to control phosphorus loss (Pease et al., 2017). They include, but are not limited to, installing blind inlets and water control structures, as well as increasing organic matter in soils through practices such as cover crops. For example, drainage water management (DWM) can reduce DRP and TP loading from tiles by >50% (Ross et al., 2016). In addition, for every 1% increase in organic matter, the soil is capable of holding an additional 0.75 in. (1 in. = 2,54 cm) of water (Hudson, 1994). However, this depends on the soil type, in particular the clay content of the soil. One recent study indicated that as the clay content of a soil increases, the influence of soil carbon decreases (Minasny and McBratney, 2018). Cover crops are a practice that can improve soil quality, but research in more northern climates with substantial spring thaws indicates that cover crops tend to reduce nitrogen and PP rather than DRP (Liu et al., 2014; Tiessen et al., 2010). Recent research indicates that this practice has the ability to decrease peak flow after rain events and increase holding time but not the total volume of water export in non-tile drained fields. This water-holding capacity may be associated with no noticeable, short-term change in DRP-retention in fields with cover crops (Carver, 2018). Further, in the Western Lake Erie Basin, recent edge of field studies indicate that cover crops can be very effective at reducing nitrogen losses with no benefit to phosphorus in the short term (Hanrahan et al., 2018). However, more research is needed as there may be long-term benefits through increased soil organic content and water-holding capacity. Interested readers may refer to the USDA Sustainable Agriculture Research and Education (SARE) program for resources on cover crops and water quality to better understand their potential role and effectiveness under a variety of conditions: https://tinyurl.com/SARECCS.

Finally, there are many other BMPs, many of which may focus on sediment retention, or filtering of nutrients from runoff. For example, tile risers can increase phosphorus runoff by creating a direct connection between the soil surface and tile drains. Eliminating these connections by converting tile risers to blind inlets can reduce phosphorus loss by 60% at the field level (Smith and Livingston, 2013). Other potential practices that help to trap and filter nutrients that will inevitably leave the field include wetlands, phosphorus filters, and filter strips. See the BMP handbook (https://agbmps.osu.edu/bmp, accessed July 2, 2018) for a full list of recommended practices with information on potential effectiveness.

Understanding farmer decisions

While several practices show promise at reducing nutrient loss, not all are equally promising from a behavioral standpoint (Beetstra et al., 2018; Prokup et al., 2017). Specifically, as of 2018, ~94% of farmers in the Western Lake Erie Basin reported a willingness to determine application rates based on regular soil testing once within the rotation. This number essentially matches the 94% already reporting soil testing once within the rotation as of the 2017 season. These data come from a survey conducted in winter 2018 that was a replication of the survey described in Prokup et al., 2017. This data represents the feedback from panel respondents who participated in both 2016 and 2018 (Beetstra et al., 2018). Similar high rates of adoption are seen among timing related practices – such as avoiding winter application (now regulated in Ohio) and delaying application prior to a significant rainfall event (Fig. 2). Similarly, as of 2018, ~75% of the target farming population reported a willingness to use subsurface placement in the future. This target audience may be persuaded with better information about the relative costs-benefits, such as increased application cost vs. decreased application rates (i.e., decreased need for phosphorus). Finally, ~55% of the target farming population reported a willingness to use cover crops in the future, but they are unlikely to do so without incentives to off-set the short-term cost and risk. These risks include potential increased management time, weather-based challenges in

