Canadian Water Network

Key questions of the science

on agricultural phosphorus losses during storm events and beneficial management practices

May 2018

Synthesis document prepared for the Ontario Ministry of Agriculture, Food and Rural Affairs

Acknowledgements

This report is built upon information provided during an expert workshop held on June 27 and 28, 2017, as well as in subsequent discussions convened via teleconference and email correspondence. Canadian Water Network would like to acknowledge the important contribution made by each of these experts and their leadership in these discussions and thank them for sharing their time and expertise. The information in this report is based on views expressed by the respective contributors and does not necessarily represent the views of their employers.

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This project was funded by the Ontario Ministry of Agriculture, Food and Rural Affairs.

Canadian Water Network is Canada's trusted broker of research insights for the water sector. When decision-makers ask, 'What does the science say about this?' we frame what is known and unknown in a way that usefully informs the choices being made.

Canadian Water Network

Contents

Acronyms and Abbreviations

BMPs	Beneficial management practices
CWN	Canadian Water Network
DIP	Dissolved inorganic phosphorus
GDP	Gross domestic product
N	Nitrogen
NRCS	Natural Resources Conservation Services
OMAFRA	Ontario Ministry of Agriculture, Food and Rural Affairs
P	Phosphorus
PP	Particulate phosphorus
SRP	Soluble reactive phosphorus
STP	Soil-test phosphorus
TP	Total phosphorus

Preface

Effective management of nutrient loss from agriculture is key to water quality protection and phosphorus (P) has been identified as the key limiting nutrient for eutrophication. As a result, the management of P losses from agricultural lands has become a core focus in addressing water quality impairments in regions with significant agricultural activity, like those whose drainage is tributary to the western basin of Lake Erie (*Canada-Ontario Lake Erie Action Plan,* 2018).

As a key stakeholder and decision maker for the implementation of nutrient management activities, Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA) is committed to supporting efforts to select, design and implement beneficial management practices (BMPs) that contribute to the reduction of P losses from agricultural landscapes. To structure and support this ongoing work, OMAFRA identified a need to generate and provide an updated consideration of the implications of leading science and practice on selecting and implementing P management options, particularly in light of:

- **Persistence or re-emergence of water quality impairments** in spite of progress through earlier nutrient management initiatives (e.g., Lake Erie, Lake Simcoe, Lake Winnipeg).
- **Increased focus on public health concerns related to nutrient impacts**, including their contributions to toxic algal blooms.
- **Climate change and concerns regarding the role of hydrologic events** (snowmelt, winter rainfall and storms) for nutrient storage, release and impact to water bodies.

As a trusted broker of insights for the water sector, Canadian Water Network (CWN) shares OMAFRA's commitment to advancing knowledge that contributes to the management of nutrient losses from agricultural landscapes. With financial support from OMAFRA, CWN undertook an updated consolidation of state of the knowledge on the efficacy of existing approaches to P management in light of new understanding and new conditions. The goal of the work is to better inform actions and investments by policy makers, conservation authorities and farmers with a common interest in mitigating P losses from agricultural lands.

CWN convened a technical advisory group to inform the design of a workshop that would obtain insight and direction from the expert community regarding consensus of the science and practice in this area. To gain the desired insights, the advisory group recommended that the workshop focus on three key questions of the scientific community:

- What is the relative importance/contribution of 'event-based' losses from the landscape to overall nutrient loads delivered to receiving water bodies compared to losses during 'average' conditions? What conditions on the land (with a focus on agricultural lands) increase susceptibility to these event-based losses?
- What are the best BMPs for controlling P losses that are exacerbated during major hydrological events?
- What is least known/most uncertain about BMPs, but is most likely to provide value for moving nutrient management forward?

Prior to the workshop, CWN worked with the advisory group to develop a pre-workshop questionnaire, which was structured to determine areas of alignment around these three questions. Workshop attendees completed the online questionnaire in early June 2017; their responses were used to finalize the workshop agenda and to seed workshop discussions. The workshop was held from June 27 – 28 in Toronto ON, with 18 technical experts in attendance (see Appendix A: Workshop Agenda and Participant List). These experts represented various perspectives within Southwestern Ontario, including academia, conservation authorities, federal and provincial governments, and the agriculture industry. To enhance the workshop discussions, several academic and federal government perspectives from Western Canada and the United States were also represented in the group of workshop attendees.

This synthesis document was developed by CWN to convey the key messages and outcomes of the workshop discussions to OMAFRA. It focuses on the high-level implications of leading science and practice for selecting and implementing P management options, including recommended approaches and next steps for BMP selection, and has been developed in consultation with the project's technical advisory group.

Executive Summary

Selecting beneficial management practices (BMPs) for agricultural nutrients is fundamentally a risk-management exercise dominated by site-specific considerations. **Understanding the nature of the risks and how management actions can best address them, but also who bears the burden, costs and responsibility for the various risks being managed, are key to effective implementation.**

Agriculture is a critical part of our society and economy, and nutrients are an essential component of agriculture. However, agricultural land-use may also lead to excessive nutrient loading that results in water quality impairments like eutrophication, harmful algal blooms or hypoxic zones.

For crop and livestock operations, the risks of crop losses due to insufficient nutrient availability, or economic losses associated with operational costs, must be balanced with the risks of negative environmental impacts from nutrient losses to surrounding water bodies. Given the established role of phosphorus (P) as the limiting nutrient for eutrophication in freshwater ecosystems (Schindler, 1977), it is the control or minimization of P losses from agricultural land to the environment that drives most regulatory goals and actions from an agricultural nutrient management perspective.

