KEEPING PHOSPHORUS ON THE LAND

Workshopping a bridge between agricultural production and water quality

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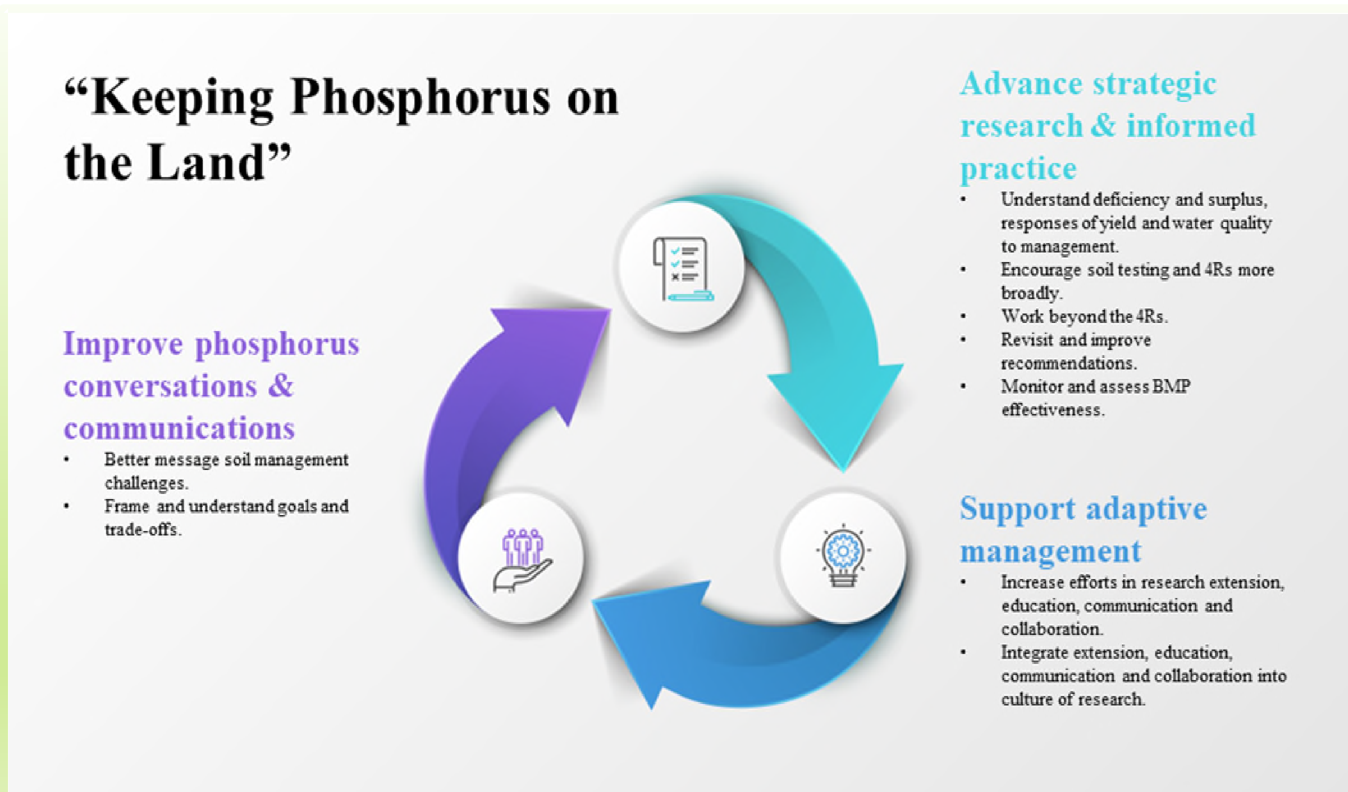
Abstract

Management of the phosphorus (P) in prairie soils presents a challenging dilemma. Phosphorus is critical to continued agronomic productivity. Yet, management of P in prairie landscapes is also crucial to the protection of prairie lakes and reservoirs, which are highly vulnerable to issues of nutrient pollution and harmful algal blooms. Here we present detailed insights from a 2-day workshop *"Keeping Phosphorus on the Land"* where we worked to bridge the disciplines of water quality, and agronomy, and better understand issues, and opportunities within and across these areas of work as they relate to managing soil P. This report includes detailed insights and recommendations that reflect outcomes of presentations, panels, and discussions engaging researchers and practitioners in government, industry and universities from each of Canada's three prairie provinces. It includes recommendations on 'actionable' areas, and areas where further research and dialogue is required. Readers are also directed to our short synthesis report, available here: Liu, J., H.M. Baulch, and J.A. Elliott. 2021. Keeping Phosphorus on the Land: Main Takeaways for Managing Soil Phosphorus in the Prairies. University of Saskatchewan, Saskatoon, Canada. DOI:10.23688/1gvs-5333.



Graphical abstract: Pathways for achieving agronomic and water quality goals in the Prairies, encapsulating key messages of the workshop *"Keeping Phosphorus on the Land"*, and next steps.

Acknowledgements

This workshop was hosted at the University of Saskatchewan on Treat 6 Territory and the Homeland of the Métis. Participants joined virtually from across the prairie provinces and from other regions. We pay our respect to the First Nations and Métis ancestors of these places, and work to reaffirm our relationships with one another. This report has been prepared based on discussions carried out during a prairie-wide workshop "Keeping Phosphorus on the Land" (February 22 & March 2, 2021) and builds upon the insights of many people, including workshop participants, and our steering committee. We thank all workshop participants for their valuable input and we are especially grateful to Dr. Don Flaten (University of Manitoba, retired), Dr. Tom Bruulsema (Plant Nutrition Canada), John Heard (Manitoba Agriculture and Resource Development), Len Kryzanowski (Alberta Agriculture and Forestry, retired), Etienne Shupena-Soulodre (Saskatchewan Water Security Agency), Dr. Henry Wilson (Agriculture and Agri-Food Canada), Sharon Reedyk (Environment and Climate Change Canada), and Trevor Wallace (Alberta Agriculture and Forestry) whose expert knowledge guided workshop planning and reporting with very constructive comments, to Stephanie Merrill (formerly with University of Saskatchewan) and Lukas Smith (formerly with University of Saskatchewan) for their input as well as technical and logistical support, and to Don Selby (University of Saskatchewan) for support of the final report. The workshop was financially supported by a Capacity Building Award (Seed Funding) provided by the University of Saskatchewan's Global Institute for Water Security and the Global Water Futures Program, Agricultural Water Futures project, and Career Launcher Internships.