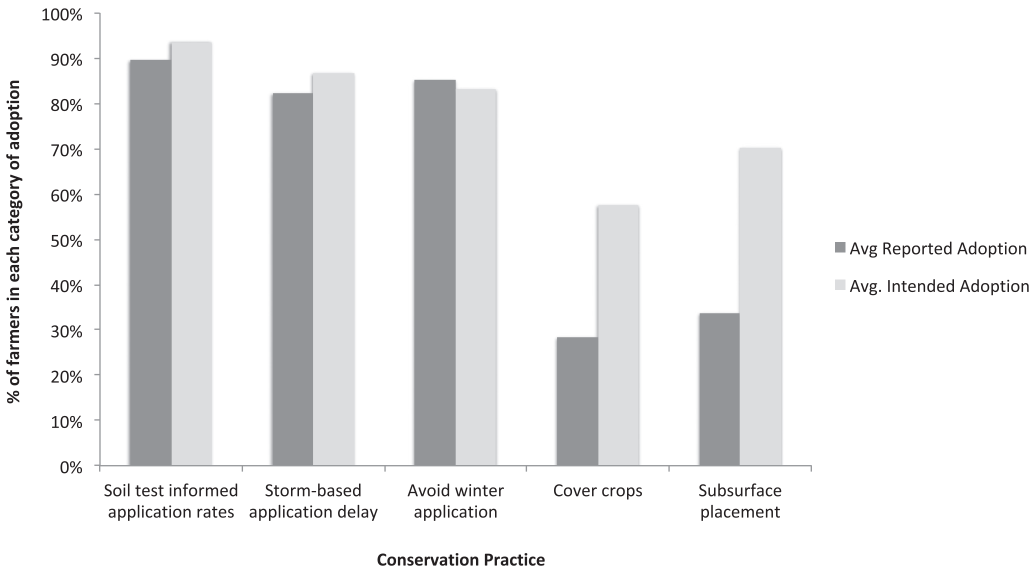

Fig. 2. Reported behavior on a representative field (i.e., average reported use from 2015 and 2017) and willingness to perform behaviors in the future (i.e., average intended future use from 2016 and 2018) for five practices with evidence that they reduce phosphorus loading into waterways from agricultural fields (see Beetstra et al., 2018 and Prokup et al., 2017 for details on survey administration and measurement). The results indicate that a majority intend to and actually use several recommended practices consistently over time (soil testing, applying at the right time), while other practices are used at much lower rates despite good intentions to use the practice by a majority of motivated farmers (cover crops, subsurface placement).

implementation, and uncertainty about the benefits and how those might translate into specific economic returns. Overall, cover crops and subsurface placement show the most behavioral plasticity, or potential to increase in the future (Fig. 2), but there still remains a gap of about 25% of the population who intend to use the practices in the future but have not yet adopted them (i.e., the difference between the average reported and intended adopters represented in Fig. 2).

Overall, survey data indicate that the biggest barrier to increased adoption is not concern or knowledge about nutrient loss or water quality. Rather many farmers are not convinced that the proposed BMPs are feasible to implement or likely to be effective (Wilson et al., 2018; Zhang et al., 2016). This barrier is identified in behavioral science as limited self and response efficacy, which are key factors in the decision to change one's behavior to address a personal risk (Ajzen, 2002; Floyd et al., 2000). Self-efficacy relates to one's own belief that he or she is able to appropriately perform or implement the practices. Response efficacy relates to the belief that the recommended practices will be effective at reducing phosphorus loading in waterways. Specifically, survey data suggest that voluntary adoption will not occur unless policies and programs build farmers' confidence in their ability to implement a set of cost-effective solutions. Current outreach efforts, such as field days and demonstration farms, are aimed at demonstrating the effectiveness of practices. However, many of these peer-to-peer learning opportunities are not evaluated to assess to what extent they build farmer confidence and belief in the effectiveness of BMPs.

There are several reasons that these two forms of efficacy are low among the farming population. One, the cost to implement BMPs is a concern for many farmers, especially when many near-term costs must be weighed against uncertain long-term payoffs. This is particularly challenging when profit margins are small, as they are now. Second, there are legitimate logistical barriers, including access to the needed equipment or supplies to perform the practices (e.g., access to equipment for subsurface placement, limited windows for application due to weather variability). These concerns about cost and logistics are likely to decrease self-efficacy or confidence in one's ability to implement the practice. Third, studies on practice effectiveness are ongoing, and at times the results can appear contradictory. It is not always clear what set of practices may be best for a given field or farm, further limiting one's response efficacy.

Possible strategies to move toward a 40% phosphorus reduction

Despite the fact that research is ongoing, there are a number of strategies that are likely to produce load reductions if we can successfully engage farmers in changing their agricultural land management practices. However, any set of strategies requires continued monitoring and assessment for potential water quality and agricultural production consequences. This adaptive management approach is critical as the relative effectiveness of each strategy may vary by field and farm (USEPA and Environment and Climate Change Canada, 2015). Speakers at the SERA-17 Conference in Toledo in August 2017 identified what they believed to be the four most important sets of actions to reduce nutrient loading: 1) soil-test-informed application rates (i.e., following tri-state guidelines and only applying the phosphorus that is needed); 2) subsurface placing fertilizer when applied (e.g., banding, in-furrow with seed); 3) working to control erosion (e.g., filter strips, grassed waterways); and 4) working to manage and minimize the amount of water leaving a field (e.g., drainage water management) (J. Reutter, Ohio State University Stone Laboratory, personal communication, July 5, 2018). These sets of actions represent a comprehensive strategy to continue the early successes at controlling PP loss, while improving the retention of DRP.