In Ontario, trends in agriculture and industry practices over the past few decades have impacted the overall challenges for nutrient management. There are fewer, but larger, farms in Ontario, and cash crop production has increased, with a decrease in use of lands for pasture or hay production (OMAFRA, 2016). In addition, crop diversity has been on the decline, with the triad of soybeans, corn and wheat dominating land use (OMAFRA, 2016). Although a trend toward no-till or low-tillage seeding practices took hold in Ontario in the 1980s and 1990s, it is unclear exactly how those practices have been implemented, particularly in relation to fall tillage practices and fertilizer application. In cases where no-till has been implemented with broadcast fertilizer application, the risk of soluble P loss from agricultural landscapes is likely increased (Daryanto et al., 2017; Jarvie et al., 2017) Moreover, there has been a reverse in the trend with increased tillage in recent years (Statistics Canada, 2017) particularly with attempts to maximize production in response to higher commodity prices. Practices that accomplish subsurface incorporation of applied nutrients are generally seen as preferable for nutrient management, but experience with subsequent P transport related to tillage practices has been mixed. Therefore, although there has been an overall decrease in fertilizer application in Ontario since the mid-1990s (Bruulsema et al., 2011), there remain significant challenges to overcome in effective nutrient management, particularly with respect to understanding and retaining phosphorus on the landscape.

An updated context for managing P losses from agriculture

The main implication of climate change for nutrient management is an increased significance of hydrologic events on overall P losses from agriculture. It is the event-based losses rather than base flow conditions that dominate P flux from watersheds dominated by agriculture. Although climate change may also influence patterns of agricultural land-use over time, it is a consideration of the changes to the timing and severity of weather events that is key to selecting best practices to minimize P losses from the landscape. In Ontario, climate change is also impacting the length of growing season.

The increased frequency of extreme hydrologic events associated with climate change typically does not fundamentally change the nature of the transport issues faced in a particular setting, but it does exacerbate them. This may significantly increase the need to focus on event-based transport to achieve effective management of P losses. Selection of appropriate management techniques will need to increasingly focus on addressing those event-based off-site transport scenarios.

Science and research advances over the past few decades have improved and deepened our understanding of P behaviour and transport related to agricultural practices, but have not fundamentally changed the conceptual model. Rather, these advances have increased the recognition that understanding and controlling critical P transport pathways and mechanisms that ultimately impact receiving waters for a given site are central to achieving environmental protection.

Management practices have historically focussed on reducing soil and associated particulate phosphorus (PP) losses, as PP often comprises the majority of P delivered to receiving water bodies. At favourable biogeochemical conditions, PP may be transformed and released as more bioavailable soluble reactive phosphorus (SRP) that may exacerbate algal growth. Given its potential significance for algal productivity (Baker et al., 2014; Kane et al., 2014) increasing attention has been placed on these 'indirect' sources of SRP as well as SRP directly exported from the landscape. This has led to a shift towards a more comprehensive evaluation of management practices in controlling P losses in its various forms. Many conventional BMPs that target PP have been observed to promote the release of SRP (Aronsson et al., 2016; Jarvie et al., 2017; Sharpley & Smith, 1994; Stutter et al., 2009); therefore, current and future research will focus on coordinating complementary management practices to achieve the reduction of PP and SRP.

Recent research advances have also increased consideration of the role of legacy P present both in soils beneath agricultural fields and within the water bodies and sediments in surrounding ecosystems due to previous activities (CWN, 2017). Remobilization and transport of legacy P within aquatic systems complicates the ability to assess the contributions of on-farm management initiatives to receiving waters, particularly at the larger watershed scale. The significance of P stored in the soils of agricultural fields, relative to its availability to future crops and potential to reduce the need for additional fertilizer application, is an area of considerable interest requiring further study. Regardless of the potential for decreasing the recommended amounts of P addition to ensure crop fertility, over-application significantly above the indicated requirements remains a concern as well as an opportunity.

Amounts of P needed for optimum crop production are very large relative to the amounts that can cause deterioration of water quality. Avoiding over-application, or reducing P application where appropriate, represents one of the most significant opportunities to reduce P loading to the environment. Measurements of P in soils have been dominated by standard soil-test phosphorus (STP) measurements, an agro-economic indicator developed in an effort to link the levels of P present in soils to risks of crop yield losses. Whereas these measurements typically provide an indication of potential source areas at higher risk for P loss, more effective site-specific measurements are needed to better determine transport and environmental impacts and to support the selection of BMPs.

Management options: source application and off-site transport control

Management options for agricultural nutrients are generally classified into one of two general categories: 1) source application and control practices that seek to maximize uptake and use of applied nutrients on-site by crops or vegetation, and 2) control of off-site transport of the nutrients not taken up by crops or vegetation.

While on-farm source control practices (i.e., amounts, types, timing and methods of manure or fertilizer placement) represent an important facet of agricultural nutrient management activities (Bruulsema et al., 2011), farmers must apply source control practices within the constraints available to them (e.g., timing/ability to get out onto a field) and variabilities in weather or conditions can diminish the success of intended practices. Short duration, more severe, episodic or unanticipated weather events (e.g., storms, seasonal rain events and snowmelts) can decrease the overall effectiveness of source control practices and, in the case of severe events such as major floods, event-based P transport may totally overwhelm the benefits of good on-site management practices. Given the increased dominance of event-based transport with climate change, as well as the low levels of P that are of environmental significance relative to agricultural use, controlling off-site transport becomes a necessary and inevitable approach in addition to source control practices. An updated consideration of the challenges facing agricultural nutrient management indicates a need for a multi-barrier approach to environmental protection.