Introduction

Prairie crop production faces critical challenges in both agronomic and environmental phosphorus (P) management. Agronomically, there is a concern over soil P deficiency. A survey of soil test P (STP) levels across commercial soil test labs showed that 81%, 64% and 59% of the sampled soils in Saskatchewan, Manitoba and Alberta, respectively, had STP concentrations below the critical P levels for optimum crop production in 2015 (IPNI, 2015). Environmentally, agriculture is an important anthropogenic source of P contributing to eutrophication of prairie waters. Although eutrophication can be a slow, natural process and there is evidence of eutrophic conditions in prairie rivers and lakes prior to European settlement and agricultural development, many lakes and ponds on the Prairies have been affected by increases in P loading from upstream areas. This can result in increasing frequency and duration of algal blooms, specifically cyanobacterial blooms. Indeed, Canadian lakes and rivers are very sensitive to P. They are classified as eutrophic when they have a total P concentration of 0.035-0.1 mg L^{-1} (CCME, 2004). Ongoing problems with eutrophication of regional water bodies such as Lake Winnipeg and many other smaller lakes suggests that there is a need to minimize all human sources of P loading to the surface waters, including sources associated with agricultural production. Careful control of nitrogen, and management of other changes in prairie watersheds is also important to address current eutrophication stressors.

Phosphorus deficiency (middle and right) leads to poor crop growth as compared to P sufficiency (left) (photos: Canola Council of Canada).

The agronomic understanding that most P in soil is strongly bound to soil particles leads to a traditional belief among many agricultural practitioners that P does not move with water or moves only within a very short distance in the soil unless the soil particles are eroded and transported from land to downstream waters (Doyle and Cowell, 1993). The loss of particulate P from prairie crop fields is generally small, due to the semi-arid or sub-humid, cold continental climate where snowmelt over frozen soils is the main runoff process. In addition, relatively flat landscapes and farmers' erosion control measures such as reduced tillage or direct seeding also help to reduce the potential for particulate P loss. However, numerous studies worldwide, including prairie studies, have shown that small, but environmentally significant amounts of soil P can be mobilized in dissolved forms and transported to downstream waters (e.g., Tiessen et al., 2010; Liu et al., 2021). Indeed, dissolved P often constitutes 80% or more of the total P loss from prairie crop fields and at the edge of field, runoff P concentrations frequently reach 0.2 to 2 mg L^{-1} (Liu et al., 2021). Although these concentrations cannot be directly related to the water quality guidelines (which are defined for lakes and streams) the runoff P concentrations are clearly much higher than the maximum guideline total P concentrations for eutrophic lakes and rivers in Canada, i.e., 0.035-0.1 mg L^{-1} (CCME, 2004). The differences between agronomic and environmental perspectives on P create both a grand challenge and opportunity for reducing P concentrations, particularly dissolved P concentrations, in cropland runoff.

Too much P in water leads to eutrophication and poor water quality.

To discuss the challenges and solutions, we hosted a two-day virtual workshop on February 22 and March 2, 2021. The workshop brought together agronomic and environmental researchers and practitioners, with the aim to foster conversation on options to improve soil P management to benefit both crop production and water quality in the Prairies. The workshop had about 50 participants from Saskatchewan, Manitoba and Alberta, which included university researchers, government researchers, extension specialists and decision-makers, industry representatives, non-government organization representatives, and producer representatives, to discuss the question **"given what we know today, what should we do to improve management related to soil P in the Prairies?"** The workshop also aimed to foster broader conversations, research ideas and extension activities. The aims were addressed through invited talks, a panel discussion, breakout discussions and follow-up surveys.

Definitions and Explanations:

Soil test P (STP): Test for assessing plant available P, typically at the 0-15 cm (0-6 inches) or 0-30 cm (0-12 inches) soil depth, to help determine fertilizer or manure rate recommendations. This test is also relevant to understanding environmental P loss. Tests widely used include extractions with sodium bicarbonate (Olsen) in Manitoba and modified Kelowna in Alberta and Saskatchewan. Ion exchange resin methods (e.g., the Plant Root Simulator™ probe) are also used to measure plant available P in soil.

Critical P levels: This is the soil test P value (measured at the 0-15 cm or 0-30 cm soil depth) at which the soil is normally capable of supplying sufficient amounts of P to achieve 90 to 95% of maximum yield without further supplementation with fertilizer or manure (IPNI, 2016).

Eutrophication: The process by which an entire body of water, or parts of it, becomes progressively enriched with nutrients, which can cause a series of effects including algal blooms, fish kills and in some cases, production of harmful toxins. According to the Canadian Water Quality Guidelines for the Protection of Aquatic Life, lakes and rivers have different trophic status based on their total P concentrations: ultra-oligotrophic (<0.004 mg L^{-1}), oligotrophic (0.004-0.01 mg L^{-1}), mesotrophic (0.01-0.02 mg L^{-1}), meso-eutrophic (0.02-0.035 mg L^{-1}), eutrophic (0.035-0.1 mg L^{-1}) and hypertrophic (>0.1 mg L^{-1}) (CCME, 2004). Additional P inputs can lead to greater primary production and push them to a higher trophic status (via the process of eutrophication) that is very difficult and costly to reverse. Water quality issues and blooms can become acute in eutrophic and hypereutrophic lakes because many lakes and ponds are P-limited.

Sources of P in water bodies: Phosphorus can enter water bodies in many ways including runoff from agricultural land, livestock and poultry production facilities, and urban and natural areas (e.g., grassland and forestland); discharge of urban and industrial wastewater; atmospheric deposition; riverbank erosion; and from sediment in the water bodies. When runoff occurs, it can transport both dissolved P and particulate P (the P bound to soil particles and organic materials) to downstream water bodies. The sum of dissolved P and particulate P is defined as total P.

Critical source areas: Zone of high risk for environmental P loss associated with high hydrologic connectivity and substantive nutrient sources. These areas can be prescribed specific management approaches that help lessen environmental risk.

4Rs: According to the 4R Nutrient Stewardship partners, "4R Nutrient Stewardship provides a framework to achieve cropping system goals, such as increased production, increased farmer profitability, enhanced environmental protection and improved sustainability. To achieve those goals, the 4R concept incorporates the Right nutrient source at the Right rate, at the Right time and in the Right place" (https://nutrientstewardship.org/4rs/).