There are several specific practices that fall within these four categories where there is evidence of both field and watershed-scale effectiveness as well as potential for future adoption. There are already high levels of use and interest in soil test informed application rates, and more careful use of soil tests to inform application rate decisions should be encouraged. However, there is greater potential for an increase in adoption of subsurface placement (i.e., as of 2018, ~75% reported a willingness to use the practice in the future; Beetstra et al., 2018), and such practices have been shown to significantly reduce DRP loss at the field and watershed scale (Gildow et al., 2016; King et al., 2015; Williams et al., 2016). While adoption of subsurface placement has its economic and logistical challenges, this particular practice may be appropriate and effective for a variety of farmers and types of operations. Converting tile risers to blind inlets and implementing DWM or control structures show similar nutrient reduction promise (Ross et al., 2016; Smith and Livingston, 2013), but farmer interest in these practices is much lower than for subsurface placement, with only ~24% of farmers interested in using blind inlets and ~29% interested in control structures (Beetstra et al., 2018). Focusing adoption of water management on legacy fields may be the most effective use of these practices given the relatively low interest in these practices and the expense relative to other practices. Legacy fields contain the highest STP and may best be served by a suite of edge of field practices aimed at capturing runoff and removing DRP (e.g., no additional phosphorus application, continual crop removal of phosphorus via planting and harvesting of crops, or the addition of iron slag or alum to ditches). Similarly, working to control erosion through something like filter strips should be carefully targeted to high-risk fields due to the reality that such a practice only provides public as opposed to on-farm benefits. However, prior research indicates that about 66% of farmers in the Maumee River watershed are likely to consider enrolling in incentive-based programs for filter strips assuming the paperwork burden is low, the payments are high, and the filter strips are minimal in width (G. Howard, East Carolina University, Department of Economics personal communication, July 9, 2018).

No matter what practices are considered, conservation practices should be spatially targeted to the fields and management scenarios where the risk of elevated phosphorus losses is greatest (Jarvie et al., 2013; Muenich et al., 2016; Powers et al., 2016; Sharpley et al., 2013). To identify greatest risk, there are several potential indicators. First, measurements of STP at both 0 to 8-in. and 0 to 2-in. soil depths can serve as an initial screening tool to identify high-risk combinations of both current management practices and soil characteristics. Second, tile risers and soil cracks and crevices that result in preferential flow of surface water through the tile system can increase phosphorus losses and should be considered as an indicator of potential risk. Third, the Phosphorus Risk Index and other assessment tools (Dayton et al., 2017; Ford et al., 2017; Williams et al., 2015) currently under development can serve to identify high-risk fields and the practices necessary to mitigate nutrient loss. As improvements are made to these tools, they will better reflect current risk given a set of agricultural management practices, as well as spatial targeting of the most appropriate BMPs.

Multiple watershed models can then be used to evaluate the effectiveness of suites of management practices at reaching nutrient reduction targets, while behavioral models can assess the likelihood of adoption. Results from ongoing watershed modeling efforts indicate that there are multiple pathways to reach the 40% phosphorus reduction target in a given year (i.e., FWMC 0.23 mg/ TP in spring) (Scavia et al., 2017; Keitzer et al., 2016; NRCS, 2016). Each of these pathways typically requires a total adoption level of 50–75% for any specific practice, which indicates that reaching recommended spring TP levels is possible in a given year without 100% adoption of any particular practice (Wilson et al., 2018). Furthermore, approximately 66% of the target audience is already using recommended practices or is willing to consider them (Wilson et al., 2014), which is within the bounds of the total adoption targets of many watershed modeling scenarios. As an example of this potential, assuming 78% adoption of filter strips across the Maumee watershed, Scavia et al. (2017) found that subsurface placement and cover crops on 50% and 58% of the Maumee watershed, respectively, can attain a 40% mass reduction of phosphorus on average across 10 years. Behavioral data indicate that these levels are possible by targeting adoption among the farmers who are open to using these practices. Specifically, there are enough farmers indicating a willingness or intention to use subsurface placement and cover crops, approximately 70 and 58% respectively, to meet the adoption targets in the modeling scenario described above (Fig. 2).