Identifying beneficial management practices

Given an updated consideration of the issues surrounding P losses from agricultural landscapes, in identifying BMPs to mitigate these losses, the key question becomes:

Which BMPs can most effectively address the dominant P transport pathways present at a given site?

Successful selection and implementation of management practices will rely on complementary approaches that target the dominant P sources and transport pathways at a given site, rather than the characteristics or overall track record of the individual technologies/practices. Therefore, management practices that are deemed effective for addressing P losses are herein termed 'beneficial' management practices (BMPs) to avoid the incorrect presumption that a particular technology or practice is always superior. This is reflected in the mixed responses of the experts consulted in this study regarding their experience of the efficacy of various transport management techniques (e.g., different tillage or strip cropping practices, use of cover crops, buffer strips and wetlands) at both average and storm conditions. Instead, the need for a multi-barrier approach which draws on different mechanisms to provide a tailored approach for managing P losses at a given site was underscored. For example, the United States Natural Resources Conservation Services (NRCS) has categorized BMPs based on their intended function(s) to avoid, trap or capture P. In addition, to be successful and have traction with users, the analysis of BMPs must extend beyond a technical evaluation to consider the costs and risks of implementation. Proposed solutions must be readily available and actionable, and must clearly address economic risks and cultural concerns facing those (largely the agricultural community) charged with implementing and operating them.

Recommended approaches and next steps for BMP selection

1. Require and support a site-based approach that assesses the most likely dominant transport characteristics/pathways for the basis of BMP selection, in alignment with existing stewardship plans (e.g., environmental farm plans), programs and policies that support a site-based approach.

2. Structure further work and research assessing efficacy of BMPs in the context of transport mechanism groupings. Investigate the potential to develop tailored regional or sub-regional assessments and characterizations that group main transport pathways, types of agricultural activity (e.g., crop types vs. livestock), and conditions for an area to better prioritize comparisons and selection of beneficial management practices.

3. Adopt a risk-based framing for BMP assessments, discussions and outreach that recognizes the different risk management considerations to better recognize and align risk sharing frameworks among producers and regulators.

4. Advance the knowledge base for existing measurements, like soil-test phosphorus, to gain a better understanding of long-term availability of soil P to avoid over-application of fertilizers and recognize risks to the surrounding environment, as well as better understand the relationship of such measures to predicting P loss from the landscape.

5. Increase support for education and training regarding best application of source control options (e.g., 4Rs), structures with incentives and regulations that recognize and reflect realities of decision needs for producers.

6. Advance initiatives that better highlight success stories and learnings from BMP applications, not specific to assessment or promotion of individual technologies/practices, but advancing knowledge of what has been learned through successes and failures about the ability to manage transport.

Introduction

The agriculture and agri-food industry contributes over $110 billion to Canada's annual gross domestic product (GDP) (Agriculture and Agri-Food Canada, 2017). Ontario's contribution accounts for almost a third of this amount and provides more than 781,000 jobs (OMAFRA, 2017), underscoring its critical importance for the well-being of both our society and economy. However, as domestic and global food demand continue to rise amidst a decreasing rural labour force, the agricultural industry must resort to more efficient, environmentally-friendly and sustainable food production methods.

Whether nutrients are applied as chemical fertilizers for crop production or generated as a result of raising livestock, they are an important resource used and/or generated by virtually all agricultural practices. However, agricultural nutrients may also result in negative environmental impacts if they are transported to surrounding waterways and water bodies. Loading of relatively small amounts of nutrients relative to what is used and managed as part of agricultural practices can lead to impaired water quality. For many freshwater systems, phosphorus (P) is usually the limiting nutrient for primary production (Schindler, 1977), and thus a key driver of health and environmental issues related to eutrophication, hypoxic zones or the occurrence of both nuisance algae and harmful (toxic) algal blooms.

Given that P can be both an important resource and a problem in some freshwater environments, selection of beneficial management goals and practices for agricultural nutrients in much of Canada focuses on both the effective management of P inputs to agriculture as well as controlling losses from agricultural land to the environment. The risks associated with agricultural production (e.g., loss of crop yield due to insufficient nutrients applied) are weighed against the risks of environmental impacts associated with the implemented agricultural practices (e.g., loss of a drinking water supply). Farmers bear the burden of risk associated with potential crop losses or failure due to insufficiently fertile soils, as well as the capital and operational costs associated with the implementation of management practices to mitigate nutrient losses from the landscape, whereas the greater public bears the risks associated with water use impairments through impacts to environmental and human health. Consequently, selection and implementation of beneficial practices for managing P are necessarily both a resource optimization as well as a risk-management exercise implicating multiple stakeholders. Therefore, the selection of effective P management practices requires an assessment of the nature of competing risks and their implications beyond solely a technical evaluation of the performance of different practices.

An updated context for managing P losses from agriculture

Risk management comprises the *identification, evaluation and prioritization of risks, followed by coordinated and economical application of resources to minimize, monitor and control the probability or impact of undesirable outcomes or to maximize the realization of opportunities* (ISO, 2018).