1. Current understanding of soil P management

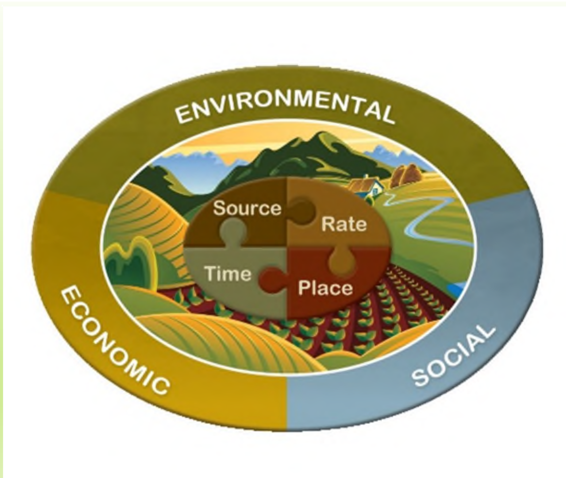
The workshop started with a series of talks aimed at introducing the current status of science and management related to STP specifically and agricultural P management generally in both agronomy and water quality contexts, complemented by further expert knowledge provided in panel discussions. Key messages from the talks and the panel discussions are summarized below.

1.1. Soil test P methods and needs in the Prairies (summarized from a talk by Dr. Jeff Schoenau, University of Saskatchewan)

Soil sampling in the field, as the first step for laboratory tests.

Soil test P is used agronomically for assessing plant available P as basis for fertilizer or manure rate recommendations, and environmentally for assessing mobile P as the basis for risk assessment and nutrient application rate adjustment for minimizing environmental P loss. Analytically, two main approaches are used for determining STP in the Prairies: aqueous extraction and ion exchange resin. While extraction methods such as sodium bicarbonate (Olsen) and modified Kelowna give a concentration of available P in the soil (ppm or lbs per acre), the ion exchange resin method (e.g., the Plant Root Simulator™ probe used on the Prairies) gives a supply rate of available P (amount absorbed per unit area per unit time). Many soil test extractions are geographically limited, to be suitable for certain soil types and chemistry. For example, the Olsen method works best on neutral-calcareous soils and the Bray extractable P method on acid soils. Therefore, the STP methods used by a commercial testing lab should be appropriate for the soils in the geographic region. In the Prairies, overall, good analytical tools are available to assess soil P availability and mobility. Currently, however, P fertilizer and manure application recommendations are largely based on the agronomic and economic aspects of P management, with few environmental considerations in different provinces.

1.2. Trends in P management and soil test P in the Prairies (summarized from a talk by Dr. Tom Bruulsema, Plant Nutrition Canada)



4R Nutrient Stewardship.
plantnutrition.ca/research/

Prairie crop producers use P fertilizer efficiently when we consider overall nutrient balances. At the regional scale, P removal by harvested crops has frequently exceeded P inputs as the sum of synthetic fertilizers and recoverable manures over the past half a century. Gross P removal almost tripled as a result of increasing crop yields and production. In contrast to the USA and Europe, a large-scale (regional) P balance indicated no history of cumulative P surplus in the Canadian prairie cropland. However, it should be noted that a balance over a broad area tends to lump together areas of surplus and deficit (and those local surpluses and deficits can be large). Currently, about 50% of the spring wheat and canola acreage receive < 30 and < 35 lbs of P_2O_5 per acre, respectively. Many producers have adopted good P management practices such as sub-surface placement, which accounts for approximately 95% of the P applied to spring wheat and canola. The adoption of 4R practices is helping to avoid depletion of soil fertility and slowly building up soil fertility. Between 2001 and 2020, the frequency of soils tested with low STP values decreased from 80% to 60%. However, it should be noted that the frequency of soils tested with high STP values meanwhile increased from 5% to 10%, which may be an indication of an increasing extent of soil P hotspots. 4R nutrient stewardship remains a key strategy for sustainable agricultural production, and it should continue to be promoted, adopted and recognized. There is a need to integrate P management with full 4R nutrient stewardship. Phosphorus management should be sustainability-driven and data-driven.

1.3. Soil test P and P management for crop production (summarized from a talk by Dr. Don Flaten, retired professor from University of Manitoba)

Although crop yield responses at different levels of STP are usually portrayed as curves, the response varies with weather conditions, cropping system and crop species/variety/hybrid, and even from year to year for the same crop and soil. Old Manitoba studies in 1950s-1960s only demonstrated significant curvilinear relationships between P responses of crop yield and Olsen-P in greenhouse tests but not in field trials. It is more appropriate to view the response as probabilities. In all three prairie provinces, crop yield response to fertilizer P declines to less than 50% at approximately 10-20 ppm Olsen P. Although soil P testing cannot predict short-term P response precisely, regular testing can help to better manage P rates.

Phosphorus application rates can be managed for short-term sufficiency or long-term sustainability (Grant and Flaten, 2019). In the strategy of short-term sufficiency, the P application rate is chosen based on economic yield response in the year of application and is usually less than crop P removal. This strategy often depletes long-term P fertility, especially for seed-row placed P rates, leading to decreasing crop yield potential over the longer-term. In contrast, the strategy of long-term sustainability targets P applications to reach and maintain an optimum STP range, by building up STP on low-P soils and depleting STP on high-P soils. Balancing rates of P application with crop P removal is essential for long term sustainable crop production. Crop yield has substantially increased in the last several decades. For example, average yield of spring wheat in Manitoba has more than doubled since 1970. The increase in crop yield means more P is removed and more P needs to be applied. Indeed, supplemental P has been demonstrated to increase crop yield in many field trials.

Soil P needs to be replaced to maintain healthy crop growth (Photo: U. Manitoba).

Phosphorus source, placement and timing management are also important. In the Prairies, the vast majority of fertilizer P is banded under the soil surface, in or near the seed-row, at planting, which is both agronomically and environmentally beneficial, as it helps to supply P to crops when cold soils restrict soil P release and root growth and also reduces the risk of P loss in spring runoff. Similarly, manure should be injected or incorporated into soil, wherever possible, especially if it is applied in fall. Manure or fertilizer broadcast on frozen soil or snow is risky for nutrient losses in spring snowmelt, leads to poor uptake by crops and pollution of water, and should be prohibited or avoided.