However, accelerated adoption of recommended practices is necessary, as current adoption rates of recommended practices range from only 20–50% across the WLEB. Given that this data came from a survey sample stratified by the size of farm, the calculations of the acreage covered by a particular practice are not different from the proportion of farmers reporting adoption in this sample (Prokup et al., 2017). A recent panel study compared 2015 adoption levels to 2017 adoption levels among the same group of farmers in the WLEB (see details on survey administration at Beetstra et al., 2018). Overall adoption rates between 2015 and 2017 were essentially the same for cover crops and subsurface placement (i.e., approximately 35% for subsurface placement and 29% for cover crops) (Beetstra et al., 2018). Although this indicates no net change in total adoption within this sample, approximately 15% of the panel participants did start using subsurface placement for the first time during the panel study, as did 12% of the participants for cover crops. However, a similar percentage for each practice stopped using the practice on their representative field, creating no net increase. To create a net increase in adopters over time, we need to remove the real and perceived barriers preventing the use of practices like cover crops and subsurface placement. The real barriers may be related to cost and time, while the perceived barriers may be related to potential effectiveness. We also need to better understand not just what motivates someone to *add* a particular practice, but what causes someone to *drop* a practice so that we can design programs that encourage long-term use.

In sum, advancing toward the 40% reduction in TP will likely require a combination of changes in practice, appropriately placed in the landscape, that address identified resource concerns and are promoted through multiple mechanisms. There are three common mechanisms that can be used to promote adoption of specific management practices. First, one can employ outreach and education to encourage voluntary adoption of recommendations. This strategy may be most appropriate for those practices perceived as accessible and effective by the agricultural community (e.g., precision in nutrient management). Next, incentives can encourage voluntary adoption of recommendations that are costly in the short term. Practices involving more farm production risk and uncertainty in the science on DRP-reduction effectiveness are often well suited for this strategy (e.g., cover crops), as are those providing a purely social benefit (e.g., filter strips). Finally, in some cases, regulation may be suitable to mandate action. This may be more appropriate for recommendations that clearly reduce P loss, are economically and logistically possible for farmers to implement, provide on-farm benefits such as improving soil quality, and maintain or enhance production. This might include practices for which future intended use is high, such as soil-test-informed application rates, assuming challenges with manure application can be managed. We expect that a combination of these mechanisms may be necessary. There is evidence that well-designed outreach and incentive programs could result in increased voluntary adoption of BMPs due to the high level of motivation to act among farmers in the WLEB (Wilson et al., 2018). An increase in voluntary actions means there will be less of a need for regulation. Additional modeling work underway will help us understand what we can achieve with voluntary adoption by focusing solely on those who are most motivated to change their practices.

Information gaps and future research needs

Below we point out some of the information needs and current gaps in knowledge in an attempt to highlight the most obvious research needs in non-rank order. More and better information about each of the following items will lead to improved policies and management decisions, but the existing gaps in knowledge should not prevent us from taking action in the near term. Specifically, identifying what and where BMPs are likely to be most effective requires a better understanding of:

- The combined influence of soil chemical and microbial activity on phosphorus dynamics. Specifically, how soil quality impacts water-holding capacity, P loss, and water infiltration, as well as determining if reductions in P losses from breaking up soil P stratification by inversion tillage are outweighed by the damage to soil quality, specifically losses to water holding capacity, after tillage.
- The relationship between phosphorus stratification and preferential flow through tile drainage, the effectiveness of subsurface application of phosphorus, and how long subsurface application of phosphorus will take to be effective if applied in fields with existing phosphorus stratification.

- The impact of drainage water management on surface and tile flow of water and phosphorus.
- Nitrogen impacts on toxin production, and which practices might accomplish both nitrogen and dissolved phosphorus reductions.
- The spatial distribution and range of soil test phosphorus values, especially locations of fields with elevated phosphorus levels.
- The contribution of colloidal phosphorus to DRP measurements and whether colloidal phosphorus loss is controlled better by erosion mitigating BMPs or nutrient management.
- Clearer understanding of phosphorus cycling and dynamics at a variety of scales, including in-field, edge-of-field, and in-stream.
- The potential for in-stream processes to either contribute or reduce phosphorus (e.g., within the stream bed and from stream bank erosion) and if certain segments within rivers always contribute nutrients at the same rate or if that rate varies by time and/or stream condition (e.g., temperature, flood stage, etc.)

Similarly, identifying the most effective policy solutions by exploring how farmers are likely to respond to a variety of policy options requires a better understanding of:

- Innovative solutions (e.g., manure cooperatives and incentives for manure transports) to help animal operations transport manure greater distances and follow tri-state guidelines for manure application rates.
- Farmer willingness to use manure as a primary nutrient source given necessary advances in manure processing technology, transport, and application
- How a variety of market-based strategies could influence voluntary actions (e.g., a phosphorus tax, consumer pressure, 4R certification-based federal subsidies).
- Site-specific cost-benefit relationships for cover crops, water management, and other BMPs (e.g., cost-benefit analysis of fertilizer placement tool bar), to promote a clear understanding of the potential yield gains, input decreases, etc.
- The impact of policies as commodity prices vary so that solutions can be identified that are effective whether corn is priced at $2 or $7/bushel (one bushel = 35.2 L).