The agricultural industry, government agencies and non-government organizations are all involved in various aspects of risk management in Ontario. This includes social, economic and environmental risks, requiring a comprehensive consideration of all relevant factors that may alleviate or exacerbate challenges associated with managing agricultural P fluxes. An additional factor to be considered is the impact of the policy instruments – including regulations, programs and incentives – that have been used to influence agricultural P management. While a comprehensive review of these factors is beyond the scope of the current work, some recommendations and insights from experts at the workshop were offered to promote uptake and overall nutrient stewardship.

Agroeconomic factors influencing agricultural P management

The selection and adoption of management practices to control P losses from agricultural landscapes are often influenced by socio-economic trends and changes associated with key farm characteristics, capacity, and farmer awareness and attitudes (Prokopy et al., 2008). Smaller farms are increasingly rare globally. Larger operations are more likely to have the capacity and resources afforded by economies of scale, making them more profitable, and gross farm receipts continue to increase for larger operations (Hoppe, Robert, 2015; Statistics Canada, 2017). Consistent with trends across Canada, the total number of farms in operation in Ontario is decreasing, but this decline is offset by a general shift to larger operations, with gross farm receipts increasing for larger operations and decreasing for smaller farms. In Ontario, there was a 4.5% decrease in the number of farms from 2011 to 2016, but total farm area decreased by only 2.5%, reflecting a modest increase of 2% in the average area per farm (Statistics Canada, 2017). Most of the farmed area in Ontario is concentrated in southern and central Ontario, within watersheds draining southward towards the Great Lakes-St. Lawrence System. In 2016, approximately 5.4% of Ontario's total land area was used for agriculture (Statistics Canada, 2017).

Changing societal demands, global food supplies and profit margins (including prices and costs of production of agricultural goods) have also driven changes in the types of agricultural operations in Ontario. Over the past several decades, hay production and land used for pasture/forage production have decreased in Ontario. There has also been an overall shift toward a decrease in crop diversity but an increase in cash-crop production. The three main crops (soybeans, corn and wheat) account for nearly 57% of agricultural land use in 2016; soybean production has continued to rise and became the dominant use of crop land (27%) in Ontario as of 2011 (OMAFRA, 2016). The conversion of pasture land and land for forage production to crop production has resulted from decreasing, but more concentrated, beef herds. This has led to a shift in the types of challenges encountered in terms of maintaining long-term soil health.

Tillage practices are of key interest for soil and nutrient management and while overall trends are captured by self-reporting of practices, the relationship of current practices to needs or options for beneficial nutrient management are more difficult to effectively assess. As part of crop production, no-till practices have been increasing in Ontario since the 1980's in an effort to reduce soil erosion and PP losses, with 33.1% of crops being produced using reduced-tillage or no-till seeding strategies in 2011. However, there has been an increase in tillage from 2011 to 2016 (Statistics Canada, 2017), which may be in response to recent increases in commodity prices (OMAFRA, 2016). The lack of reliable data on the extent of fall tilling of lands, which may contribute to loss of soil and P due to non-growing season events, makes it difficult to assess the need for increased consideration or management of losses that may be resulting in the fall as a result.

Use of cover crops to help maintain soil health and decrease loss of soil or nutrients is an area of recent focus for practitioners and is increasing in use and interest in Ontario, with 15-20% of Ontario farmers reporting using cover crops in 2011 (OMAFRA, 2016). Identifying effective use of cover crop schemes that are both economically viable for producers and effective in maintaining soil productivity is an active area of practice and research and one that may have significant implications for P management by shifting the timing or magnitude of off-farm losses.

To ensure successful uptake and implementation, the analysis of beneficial management practices (BMPs) must extend beyond a technical evaluation to reflect a clear consideration of which practices will have traction among users, including how the costs and risks of implementation are handled. Proposed solutions must be readily available and actionable, and clearly address economic risks as well as cultural concerns facing those (largely the agricultural community) charged with implementing and operating them. Better addressing how various BMP options relate to current and changing socio-economic concerns of the agricultural community and what combination of regulatory, incentive or support structures best encourage their implementation remains a key area of active focus and particular opportunity.

Climate change impacts on agricultural P management

Climate change has been recognized to be particularly influential for crop production (Ockenden et al., 2017). For example, hydrology is essential in determining the biophysical limiting factors, such as the length of growing seasons, average temperature ranges, pest varieties and populations, as well as humidity and precipitation patterns. This in turn will result in the selection of the most resilient crops and may alter the uptake of P and other nutrients through changes to plant physiology. However, climate change has more direct impacts for the transport of P on and within the landscape. Essentially all P transport is associated with the occurrence of hydrological events. The timing and severity of weather events critically impacts the availability, and most importantly, the location of P relative to plant roots where it can be delivered to the crop as intended. This presents the greatest focal point for selection of agricultural practices to minimize P losses from the landscape.

The occurrence, or increased frequency, of extreme hydrologic events associated with climate change typically does not fundamentally change the nature of the P transport issues faced in a particular setting. However, it often exacerbates them and can overwhelm management practices designed to minimize P losses from agricultural landscapes. All hydrologic events can result in P loss from the landscape, but the main hydrologic events of concern for any site are those – like snowmelt and large storms – that trigger transport through dominant hydrologic pathways, resulting in significant and rapid transport of particulate and/or dissolved P. While this points to the need to focus efforts on minimizing event-based transport (especially the 20% of storms that result in 80% of the P losses from the landscape), it is often not useful or practical to define threshold storms for the design and/or selection of BMPs, given the highly site-specific nature of transport issues and heterogeneity of microclimatic conditions. In theory, it is possible to define events that require response or prioritization based on a comparison of hydrologic conditions to typical events (e.g., amounts and timing of rainfall or runoff relative to annual or seasonal averages). However, the variable and contextual nature of these events suggests that creating a formal definition or 'trigger' is unlikely to be helpful as a policy construct in driving the selection of BMPs.