1.4. Soil P and P in runoff (summarized from a talk by Dr. Henry Wilson, Agriculture and Agri-Food Canada)

In the Prairies, roughly 80% of agricultural runoff P loss occurs during snowmelt and 80% of the P in runoff is in the dissolved form, as a result of combined climate, landform and soil characteristics. Therefore, many conservation practices that are developed for erosion control in warm regions, such as conservation tillage, cover crops and riparian buffer strips, have lower efficacy or are only seasonally effective in reducing annual total P losses. In addition, these practices have the potential to increase dissolved P losses in snowmelt due to P stratification in surface soils or release of P from vegetation after freeze-thaw cycles. In water bodies, P concentration and load have somewhat different ecological relevance. While concentration is important for the productivity of aquatic systems with shorter residence times such as rivers, small lakes and reservoirs, load is more important for systems with longer residence times such as Lake Winnipeg.

Snowmelt dominates annual nutrient losses from cropland in the Prairies.

Both laboratory and field experiments have shown increasing dissolved P concentrations in snowmelt and rainfall runoff with increasing STP concentrations such as Olsen-P and modified Kelowna P. However, field studies indicated that runoff concentrations at sites with STP levels within recommended ranges for soil fertility can be quite variable from year-to-year and from site-to-site. To understand the reasons for this variation, edge-of-field studies in Manitoba have been completed across a range of STP from low to high levels, with a range of inputs and tillage practices, and over multiple years of monitoring. The results of this research clearly showed that variation in total dissolved P concentrations in snowmelt runoff can be predicted based on STP concentrations (0-5 cm depth; 0-2 inches), and that year-to-year variation in that predictive relationship is mostly the result of how much runoff occurs, with lower runoff P concentrations on average (dilution) in years when a large volume of runoff occurs and higher concentrations in dry years (Wilson et al., 2019). It is important to note that runoff P concentrations were more poorly predicted by STP at the depth used for fertility recommendations (0-15 cm). This is a result of elevated soil P near the soil surface at sites without tillage and with almost all placement of fertilizer occurring within the 0-5 cm depth. These factors controlling runoff concentrations are linked primarily to the amount of P that is present near the soil surface and that might leach into runoff, defining the potential for a runoff event to result in the loss of a larger P load from the field. Variation in P load was mostly explained by water yield, which is in-turn mainly a function of precipitation and snowpack size, indicating that climatic factors, rather than P management control most of the year-to-year variation in how much P leaves a field. That said, STP remains a strong predictor of variation in P load when controlling for water yield and that can be more easily modified on-farm with fertility management as compared to quantity of runoff, given that in most years any practices that might reduce snow retention and soil moisture on cropland could result in lack of water availability for the following crop.

In a recent synthesis of edge-of-field P runoff across about 150 site-years in Manitoba, the relationship between STP and potential for P runoff loss was examined for both snowmelt and rainfall events. This study controlled for inter-annual climatic variability by averaging several years with a range of runoff volumes for each field and showed a strong linear correlation between flow-weighted mean concentrations of total dissolved P and STP for a range of 0-45 mg Olsen-P kg^{-1} in the surface soil layer (0-5 cm depth) (Liu et al., 2021). These relationships between STP and average runoff P concentrations have important management implications, because STP in approximately 90% of the prairie soils falls in this range. Field studies demonstrated that depleting Olsen-P (0-5 cm) from 30-35 mg kg^{-1} to 15-20 mg kg^{-1} significantly reduced runoff P concentrations without impacting crop yield (Liu et al., 2019). It should be noted that, however, in drier years the flow-weighted mean concentrations of total dissolved P in both snowmelt and rainfall runoff at a low STP of 10 mg kg^{-1} can still be higher than the concentration threshold of 0.035 mg total P L^{-1} that defines eutrophic conditions in Canadian lakes and rivers, again highlighting the challenge of reducing total P concentrations in crop fields. Moreover, runoff P concentrations correlate better with STP in 0-5 cm soil than with that in 0-15 cm, which suggests the need to consider environmental soil sampling of the surface soil layer and whether the stratification of P in many fields might also have an impact on interpretation of STP for agronomic decisions. Given the importance of STP, new management strategies to maintain high yield with low and moderate P fertility are likely needed to meet water quality objectives. In addition, open questions remain as to the relative importance of loss of P from vegetation to snowmelt and impact of vegetation management on patterns of STP stratification.

1.5. Availability and accessibility of P recommendation information (summarized from a talk by Lukas Smith, formerly with University of Saskatchewan)

A web scan was conducted in 2021 to review the availability and accessibility of recommendation-related information for agronomic and environmental P management from governmental/ university/industrial sources. The search showed that provincial governments were the most accessible web-based source of agronomic and environmental P recommendations, but the recommendations available on government web sites were not always based on recent data. While agronomic and environmental P recommendations are both covered by Alberta and Manitoba governments, environmental concerns were barely mentioned in Saskatchewan.

Industry is another major source of P recommendations for producers and indeed producers are most reliant on industry recommendations in their decision making. However, the information provided to producers is generally less accessible than provincial recommendations. In the Prairies, about half of producers use soil testing to decide fertilizer rates and half use their past experience instead (some producers use multiple approaches in their decision). Many private labs and consulting firms offer soil testing and fertilizer recommendation services. Crop consultants help producers develop crop nutrition plans using soil test, tissue test, remote-sensed imagery and models. Fertilizer recommendations tools have evolved from sheet of paper to decision support software over time.

While industry would have the greatest influence on agronomic and environmental P fertilizer recommendations, environmental aspects of P are seldom mentioned on websites, which suggests the need to increase the awareness of environmental P management within industry.

1.6. Industry and extension perspectives

An industry and extension panel consisting of Lyle Cowell (Nutrien), Sharon Reedyk (ECCC), Jason Voogt (Field 2 Field Agronomy), Tom Bruulsema (Plant Nutrition Canada) and John Heard (Manitoba Agriculture and Resource Development) presented their views on gaps and opportunities to improve P management on the Prairies. The need to improve prediction of crop response to fertilizer and to understand the level of STP that impacts runoff into surface waters was a common theme. There was some surprise and concern that even within an agronomic maintenance range, STP levels were still high enough to adversely impact P in runoff. Key messages heard from the panel discussion:

- There is a need for prairie solutions that go beyond blanket rate recommendations. Solutions need to incorporate other management practices.
- Targeting was another focus of discussion, the need to create achievable water quality targets to work towards. Also highlighted was the need to target P management solutions to the right places, within watersheds and within fields.
- Soil testing by in-field zone was seen as an improvement over field composites giving more efficient fertilizer applications. There is the potential to extend zone-based management to account

for variation in P risk associated with areas of high or low connectivity to watercourses and landforms.