In addition to these gaps in the science, there are no standardized methods to track adoption rates of practices, so data collection methods should be developed for this purpose to increase our ability to track progress over time. Also, easy to use decision support tools are needed to evaluate current nutrient loss and identify what and where to place BMPs on the landscape to meet nutrient reduction goals. The ability to develop projections of phosphorus losses or reductions based on specific practice adoption at a field scale would help to motivate on-farm changes in practices. Such clear field-scale recommendations for farmers are needed, including alternative strategies for those dealing with manure application and distribution challenges.

Conclusion

This commentary outlines the past challenges with algal blooms in Lake Erie and how targeting point-source polluters largely solved that problem. The current algal blooms and hypoxia in the lake are primarily the result of phosphorus runoff from non-point sources, the majority of which comes from agricultural fields. The decentralized sources of the excess non-point phosphorus make the present situation more challenging to tackle than in the past, so an interdisciplinary toolkit will be necessary to achieve substantial phosphorus reductions. Based upon the potential effectiveness of many recommended practices, as well as current and potential future adoption rates, achievement of this reduction target is possible. However, farmers will need better cost-benefit information, site-specific decision support tools and field-scale recommendations, as well as improved technical assistance to successfully adopt and execute the placement of BMPs. A combination of voluntary and mandatory approaches may be needed, but policies and programs promoting voluntary adoption may need to be designed to better address concerns about feasibility and effectiveness of BMPs. With continued research and increased collaboration among the various stakeholders, we are hopeful that Lake Erie's water quality will improve through reduced nutrient inputs to Lake Erie.

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References

Ajzen, I., 2002. Perceived behavioral control, self-efficacy, locus of control, and the theory of planned behavior. J. Appl. Soc. Psychol. 32 (4), 665–683.

Baker, D.B., Confesor, R., Ewing, D.E., Johnson, L.T., Kramer, J.W., Merryfield, B.J., 2014a. Phosphorus loading to Lake Erie from the Maumee, Sandusky and Cuyahoga rivers: the importance of bioavailability. J. Great Lakes Res. 40, 502–517.

Baker, D.B., Ewing, D.E., Johnson, L.T., Kramer, J.W., Merryfield, B.J., Confesor, R.B., Richards, R.P., Roerdink, A.A., 2014b. Lagrangian analysis of the transport and processing of agricultural runoff in the lower Maumee River and Maumee Bay. J. Great Lakes Res. 40, 479–495.

Baker, D.B., Johnson, L.T., Confesor, R.B., Crumrine, J.P., 2017. Vertical stratification of soil phosphorus as a concern for dissolved phosphorus runoff in the Lake Erie Basin. J. Environ. Qual. 46, 1287–1295.

Beetstra, M., Tellez, C., Wilson, R., 2018. 4R Nutrient Stewardship in the Western Lake Erie Basin Part II: A Panel Study. The Ohio State University, School of Environment & Natural Resources, Columbus, OHhttp://research.ipni.net/page/RNAP-7227.

Bertani, I., Obenour, D.R., Steger, C.E., Stow, C.A., Gronewold, A.D., Scavia, D., 2016. Probabilistically assessing the role of nutrient loading in harmful algal bloom formation in western Lake Erie. J. Great Lakes Res. 42 (6), 1184–1192.

Bullerjahn, G.S., McKay, R.M., Davis, T.W., Baker, D.B., Boyer, G.L., D'Anglada, L.V., Doucette, G.J., Ho, J.C., Irwin, E.G., Kling, C.L., Kudela, R.M., Kurmayer, R., Michalak, A.M., Ortiz, J.D., Otten, T.G., Paerl, H.W., Qin, B., Sohngen, B.L., Stumpf, R.P., Visser, P.M., Wilhelm, S.W., 2016. Global solutions to regional problems: collecting global expertise to address the problem of harmful cyanobacterial blooms. A Lake Erie case study. Harmful Algae 54, 223–238.

Carver, R.E., 2018. Cover Crop and Phosphorus Fertilizer Management Effects on Phosphorus Loss and Nutrient Cycling. M.S. thesis. Kansas State University, Manhattan, KS http://hdl.handle.net/2097/39057 (127 pp).