Table 1. Potential climate change impacts and their implications for agriculture and nutrient management

Climate change trend	Impact to crops and/or P transport (biophysical impacts)	Examples of adaptive mitigation strategies
Truncated/shifted growing season	Plant requirements impacted	Crop choice/variety
Drier summers	Reduced plant uptake of water and nutrients, reduced plant growth; can lead to instability of soil structures Wind erosion of drier soils leading to loss of both soil and particulate P	Crop choice/variety (drought resistance) Install wind breaks, erosion control measures
More frequent events in winter (snow + melt)	Influence on performance of cover crops (if used) Winter dominated losses of P	Avoid fall/winter application of P; consider P application at time of planting Evaluate cover crop species for effectiveness at retaining P on fields without releasing SRP through freeze/thaw cycles (Cober et al., 2018; Liu et al., 2015) Monitor to estimate/account for losses in P balance in soils

Advances in P transport science and technologies

Incremental advances in our understanding of the science of P fate and transport in recent decades have provided increased insight into the complex behaviour of P in the environment, leading to informed management efforts and improved adaptive capacity in light of climate change and other stressors (see Table 2). However, the persistence of significant eutrophication challenges (e.g., Lake Winnipeg) points to a clear need for more application of best knowledge of science and beneficial practices for agricultural nutrient management. The widespread occurrence and impacts of hazardous algal blooms over the past decade, particularly where they have threatened human health such as in Lake Erie, has further heightened the relevance of recent advances in the science of P transport. The question facing managers is how the advances in our understanding of P transport and agricultural practices can improve prioritization decisions for how and where management activities are most needed and will be most effective.

The evolution of P management has been inspired and heavily influenced by key scientific findings throughout history, and generally alternates between a desire to ensure sufficient nutrients are applied to the landscape to support healthy and abundant crops and a desire to limit landscape losses of P based on anticipated aquatic ecosystem impacts. The relationships elicited have shifted from purely empirical relationships to an increasingly mechanistic and systems-based understanding of the key drivers and controls of nutrient losses from the landscape. Accordingly, this has led to incremental changes in agriculture practice.

Table 2. Key agricultural scientific/technological advancements and implications for practice. Ordered chronologically, there is an incremental shift from empirical knowledge (correlations) to mechanistic, as well as relatively simple concepts to multi-faceted systems (Canadian Water Network, 2017).

	Scientific principles and technological advances	Implications for practice
Mid-19th century	Justus von Leibig, among others, document the role of manure and plant nutrients for crop growth	Use of P chemical fertilizers for increasing soil fertility
1970s	Nutrient enrichment is linked to eutrophication; discover P is the primary limiting nutrient in freshwater systems	P detergents ban, control of P from wastewater, etc.; primary focus is on point source P control
1970s – 1980s	P mostly sediment associated	Primary focus is on controlling P losses through erosion control measures and the development of P management practices

1980s – 1990s	P can be re-released depending on redox conditions	Fundamental research on P sequestration, understanding of complex biogeochemical cycling in aquatic and terrestrial ecosystems
1990s – present	SRP most bioavailable form	Efforts to monitor and investigate BMPs that reduce SRP losses
1990s – present	Preferential pathways (e.g. tiles, hydrogeology, soil types, etc.) and legacy stores of P	Creation of more strategic monitoring networks, better able to account for accumulation and losses of P
1990s - present	Improved crop species, genetically modified crops	Crops that are more efficient in nutrient uptake, robust in harsher conditions, and pest and drought resistant
2000s - present	Geographic Information System (GIS) linked technology for controlling nutrient assessment and application	Precision agriculture Implementation of 4Rs of nutrient stewardship (right source, right time, right place, right rate) (Johnston & Bruulsema, 2014).

Science and technological advances over the past century, but particularly the past few decades, have improved and deepened our understanding of P behaviour and its transport across agricultural landscapes. While advances in the science have not fundamentally changed the conceptual model of P transport, our ability to measure and validate the conceptual models for understanding the relative significance of various transport pathways at a site has substantially improved. This understanding facilitates improved identification and control of critical P transport pathways and mechanisms for a given site that may help alleviate the ultimate impacts on receiving waters, which is central to achieving environmental protection.

PP remains the dominant fraction of P lost from agricultural landscapes. However, advances in the understanding of the role of SRP transport and its timing in the fueling of algal growth that may thwart management goals has driven an increase in research and consideration of the significance of controlling SRP losses from the landscape and within-lake releases of SRP. It has been observed that some management practices that are designed to target PP losses may result in increased SRP losses (Jarvie et al., 2017), including no-till practices (Sharpley et al., 1994), vegetated buffer strips (Stutter et al., 2009) and cover crops (Aronsson et al., 2016; Bechmann et al., 2005). To achieve the goal of reducing overall agricultural P losses regardless of form, a combination of management practices on the field, in the field and at the edge of field is likely necessary in many cases and advisable for addressing weaknesses in the implementation of any one individual management practice.