- The relationship between the crop consultant and the producer was described and emphasized. Industry's role is supporting what the producer is trying to achieve while developing a site and crop specific fertilizer plan.
- The Manitoba winter manure and fertilizer application regulations were presented as an example of successful regulation where water quality was being protected. Notable is the flexibility to modify the prohibition dates depending on weather conditions of a given year.

Overall there was consensus that the soil test P dilemma was an old problem that would not be easily solved. Some progress has been made but many of the knowledge gaps identified 20-30 years ago had yet to be filled.

2. Pathways for simultaneously achieving agronomic and water quality goals

A key goal of the workshop was to discuss options for improving P management to benefit both water quality and crop production in the Prairies. Therefore, all workshop participants were engaged in breakout groups to discuss the pathways for P management to achieve agronomic and water quality goals in the Prairies. The discussions were complemented with an additional written survey. Key information from the discussions and the survey is synthesized below.

Most of the workshop participants were optimistic that agronomic and water quality goals could be achieved simultaneously. Improved P use efficiency means reduced P loss. Based on the discussion during the workshop, progress towards agronomic and water quality goals is achievable through the pathways summarized below. They are reported with respect to the context, opportunities, challenges and needs.

2.1. Better message the soil P management challenges in the Prairies

Prairie agriculture is facing dual challenges with **P deficiency** in many soils that reduces yield potential, and **P surplus** and/or stratification in soils that elevates environmental P loss and contributes to eutrophication in downstream water bodies. The agronomic P deficiency challenge exists in that most producers apply P based on seed safe rates that can be applied in the seed-row. Economics and soil test P may come into play as well but typically, these rates are less than crop removal, which leads to mining of the soil. The challenge will increase with increasing crop P removal associated with high-yielding crops.

The environmental water quality challenge is largely due to the sensitivity of lakes to nutrients, and the large watersheds and shallow lakes of the Prairies are particularly prone to blooms, associated with elevated nutrients. These issues will increase as a result of climate change, agricultural intensification, and adoption of reduced tillage.

To work towards improving soil P management, these agronomic and water quality challenges need to be better understood by agronomists, water quality specialists and the agriculture community alike, to help find joint solutions. Communications on these issues are important, but sensitive.

2.2. Better frame and understand crop production and water quality goals and trade-offs

If the goal of crop production is only to optimize crop yield, water quality targets will be difficult to meet. Target yields tend to promote maximum crop yield objectives achievable under optimal conditions. Unrealistic target yields can promote excessive nutrient application. Previous research in the Prairies has found infrequent wheat yield response to P fertilizers in some high STP soils. However, high STP and P application rates would increase the risk of P loss and might not be

WHEN MESSAGING, WE SHOULD BE AWARE THAT

- Areas of the Prairies have shown declining soil P, which may be a risk to crop yields.
- Most producers act as stewards of their land and care about the environment, as well as maintaining and growing food production capacity. Highlighting the complexity of P management is important, but no messages should be heard as blame.
- Although agriculture is not the only source of P in surface waters, we must acknowledge our contribution and improve our management trusting that other contributors will do the same.
- Phosphorus loss from land usually occurs at agronomically small amounts (e.g., < 1 lb/ac) but we can have a big water quality impact in downstream water bodies that is hard to remedy.
- It should be clarified that although P is regarded immobile from an agronomic perspective, environmentally significant amounts of P are mobile. Agronomically small but environmentally significant amounts of P can indeed move with water on the soil surface and within the soil profile, and be transported by runoff to downstream water bodies. In the Prairies, dissolved P is frequently observed as the major form of P in snowmelt and rainfall runoff.
- Opportunities should be sought to reduce P inputs and fertilizer costs while increasing crop yield, thus benefiting both producers and the environment. This needs to integrate input (rate) management with nutrient source, placement and timing management under the guidance of the 4R nutrient stewardship, as well as with soil and water management, to achieve both production and water quality objectives.

economically favorable for producers. Further, benefits may be attained only rarely when moisture conditions are near-ideal. We need to acknowledge the trade-off between benefits of increased yields with increased STP and costs of elevated nutrients in runoff. And we need to better identify and navigate options to balance goals for crop production and water quality.

We also need to better understand achievable water quality targets. Concentration of P in agricultural runoff is frequently higher than the in-stream and in-lake P concentration threshold that can trigger eutrophication. In some regions, proposed targets for reducing agricultural P loss are seen as unattainable by some. To achieve both crop production and water quality goals, short and long-term water quality targets may be needed. This could help to ensure targets are seen as achievable and enhance the incentive to pursue practices to minimize nutrient losses from agriculture and other sectors. Farm economics and environmental costs to society should be considered.

SOME EXISTING CHALLENGES FOR ADDRESSING WATER QUALITY GOALS

Many prairie ponds and lakes already have algal bloom problems and pose a risk to water use for drinking, wildlife habitat or recreation. Water quality issues are harder to resolve than they are to prevent.

Phosphorus concentrations and loads in runoff are influenced by weather, which is unmanageable and could affect the meeting of water quality targets if they are not developed to account for variability in flow.

Other nutrient sources, such as urban, industry, natural areas, and livestock coexist with managed cropping systems. Efforts should not be seen as targeting crop producers, but as strategic actions based on understanding of all sources and mitigation options.

2.3. Better understand soil P deficiency and surplus, and the responses of crop yield and water quality to P management

As discussed above, prairie farmers face dual challenges of managing P deficiency in most soils and P surplus in other soils. Soil P hotspots are critical source areas where high STP overlaps with active transport pathways, and constitute a large source of potential P loss. The risk of P loss increases in highly connected areas. Research is needed to better identify critical source areas P hotspots.

Identification of a STP range for optimum crop production based on yield-fertility response is very important for both agronomic and environmental P management. In the Prairies, however, research on the yield-fertility response has been very limited for decades. This is largely due to the lack of funding in this area. Most of today's yield response recommendations were developed 30 or more years ago, and the recommended STP maintenance range has not been updated since then. It is unlikely that those response data and the maintenance range would still hold true for today's new crop varieties/hybrids and tillage practices.

There is a need to re-visit the soil test calibration and correlation work done in the 1990s and update the database, with considerations of new crops and management practices, and consider new approaches to relating soil tests to management recommendations. For water quality, although the overall trend of increasing runoff P concentrations with increasing STP has been documented, there is still a need to further clarify the relationship for different soils, climates and cropping systems. There is also a need to look at beneficial management practices (BMPs) to mitigate the effects of this relationship.