Chaffin, J.D., Davis, T.W., Smith, D.J., Baer, M.M., Dick, G.J., 2018. Interactions between nitrogen form, loading rate, and light intensity on *Microcystis* and *Planktothrix* growth and microcystin production. Harmful Algae 73, 84–97.

Dayton, E.A., Holloman, C.H., Subburayalu, S., Risser, M.D., 2017. Using crop management scenario simulations to evaluate the sensitivity of the Ohio phosphorus risk index. J. Environ. Prot. 8, 141–158.

De Pinto, J.V., Young, T.C., McIlroy, L.M., 1986. Great Lakes water quality improvement. Environ. Sci. Technol. 20, 752–759.

Duncan, E.W., King, K.W., Williams, M.R., LaBarge, G., Pease, L.A., Smith, D.R., Fausey, N.R., 2017. Linking soil phosphorus to dissolved phosphorus losses in the Midwest. Agric. Environ. Lett. 2, 1–5.

Ellison, M.E., Brett, M.T., 2006. Particulate phosphorus bioavailability as a function of stream flow and land cover. Water Res. 40, 1258–1268.

Floyd, D.L., Prentice-Dunn, S., Rogers, R.W., 2000. A meta-analysis of research on protection motivation theory. J. Appl. Soc. Psychol. 30 (2), 407–429.

Ford, W.I., King, K.W., Williams, M.R., Confesor, R.B., 2017. Modified APEX model for simulating macropore phosphorus contributions to tile drains. J. Environ. Qual. 46, 1413–1423.

Gildow, M., Aloysius, N., Gebremariam, S., Martin, J., 2016. Fertilizer placement and application timing as strategies to reduce phosphorus loading to Lake Erie. J. Great Lakes Res. 42, 1281–1288.

Hanrahan, B.R., Tank, J.L., Christopher, S.F., Mahl, U.H., Trentman, M.T., Royer, T.V., 2018. Winter cover crops reduce nitrate loss in an agricultural watershed in the central U. S. Agric. Ecosyst. Environ. 265, 513–523.

Herman, M.C., 2011. Laboratory evaluation and soil test phosphorus trends in Ohio. M.Sc. thesis. The Ohio State University, Columbus, Ohio (77 pp).

Hudson, B.E., 1994. Soil organic matter and available water capacity. J. Soil Water Conserv. 49, 189–194.

International Joint Commission, 1972. Great Lakes water quality. http://ijc.org/files/publications/C23.pdf.

International Joint Commission, 1978. Great Lakes water quality agreement of 1978. http://agrienvarchive.ca/download/GLWQ_agreement_78.pdf.

International Joint Commission, 2014. A balanced diet for Lake Erie: reducing phosphorus loadings and harmful algal blooms. Report of the Lake Erie Ecosystem Priority http://www.ijc.org/files/publications/2014%20IJC%20LEEP%20REPORT.pdf.

International Plant Nutrition Institute, 2017. Soil test levels in North America 2015. http://soiltest.ipni.net/.

Jarvie, H.P., Sharpley, A.N., Spears, B., Buda, A.R., May, L., Kleinman, P.J.A., 2013. Water quality remediation faces unprecedented challenges from legacy phosphorus. Environ. Sci. Technol. 47, 8997–8998.

Johnston, A.M., Bruulsema, T.W., 2014. 4R nutrient stewardship for improved nutrient use efficiency. Procedia Eng. 83, 365–370.

Kane, D.D., Conroy, J.D., Richards, R.P., Baker, D.B., Culver, D.A., 2014. Re-eutrophication of Lake Erie: correlations between tributary nutrient loads and phytoplankton biomass. J. Great Lakes Res. 40, 496–501.

Keitzer, S.C., Ludsin, S.A., Sowa, S.P., Annis, G., Arnold, J.G., Daggupati, P., Froehlich, A.M., Herbert, M.E., Johnson, M.-V.V., Sasson, A.M., 2016. Thinking outside of the lake: can controls on nutrient inputs into Lake Erie benefit stream conservation in its watershed? J. Great Lakes Res. 42 (6), 1322–1331.

King, K.W., Williams, M.R., Macrae, M.L., Fausey, N.R., Frankenberger, J., Smith, D.R., Kleinman, P.J.A., Brown, L.C., 2015. Phosphorus transport in agricultural subsurface drainage: a review. J. Environ. Qual. 44, 467–485.