The incremental understanding of the relevance of legacy P (i.e., P that may be present in soils of agricultural lands, in the sediments, and terrestrial as well as aquatic systems beyond farm boundaries) is leading to recognition that it may play a significant role in controlling ultimate impacts to receiving water bodies. Legacy P and its remobilization and transport within aquatic systems may have a significant impact on the ability to assess the contribution of individual management actions to success in attaining established receiving-water goals (Canadian Water Network, 2017). The significance of legacy P that is stored in the soils of agricultural fields and its potential availability to future crops, thereby reducing the need for additional fertilizer applications, is an area of considerable interest in need of further study.

Management options: source application and off-site transport control

To identify the key needs and opportunities for nutrient management in agriculture, both science and practice have focused on two core areas: (1) source application and control practices that seek to maximize uptake and use of applied nutrients on-site by crops or vegetation; and (2) controlling off-site transport of the applied nutrients that are not taken up by crops or vegetation.

Efficacy of source control BMPs for managing agricultural P

On-farm source control practices (i.e., amounts, types, timing and methods of manure or fertilizer placement) remain a key component for agricultural nutrient management by seeking to maximize the amount of applied nutrients that are taken up by crops and vegetation, and to minimize nutrients that can be lost to the surrounding environment (Johnston et al., 2014). Nutrient losses through transport mechanisms may be substantially reduced if the nutrients were not applied or minimally applied in the first place. Accordingly, source control remains the undisputed practice that is known to be effective for minimizing P losses from the landscape, irrespective of hydrological conditions. The levels of P on agricultural landscapes can be orders of magnitude above those associated with eutrophication effects in the environment. However, famers must apply source control practices within the constraints available to them (e.g., timing/ability to get out onto a field) and variabilities in weather or conditions can diminish the success of intended practices. Short duration, more severe, episodic or unanticipated weather events (e.g., storms, seasonal rain events and snowmelts) can decrease the overall effectiveness of source control practices, as well as dominating annual off-site transport of nutrients (and therefore loading to receiving waters).

Manure management efforts are intrinsically more complex due to the greater variability of P forms and quantity over chemical fertilizers, as well as additional considerations of fecal microbial contamination of water supplies. Current developments have focused on practices and technologies to improve nutrient recovery from manure, and the redistribution of these nutrients to croplands where nutrients are depleted during crop growth and harvest (Hilborn, 2015). Although off-site transport of manure can be costly, it presents an opportunity for better balancing of P flows between regions, sub-regions and the farm level. Overall, there are significant opportunities for continued innovation for P recovery and reuse, while supporting the goals of preventing over-application of manure to soils and in physiographic settings (e.g., steep slopes) that are known to promote P transport to water sources.

P is applied to agricultural soils in amounts that operators determine is necessary to mitigate the risk of poor crop performance. Two schools of thought on soil fertility management strategies exist, where soils are fertilized to a) the point of sufficiency as anticipated based on crop species (i.e., P applied annually =

P required for maximum economic yield), or b) build-and-maintain (i.e., increasing soil fertility by nutrient application and sustaining levels by replacing the nutrients that are removed each year). Regardless of the approach selected, P and nutrient applications are typically gauged based on measurements of P already in the soil. Soil-test phosphorus (STP) measurements (which assess chemically extractable P that has been related to plant available P) represent the core P measurement technique in agricultural soils to determine the amount of P needed to support crops. These measurements were developed as agroeconomic indicators; a way to assess the need for additional P fertilization of soils to minimize risk of crop losses.

Recommendations for soil P requirements are based on response curves that were developed to relate STP results to expected crop results. As crop varieties and environmental conditions change, there is an opportunity to update and refine soil P requirement curves to adapt to new information and updated knowledge on the relationship between crop yield and STP. However, because STP was developed as an indicator of soil fertility, rather than an environmental indicator, the value and accuracy of STP for transport risk assessments, or for evaluation of BMP performance is limited (Duncan et al., 2017; Sharpley, 2011; Wang et al., 2016). In practice, STP has been used as an overall indicator of potential fields or in-field areas that are at greater risk for P loss and integrated into environmental P indices, indicating where it may be appropriate to target BMPs (Duncan et al., 2017; Sharpley, 2011; Wang et al., 2016). Although not a particularly sensitive indicator of degree of environmental risk from P losses, it has been commonly used to provide an indication of spatial variations of levels of P in the soil and is assumed to provide an overall indication of risk of P loss. As a result, it generally comprises a significant portion of the calculation of P indices used by jurisdictions to classify overall P risk in management schemes. While this provides a reasonable approach to identifying potential sources of excess P, moving forward to better assess actual P transport from the point of view of environmental risk and impacts, more sensitive and site-specific measurements of P will be required.

Efficacy of off-site transport control BMPs for managing agricultural P

Although there was consensus among experts who submitted responses to the pre-workshop questionnaire on the efficacy of source control measures, there were mixed responses to the efficacy of various transport management techniques (e.g., different tilling or crop stripping practices, use of cover crops, buffer strips and wetlands) under both average and storm conditions (see Supporting Document: Pre-Workshop Questionnaire Summary). This reflected, in large part, the strong site-specific context reflected by their experience with effectiveness of transport management techniques. Effective identification of a set of BMPs for mitigation of P losses must be site specific. It requires a good understanding of the site-specific transport pathways that are dominant for a given farm or region, and optimizing the selection and use of BMPs from among the array of available management practices to best address the relevant transport characteristics.