A few key questions:

Soil P management: When is soil P truly deficient for crop yield? How does the soil P pool including the P in crop residues cycle, and how do these pools and their cycling impact crop P uptake and P loss? *Changing practices and their impacts:* How have crop nutrient requirements, P uptake and response changed with different and newer crops, varieties and tillage practices? What are the mechanisms impacting the response? How are crop and soil biology interacting with soil P?

Research and management needs:

Managing agronomic P needs

- Quantify probabilities of yield response to fertilizer to reflect changes in farming technology and crop nutrient demand, placement methods, and fertilizer products. Update databases on P vs crop yield for new varieties of existing crops as well as crops that were not previously grown in the region that are becoming more common. Ensure research covers a range of crops and cropping systems, for both fertilizer and manure P.
- Perform fertility experiments with both 0-5 and 0-15 cm (or 0-30 cm as done in some laboratories) soil test P considered, on differing soils. Use modern cultivars and low-tillage production with banding to define what the appropriate maintenance range is.

KEY AREAS WE NEED TO BUILD BETTER UNDERSTANDING

Adequacy and deficiency: What is an 'adequate' level (or appropriate maintenance range) of STP for current production systems, in terms of trade-offs between production and potential for runoff loss? What are the crop- and site-specific soil test P critical levels?

Environment: What level of soil and runoff P create eutrophication stressors, and how can we define what this level is, or what these levels are across diverse lakes and catchments? Is there a common STP – water quality relationship in the Prairies?

Bridging agronomic and environmental goals: What is the yield potential at high, medium, and low soil test P? Can we reduce P applications to those soils without impacting crop yield? And where are the P hotspots located?

- In addition to field trials, use mechanistic and predictive models to inform crop nutrient use and removal and quantify probabilities of yield response to fertilizer for new crops and varieties in a range of field conditions. Develop models of producer benefits to P addition and probability response curves.
- Use a long-term sustainability approach of fertilizing to approach a target response range (for example 50% response or 10-20 ppm STP) and apply removal rates over the course of the crop rotation.

Managing high P and environmental risks

- Promote soil testing at both 0-5 cm and 0-15 cm (and, possibly, 0-30 cm) to identify hotspots and couple this to research to determine the viability and economics of drawing down concentrations in hotspot areas.
- Set upper STP and P rate thresholds for recommendations in Saskatchewan and Alberta where such thresholds do not exist, and refine the existing thresholds in Manitoba based on improved understanding of yield response under modern farming conditions and potential reductions in P loss by lowering STP.
- Assess the risk of P loss from agricultural fields by considering both soil test P and transport pathways, and place the risk in the context of hydrological connectivity and P loss from other sources within the watershed. This would require the use of a P loss assessment tool.

Understanding the balance, and tradeoffs between agronomic and environmental needs and risks

- Perform economic analysis of costs associated with declining water quality and benefits for increased crop yield with P additions.
- Rebuild P-depleted fields or management zones within fields in the very low and low STP levels into more agronomically productive ranges, and draw down P in fields with very high STP.
- Recognize that many of the fields with very high STP result predominantly from manure and the STP will continue to increase unless manure is transported to P-deficient fields, highlighting the need for targeted policies or incentives to manage this issue.

2.4. Encourage soil testing and 4Rs more broadly

While many prairie farmers are routinely testing their soils, many others are not doing so. Extension programs should aim to educate more farmers to practice soil testing. Recent prairie research has shown that STP stratifies in the surface soils and that STP at the 0-5 cm depth predicts the average risk of P runoff from a field. The research shows a benefit to including 0-5 cm samples in routine soil testing from the perspective of environmental P management.

Still, there are some knowledge **gaps and management challenges related to soil P testing:**

- Are there better indicators of available P for crop production (e.g., plant tissue P)?
- Can we develop a stratification index and use it to recommend testing to determine if tillage should be recommended?
- How can we better define the implications of higher levels of P close to the soil surface where tillage has been reduced and where long-term nitrogen fertilization (that affects soil pH) may have altered soil P chemistry/solubility (Chen et al., 2021)?
- How is STP at 0-5 cm related to that at 0-15 cm (or 0-30 cm)? Can STP at 0-5 cm work to inform agronomic recommendations? If both tests are needed, who will pay for the 0-5 cm testing?

Many prairie farmers are practicing 4Rs for fertilizer and manure management. However, there are also some undesirable practices that have long existed or are re-emerging. For example, using floaters to broadcast all nutrients on cropland is becoming more common on large farms as a workload management tool. There are numerous ways to improve nutrient applications and nutrient use efficiency, and use new crop hybrids, new equipment and new fertilizer technologies to better manage nutrients and improve crop production.

Areas for added benefits associated with **4R nutrient management to achieve both agronomic and environmental goals include**:

- Ensuring that the P added to the soil is in an available form when the crop needs it, maximizing yield benefits from applied P fertilizers.

Phosphorus fertilizer is placed into the soil with the seed or in a band.

- Avoid surface application of fertilizers; place P fertilizers into the soil with the seed or in a band; Inject or incorporate manure below the soil surface; note that the recommended rate for broadcast is much higher than for seed placement or banding and broadcasting decreases nutrient use efficiency and increases nutrient runoff losses.
- Avoid winter applications of fertilizers and manures. Restrict fall-applied manure and fertilizer to injected or incorporated applications wherever possible.
- Rates of P fertilization for some high P using crops like canola may need to be adjusted upward to meet crop need.
- Manure is often the cause of P hotspots, and thus it should be better managed in terms of where, how and the rate it is applied, in combination with better monitoring of soil P levels in manured fields. Nutrient availability in manure and struvite also need to be better understood to determine the right application rate for both agronomic and environmental goals.

As the distribution of soil test P and hydrological connectivity vary between fields and within a field, the spatial variability needs to be considered in nutrient and land management. **Place-based P management is particularly important.**

Opportunities and challenges for place-based P management:

Understanding soil P variability is important for management.

- Variable rate fertilizer application technology is useful, but little research has been conducted to quantify the agronomic, environmental and economic effects of variable rate P applications. Opportunity exists for field-scale research with extensive landscape position replication to assess these effects.
- Work to identify and test critical source areas (within watersheds and fields).
- Implement more stringent P management in areas where the water and land have high connectivity.
- Consider whether some areas are of lower risk for runoff where higher concentrations of nutrients may have lesser negative impacts on the environment. These may be areas that are usually non-contributing to the regional watershed, although the water quality in local wetlands or sloughs can be influenced.
- Assess connectivity of these "non-contributing" areas during wet periods when significant build up of P can yield high export.