Liu, K., Elliott, J.A., Lobb, D.A., Flaten, D.N., Yarotski, J., 2014. Nutrient and sediment losses in snowmelt runoff from perennial forage and annual cropland in the Canadian prairies. J. Environ. Qual. 43, 1644–1655.

Ludsin, S.A., Kershner, M.W., Blocksom, K.A., Knight, R.L., Stein, R.A., 2001. Life after death in Lake Erie: nutrient controls drive fish species richness, rehabilitation. Ecol. Appl. 11, 731–746.

Makarewicz, J.C., 1993. Phytoplankton biomass and its species composition in Lake Erie, 1970 to 1987. J. Great Lakes Res. 19, 258–274.

Matisoff, G., Kaltenberg, E.M., Steely, R.L., Hummel, S.K., Seo, J., Gibbons, K.J., Bridgeman, T.B., Seo, Y., Behbahani, M., James, W.F., Johnson, L.T., Doan, P., Dittrich, M., Evans, M.A., Chaffin, J.D., 2016. Internal loading of phosphorus in western Lake Erie. J. Great Lakes Res. 42, 775–788.

Minasny, B., McBratney, A.B., 2018. Limited effect of organic matter on soil available water capacity. Eur. J. Soil Sci. 69, 39–47.

Muenich, R.L., Kalcic, M., Scavia, D., 2016. Evaluating the impact of legacy P and agricultural conservation practices on nutrient loads from the Maumee River watershed. Environ. Sci. Technol. 50, 8146–8154.

Mullen, R., 2013. Ohio nutrient balance. Ohio Phosphorus Task Force presentation. http://epa.ohio.gov/Portals/35/lakeerie/ptaskforce2/Mullen.pdf.

Munawar, M., Munawar, I.F., 1976. A lake-wide study of phytoplankton and its species composition in Lake Erie, April-December, 1970. J. Fish. Res. Board Can. 33, 581–600.

Natural Resources Conservation Service, 2013. Nutrient management: code 590. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1192371.pdf.

Natural Resources Conservation Service, 2016. Effects of Conservation Practice Adoption on Cultivated Cropland Acres in Western Lake Erie Basin, 2003–06 and 2012 (120 pp).

NOAA, 2017. Experimental Lake Erie harmful algal bloom bulletin. 35. https://tidesandcurrents.noaa.gov/hab/lakeerie_bulletins/HAB20171107_2017035_LE.pdf.

Ohio Department of Agriculture, Ohio Department of Natural Resources, Ohio Environmental Protection Agency, Ohio Lake Erie Commission, 2013. Ohio Lake Erie Phosphorus Task Force II final report. http://lakeerie.ohio.gov/Portals/0/Reports/Task_Force_Report_October_2013.pdf.

Ohio Environmental Protection Agency, 2016. Nutrient mass balance study for Ohio's major rivers. http://epa.ohio.gov/Portals/35/documents/Final%20Nutrient%20Mass%20Balance%20Report_12_30_16pdf.pdf.

Ohio Environmental Protection Agency, 2018. Nutrient mass balance study for Ohio's major rivers. http://epa.ohio.gov/Portals/35/documents/Nutrient%20Mass%20Balance%20Study%202018_Final.pdf.

Pease, L.A., Fausey, N.R., Martin, J.F., Brown, L.C., 2017. Projected climate change effects on subsurface drainage and the performance of controlled drainage in the Western Lake Erie Basin. J. Soil Water Conserv. 72 (3), 240–250.

Powers, S.M., Bruulsema, T.W., Burt, T.P., Chan, N.I., Elser, J.J., Haygarth, P.M., Howden, N.J.K., Jarvie, H.P., Lyu, Y., Peterson, H.M., Sharpley, A.N., Shen, J., Worrall, F., Zhang, F., 2016. Long-term accumulation and transport of anthropogenic phosphorus in three river basins. Nat. Geosci. 9, 353–356.

Prokup, A., Wilson, R., Zubko, C., Heeren, A., Roe, B., 2017. 4R nutrient stewardship in the Western Lake Erie Basin. https://4rcertified.org/wp-content/uploads/2017/05/Prokup.etal_.2017.4R-Nutrient-Stewardship-in-the-western-Lake-Erie-basin.pdf.

Ross, J.A., Herbert, M.E., Sowa, S.P., Frankenberger, J.R., King, K.W., Christopher, S.F., Tank, J.L., Arnold, J.G., White, M.J., Yen, H., 2016. A synthesis and comparative evaluation of factors influencing the effectiveness of drainage water management. Agric. Water Manag. 178, 366–376.