In the case of severe events such as major floods, event-based transport may totally overwhelm the benefits of good on-site management and transport control practices. This does not diminish their importance. Rather, it reflects the inevitable uncertainties and increases an understanding of the degree to which we can rely on these practices alone to achieve environmental protection. Analogous to the recognition of a need to manage drinking water risks through a multi-barrier approach following the Walkerton, Ontario disaster in 2000, an updated consideration of the challenges facing management of agricultural nutrients indicates a need for a similar multi-barrier approach to the prevention of off-site P migration.

In the literature, the performance of individual BMPs has often been considered independent of other BMPs rather than within a multi-barrier approach (i.e., dependent on the performance of other implemented practices). Accordingly, development of evaluation metrics of these management practices involves moving away from a strictly numbers-based approach for estimating ‘percent reduction’ (i.e., the amount of P removed or retained by a specific BMP) based on observational studies, as the evaluation of the BMP performance may be biased when source P concentrations are typically low. Instead, emphasis must be placed on a systems-based approach, where evaluation of the robustness and resilience of the collective management practices are considered. To assist with screening of preliminary BMPs for consideration at a given site, it may be beneficial to group management practices based on 1) their ability to target different physical P forms, 2) suitability for landscape characteristics, 3) suitability for farming type and scale, and 4) potential for adoption considering logistics and costs. Commonalities among sites at a regional level may further provide insight regarding the effectiveness of management practices. The selection and implementation of a range of BMPs from the farmstead to the edge-of-field, targeting the dominant physical forms of P loss from the site through key pathways, will ultimately provide redundancy to support P management goals.

Table 3. Summary of BMP locations, targeted P forms, impact of tile drains and confidence in their efficacy during storm events (adapted from Macdonald et al., 2013).

Beneficial management practice	Location of BMP on landscape	Targeted physical P form	Impact of tile drains	Confidence in efficacy of BMP during significant hydrological events[1]
Cover crops[2]	Farmstead	Particulate	Complementary	Varied between slight reduction and strong reduction
Clean water diversion	Farmstead	Dissolved	N/A	Not discussed
Fragile land retirement	Field	Particulate	Complementary	Not discussed
Filter strips	Edge of field	Dissolved and particulate	Antagonistic	Slight effect/reduction
Residue management, conservation tillage	Field	Particulate	N/A	Strong effect/reduction
Soil conservation planning	Field	Dissolved and particulate	Complementary	Generally strong agreement
Strip cropping	Field	Particulate	Complementary	Varied between no effect and moderate effect
Terraces	Field	Dissolved and particulate	Neutral[3]/ Antagonistic	Not discussed
Water and sediment control basins	Field	Particulate	Neutral[3]/ Antagonistic	Not discussed
Wetland creation	Field	Particulate	Complementary	Varied from slightly counter-productive to strong
Crop rotation	Field	Dissolved and particulate	Neutral[4]/ Antagonistic	Not discussed

Buffer strip	Edge of field	Dissolved and particulate	Antagonistic	Variable, most responses between no effect and moderate effect
Drop structure	Edge of field	Particulate	Complementary	Not discussed
Grassed waterway	Edge of field	Dissolved and particulate	Complementary	Not discussed
Setback or separation distance	Edge of field	Dissolved	Antagonistic	Not discussed
Windbreaks	Edge of field	Particulate	N/A	Not discussed
Streambank stabilization	Stream bank	Particulate	Variable	Moderate-strong effect
Tile outlet control structures	Stream bank	Dissolved and particulate	Complementary	Not discussed
Tile outlet stabilization	Stream bank	Particulate	Complementary	Not discussed

[1] Per pre-workshop questionnaire responses from the technical advisory group consulted in this project
[2] Can be considered both a source and transport control measure
[3,4] It has been suggested that tile drains have a neutral impact on terraces and water and sediment control basins since tile drains are considered in their design. Additionally, tile drains have a neutral impact on crop rotation, since many crop rotations are only possible because of the presence of tile drains.

Framing BMP Selection

In identifying key transport pathways and selecting phosphorus management BMPs from among a menu of available options for phosphorus management to be applied to any given location, the following selection considerations should be taken into account.

Hydrologic events dominate phosphorus losses from agricultural landscapes

Transport of agricultural phosphorus off-property to water bodies is the dominant issue from the point of view of environmental impact and phosphorus loads from transport are dominated by the occurrence of hydrologic events, particularly for PP.

BMP implications: Site characterizations should prioritize identification and measurement of main pathways for phosphorus transport, particularly during short-term, more intense events. BMPs must address effective management of the main transport pathways identified, including recognizing that they may be temporarily overwhelmed by extreme events.

Source controls represent an important opportunity and low-hanging fruit

Although it is ultimately the control of off-site transport of phosphorus to the broader watershed that must be addressed, on-farm use of nutrients can be orders of magnitude above the quantities that are of concern for off-site impacts. As a result, source control measures for fertilizers and manure use and handling that minimize phosphorus losses represent the lowest-hanging fruit in terms of mitigating overall impacts.

BMP implications: Source control and management activities (e.g. the 4R approach) represent a core element of nutrient management practice. Policies that encourage identification and implementation of practices best suited to site-specific conditions – including training and support programs that are well matched to addressing user needs – are key. To identify BMPs, continuing science and practice advancements are needed to better define how much nutrient application is enough/too much, and how to avoid over-application and ineffective application as a result.