2.5. Work beyond 4R Nutrient Stewardship

Beyond the 4Rs for nutrient management there are opportunities to improve soil, crop, and water management practices in ways that will help achieve crop production and water quality goals. These include the management of tillage, crops and crop residues, livestock, drainage and runoff control, wetland retention, and managing stream bank stability.

Research needs:

- Investigate the environmental and agronomic effectiveness of periodic tillage to reduce stratification on conservation tillage soils while maintaining some surface residue and roughness to conserve moisture and alleviate erosion concerns (e.g., after cereal in rotation).

- Better understand P solubility, soil water saturation and runoff generation, interception by wetlands and assimilation that all affect potential for applied P to enter water bodies.
- Better understand the impacts of P in runoff at the watershed and regional scales.

Management needs:

- Maintain the soil P at adequate levels for crop production through fertilizer and/or manure applications, and minimize P losses from soils to waterways through better management of soil, crop and water to control P transport under different soil-climatic scenarios.
- Manage non-agronomic factors (e.g., wetland retention) to complement the agronomic measures.

Management practices have **trade-offs**, which should be better understood and considered in recommendations:

- Zero or conservation tillage reduces soil erosion and benefits soil carbon and moisture but can result in P stratification near the soil surface, particularly where rates of P application exceed crop uptake during a growing season. This in turn increases the risk of dissolved P loss from soil and vegetative residues. Rotational tillage every second year in fall has been found to reduce the transport of dissolved P (but increased nitrogen transport) (Liu et al., 2014). In addition, no-till fields with lower rates of fertilizer application tend to show a lesser degree of stratification.
- Livestock manure is a great source of nutrients for crops but repeated annual applications create P hotspots and increases P loss. It is difficult to prevent P accumulation in manured fields without reducing the frequency of manure application, which usually results in transporting manure farther to more P-deficient fields, but the cost for transporting manure long distances is high. Technology to extract P from manure in forms compatible with fertilizers is required to facilitate transport.
- Cover crops and crop residues can be important for soil health, but they can also become a source of P loss from land to water, especially during snowmelt.

2.6. Revisit and improve recommendations

The prairie provinces have widely used agronomic P recommendations, but environmental P recommendations are relatively weak and differ among the provinces. For example, among the three provinces only Manitoba regulates P applications on high P soils, and even so the regulations in Manitoba still allow manure application on soils that have Olsen P between 60 ppm and 180 ppm (0-15 cm) (Manitoba Environment Act, 1998). The STP threshold of 180 ppm for banning additional manure applications is too high from the water quality perspective. While Alberta conducted a study on setting STP limits in 2006, it was concluded that additional research and policy analyses were needed (at that time) before setting such limits. Generally, Saskatchewan has fewer water-quality related nutrient management guidelines and regulations than Manitoba and Alberta, as exemplified by their tolerance of winter manure applications that are banned or discouraged in the other prairie provinces.

Most of the extension information that farmers receive is from industry agronomists or independent professionals, and has a strong focus on production. In many cases, fertilizer application rates are driven by the farmers' own experiences and values with respect to willingness to spend, observation of yield benefit, environmental awareness, and operation size among others. Thus, there is a need to revisit and improve recommendations to reflect water quality goals in addition to agronomic goals.

Some considerations for improving the recommendations:

- Phosphorus recommendations should be based on STP, soil properties (e.g., pH, soil texture and salinity) and hydrology (e.g., crop water availability and runoff potential), and be made on a field by field and crop by crop basis (rather than blanket recommendations). They should also be based on a better understanding of what runoff P concentration is reasonable.
- Revision of recommendations should be based on:
    - better understanding of the mechanisms of P behavior and risks of P runoff
    - better understanding of crop P removal especially with newer crops, varieties and yield potentials.
    - more evidence supporting crop- and site-specific soil test P critical levels.
    - short-term sufficiency and long-term sustainability.
- Recommendations should better define when soil P should be drawn down (i.e., when fertilizer or manure applications should be reduced or ceased to protect water quality).
- Recommendations should be adjusted based on soil sampling strategy (location, timing and method). Be aware that the use of 0-30 cm soil samples for determining STP will result in lower STP levels than using 0-15 cm samples and it can inflate fertilizer rates when using recommendations that have been developed based on the latter soil. There is a need to clarify commercial soil sampling strategies, and reconnect commercial laboratory recommendations and provincial guidelines.

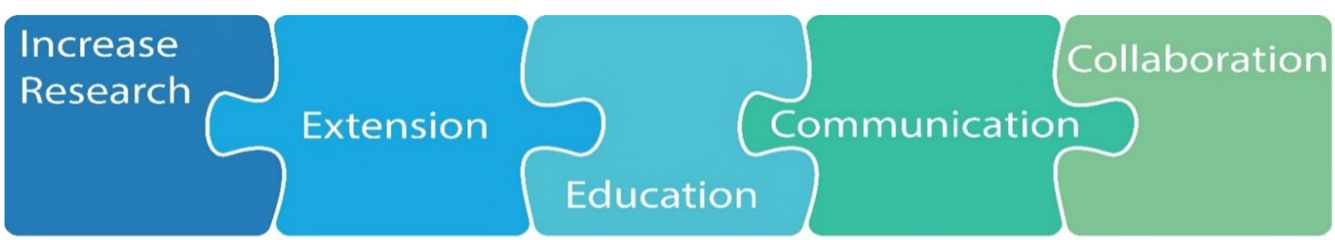
2.7. Monitor and assess BMP efficiencies

In the Prairies, water quality baseline data are generally lacking, especially on tributaries to nutrient sensitive bodies such as shallow lakes. There is also a lack of apportionment of P inputs across sources including urban sewage and runoff, and crop and livestock management in many watersheds. These knowledge gaps are limiting the capability to quantitatively evaluate the effectiveness of field- and farm-level management practices in reducing nutrient loading to rivers and lakes. Moreover, there is often little or no monitoring and assessment of the efficacy of current recommendations and regulations. It is time to consider increasing monitoring efforts to measure the effectiveness of such regulations and enhance buy-in for water quality targets by showing that improvements are achievable. Similarly, monitoring efforts are also needed for soils as closure of some soil testing facilities on the Prairies may be hindering the development of locally relevant tests and recommendations. Some examples of needed monitoring efforts include evaluating long-term impacts of soil P management on dynamics of STP and water quality, and evaluating the impacts for different levels of STP (e.g., 60 ppm vs 100 ppm).