Scavia, D., Allan, J.D., Arend, K.K., Bartell, S., Beletsky, D., Bosch, N.S., Brandt, S.B., Briland, R.D., Daloğlu, I., DePinto, J.V., Dolan, D.M., Evans, M.A., Farmer, T.M., Goto, D., Han, H., Höök, T.O., Knight, R., Ludsin, S.A., Mason, D., Michalak, A.M., Richards, R.P., Roberts, J.J., Rucinski, D.K., Rutherford, E., Schwab, D.J., Sesterhenn, T., Zhang, H., Zhou, Y., 2014. Assessing and addressing the re-eutrophication of Lake Erie: central basin hypoxia. J. Great Lakes Res. 40, 226–246.

Scavia, D., Kalcic, M., Muenich, R.L., Read, J., Aloysius, N., Arnold, J., Boles, C., Confessor, R., Gildow, M., Martin, J., Redder, T., Sowa, S., Yen, H., 2017. Multiple models guide strategies for agricultural nutrient load reductions. Front. Ecol. Environ. 15, 126–132.

Sharpley, A., Jarvie, H.P., Buda, A., May, L., Spears, B., Kleinman, P., 2013. Phosphorus legacy: overcoming the effects of past management practices to mitigate future water quality impairment. J. Environ. Qual. 42, 1308–1326.

Smith, D.R., Livingston, S.J., 2013. Managing farmed closed depressional areas using blind inlets to minimize phosphorus and nitrogen losses. Soil Use Manag. 29, 94–102.

Stumpf, R.P., Johnson, L.T., Wynne, T.T., Baker, D.B., 2016. Forecasting annual cyanobacterial bloom biomass to inform management decisions in Lake Erie. J. Great Lakes Res. 42, 1174–1183.

Tiessen, K.H.D., Elliott, J.A., Yarotski, J., Lobb, D.A., Flaten, D.N., Glozier, N.E., 2010. Conventional and conservation tillage: influence on seasonal runoff, sediment, and nutrient losses in the Canadian prairies. J. Environ. Qual. 39, 964–980.

Tourism Economics LLC, 2018. The economic impact of tourism in the Lake region of Ohio. Tourism Economics an Oxford Economics Company, Wayne, PA Retrieved from the Ohio Travel Association Website. https://ohiotravel.org/aws/OHTRV/asset_manager/get_file/266481?ver=0.

USEPA, Environment and Climate Change Canada, Annex 4 Objects and Targets Task Team, 2015. Recommended phosphorus loading targets for Lake Erie. https://www.epa.gov/sites/production/files/2015-06/documents/report-recommended-phosphorus-loading-targets-lake-erie-201505.pdf.

Verhamme, E.M., Redder, T.M., Schlea, D.A., Grush, J., Bratton, J.F., Depinto, J.V., 2016. Development of the Western Lake Erie Ecosystem Model (WLEEM): application to connect phosphorus loads to cyanobacteria biomass. J. Great Lakes Res. 42 (6), 1193–1205.

Vitosh, M.L., Johnson, J.W., Mengel, D.B., 1995. Tri-State Fertilizer Recommendations for Corn, Soybeans, Wheat and Alfalfa. https://www.extension.purdue.edu/extmedia/ay/ay-9-32.pdf.

Williams, M.R., King, K.W., Dayton, E., Labarge, G.A., 2015. Sensitivity analysis of the Ohio phosphorus risk index. Trans. ASABE 58, 93–102.

Williams, M.R., King, K.W., Ford, W., Buda, A.R., Kennedy, C.D., 2016. Effect of tillage on macropore flow and phosphorus transport to tile drains. Water Resour. Res. 52, 2868–2882.

Williams, M.R., King, K.W., Fausey, N.R., 2017. Dissolved organic carbon loading from the field to watershed scale in tile-drained landscapes. Agric. Water Manag. 192, 159–169.

Wilson, R.S., Howard, G., Burnett, E., 2014. Improving nutrient management practices in agriculture: the role of risk-based beliefs in understanding farmers' attitudes toward taking additional action. Water Resour. Res. 50, 6735–6746.

Wilson, R.S., Schlea, D.A., Boles, C.M., Redder, T.M., 2018. Using models of farmer behavior to inform eutrophication policy in the Great Lakes. Water Res. 139, 38–46.

Zhang, W., Wilson, R.S., Burnett, E., Irwin, E., Martin, J., 2016. What motivates farmers to apply phosphorus at the "right" time? Survey evidence from the Western Lake Erie Basin. J. Great Lakes Res. 42, 1343–1356.