Choices should be framed as balancing risks and recognizing cost allocations for risk mitigation

Decisions related to nutrient use and management in agriculture are essentially risk management discussions. This makes it important to identify where risks are experienced, at what cost they are being mitigated, and how and where those costs are being allocated. Agricultural producers must weigh a host of decisions against risks such as crop fertility losses due to insufficient nutrient uptake or changed practices, economic losses resulting from operational costs of management, and market or regulatory influences. Policy makers must coordinate efforts across different departments and ministries (e.g., Environment and Climate Change Canada, Ontario Ministry of Environment and Climate Change, OMAFRA) and establish the systems that ensure the risks of impacts on the environment and broader society are appropriately managed, and allocate the costs for that risk management.

BMP implications: Success in selection and implementation of appropriate BMPs will depend on clarifying site-specific management goals and establishing metrics and measurements that allow better understanding of how and where the risks are being experienced and mitigated. Careful risk delineation will be helpful to clarifying how risk mitigation is best approached and by whom, including the role of a multi-barrier approach. This includes the need to deal with variability and uncertainties about BMP efficacy. This moves BMP selection beyond a technical assessment and selection process, to one that more explicitly recognizes selection as an integrated risk management process; taking multiple risks and options to address them into account.

Recommended approaches and next steps for BMP selection

1. Require and support a site-based approach that assesses the most likely dominant transport characteristics/pathways for the basis of BMP selection, in alignment with existing stewardship plans (e.g., environmental farm plans), programs and policies that support a site-based approach.
2. Structure further work and research assessing efficacy of BMPs in the context of transport mechanism groupings. Investigate the potential to develop tailored regional or sub-regional assessments and characterizations that group main transport pathways, types of agricultural activity (e.g., crop types vs. livestock), and conditions for an area to better prioritize comparisons and selection of beneficial management practices.
3. Adopt a risk-based framing for BMP assessments, discussions and outreach that recognizes the different risk management considerations to better recognize and align risk sharing frameworks among producers and regulators.
4. Advance the knowledge base for existing measurements, like soil-test phosphorus, to gain a better understanding of long-term availability of soil P to avoid over-application of fertilizers and recognize risks to the surrounding environment, as well as better understand the relationship of such measures to predicting P loss from the landscape.
5. Increase support for education and training regarding best application of source control options (e.g., 4Rs), structures with incentives and regulations that recognize and reflect realities of decision needs for producers.
6. Advance initiatives that better highlight success stories and learnings from BMP applications, not specific to assessment or promotion of individual technologies/practices, but advancing knowledge of what has been learned through successes and failures about the ability to manage transport.

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Appendix A: Workshop Agenda and Participant List

This workshop and project are funded by the Ontario Ministry of Agriculture, Food and Rural Affairs

Tuesday, June 27, 2017		
8:00 am – 9:00 am	Breakfast provided	Carlyle Foyer
9:00 am – 9:45 am	**Introductions and meeting overview** *Bernadette Conant, Canadian Water Network &* *Deborah Brooker, Ontario Ministry of Agriculture, Food and Rural Affairs*	Carlyle Room
9:45 am – 10:30 am	**Session I:** Establishing the context for agricultural nutrient management efforts in Ontario – physiographic and climate controls of P losses from the landscape	
10:30 am – 10:50 am	Refreshment break	Carlyle Foyer
10:50 am – 12:15 pm	**Session II:** Identifying “hotspots” in time and space – critical thresholds, indicators and metrics for phosphorus losses from the landscape	
12:15 pm – 1:30 pm	Lunch provided	Carlyle Foyer
1:30 pm – 3:00 pm	**Session III:** Soil phosphorus supply/fertility recommendations – managing P from the source	

3:00 pm – 3:20 pm	Refreshment break	Carlyle Foyer
3:20 pm – 5:00 pm	**Session IV:** Performance of agriculture-specific BMPs at different climatic and physiographic conditions	
5:00 pm – 6:00 pm	Workshop break	
6:00 pm – 8:00 pm	Dinner provided	Plaza B Room

Wednesday, June 28, 2017		
7:30 am – 8:30 am	Breakfast provided	Carlyle Foyer
8:30 am – 9:00 am	**Recap from Day 1** *Bernadette Conant, Canadian Water Network* Summary table of various BMPs performance: what we heard, areas of alignment, areas of contention Key insights, learnings and questions raised during Day 1	Carlyle Room
9:00 am – 10:30 am	**Session V:** BMP interactions: source x transport synergistic and antagonistic effects, impacts on non-target nutrients and contaminants	
10:30 am – 10:50 am	Refreshment break	Carlyle Foyer
10:50 am – 12:15 pm	**Session VI: Pulling it all together** (I): What are reasonable performance expectations of the BMPs discussed to achieving target P loss reductions in Ontario climates/physiographic settings?	
12:15 pm – 1:15 pm	Lunch provided	Carlyle Foyer
1:15 pm – 2:45 pm	**Session VI: Pulling it all together** (II): Priority needs for knowledge regarding these BMPs to result in better uptake and direction for implementation?	
2:45 pm – 3:00 pm	**Next steps and wrap up** *Bernadette Conant, Canadian Water Network*	

3:00 pm	Adjourn	

Meeting Participants:

Technical Advisory Group
Merrin Macrae, University of Waterloo
Douglas Smith, United States Department of Agriculture
Keith Reid, Agriculture and Agri-Food Canada
Andrew Sharpley, University of Arkansas
Barbara Cade-Menun, Agriculture and Agri-Food Canada
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