Edge of field runoff monitoring station.

2.8. Increase research, extension, education, communication and collaboration

There is a strong need to increase research, extension, education, communication, and collaboration to achieve both crop production and water quality goals. Researchers, extension specialists, policy-makers and the industry need to seek synthesis and consensus on priorities for research, innovation, education, and regulation. There was agreement that universities and government agencies should continue research along with education of professionals; however, there are numerous ways **partnered research** can and should be strengthened.



The following points were raised:

- Agronomic research through universities and provincial governments has declined in recent decades, due to difficulty to attract funding and/or political decisions. This has led to loss of expertise in universities and government agencies, but there is a pressing need to overcome this by more financial support from the government and industry.
- Industry does not have the capacity to do systematic soil test calibration research, but commodity groups and applied research associations can potentially contribute to research through collaborations with university and government researchers.
    - There should be more clarity among farmers and agri-service providers on the meaning of critical levels for agronomic and environmental interpretations.
- Demonstration projects and success stories have multiple benefits. Producers, researchers and industry groups should collaborate to demonstrate examples of effective management of nutrients and other factors in the context of improving crop production and protecting water resources.
    - Such examples include farmers' success stories showing economics and yield outcomes, which can be relatable for other farmers.
    - Given the time lags between research, demonstration and implementation, enhancing demonstration projects and amplifying success stories is an important near-term goal.

Across the Prairies:

- Enhance interprovincial communications about agronomic and environmental aspects of agricultural P management (in several sectors, including industry, research and government).
    - An advisory group (as used for this workshop) should be established and maintained. This group can aim to enhance communications and build networks.
    - There appears to be a need for more provincial extension specialists or the development of a robust network of independent crop advisors cognizant of water quality issues.
    - Most farmers have an understandably stronger interest in economics and agronomics than in water quality. This also drives extension activities and information. There needs to be more education on how management practices influence water quality at the producer level to push to adoption of changes in practice and technology.

A few ways to increase water quality awareness within the industry and among farmers include:

- Better messaging of water quality issues (cognizant of audience, framing, focussing on pragmatic options and on broad considerations producers must include in their decisions. Note that a small agronomic P loss could have a big impact on downstream water quality).
- Ensuring that education of crop consultants (e.g., professional agrologists and CCA agronomists) and farmers includes both environmental and economic aspects of nutrient management.
- Improving the communication of peer-reviewed research from researchers to practitioners.

- More discussion and synergy between the industry and water resources.
- Creating economic benefits for environmental stewardship. (Note: Certification and incentive programs can be useful, but paperwork is an obstacle).
- Demonstrating the long-term consequences of elevated P in runoff.

Themes of multi-faceted sustainability involving agronomic, economic, environmental and social impacts can all play a role in messaging. Messaging clarity is very important but sometimes can be difficult especially when P management is considered as one of the many components for crop production and the environment. Ideally, criteria should be established for assessing pros and cons of management practices, with considerations of trade-offs such as production vs environment, and water quality vs greenhouse gas emissions. In this context, a decision support tool that brings in all considerations may be beneficial.

3. Summary

There is concern about soil P deficiency for crop production in many areas of the Prairies. Based on current agronomic recommendations, many soils on the Prairies are deficient in P. In addition, harvesting of agricultural crops results in exports of P from agricultural lands. Hence agricultural cropland requires additions of fertilizer or manure to sustain crop production. At the same time, water quality concerns due to excess P are widespread. There is a substantial, linear increase in runoff P with increases in STP, even within the typical range of STP values (0-45 mg Olsen-P kg^{-1} in the 0-5 cm soil depth). The P concentrations in runoff are often high enough to accelerate water quality problems within prairie lakes (i.e., P in runoff is typically above eutrophication thresholds). Some prairie soils have excessive P accumulations that need to be reduced to improve water quality. Innovative solutions are needed to address this challenging dilemma and manage P for agronomic and environmental benefits. The workshop suggests that to achieve the agronomic and environmental goals, we need to: (1) better message the soil P management challenges; (2) better frame and understand crop production and water quality goals and trade-offs; (3) better understand P deficiency and surplus in the soils, and the responses of crop yield and water quality to P management; (4) encourage soil testing and 4Rs more broadly; (5) work beyond 4R nutrient management to include soil, crop, and water management; (6) revisit and improve recommendations; (7) monitor and assess BMP efficiencies; and (8) increase research, extension, education, communication and collaboration.

Some outstanding knowledge gaps and/or research and extension needs include:

- Many aspects of crop response to soil and fertilizer or manure P are difficult to generalize due to variable soils and changing weather conditions, cropping systems, and crop species and varieties or hybrids. The level of soil P fertility required to maintain crop production needs to be revisited with consideration of changes in prairie agriculture, and environmental considerations.
- High concentrations of P in runoff have led to significant water quality problems across much of the Prairies. Solutions for water quality problems will vary from one place and time to another. While our conversations focused on levels of soil P, there was a recognition that managing soil P alone, is likely inadequate to meet water quality goals. Broader concepts of 4R nutrient stewardship of P are important, as are soil and water conservation practices. As well, non-agricultural nutrient sources, such as urban, industrial, and natural sources coexist in most prairie catchments. Efforts to manage P losses should not be seen as targeting agriculture, but should be based on strategic action based on understanding all sources and mitigation options.
- We need place-based and time-based BMP targeting at multiple scales. This means considering which watersheds, which fields, and which landscape positions are best for different practices. Functionally, we need the right BMP in the right place in the right watershed at the right time –

which requires considerable local insight in terms of agronomic needs and water quality concerns, as well as BMP benefits and trade-offs.

- Work to identify P hotspots, identify critical time periods, and target BMPs holds major promise to maximize the efficiency and effectiveness of those BMPs.
- Technologies, like variable rate nutrient applications, also hold major promise to advance both agronomic and environmental goals.
- The good news is that decreasing soil test P in high P prairie soils can lead to water quality benefits by reducing P in runoff within the period of a few years. Indeed, we see that there is less 'legacy P' in prairie soils than in other regions, suggesting we can more rapidly attain water quality improvements. However, some time lags between management changes and runoff response are still likely due to legacy P. Managing soil P is an important part of any nutrient, soil, crop, and water management toolbox for water quality solutions.
- Managing soil P requires balancing agronomic and environmental goals, and strategic thinking, such as considering managing zones with high connectivity to the water differently.
- To better manage soil P in the Canadian Prairies we need to better understand key agronomic thresholds for P given: new crops, common observations of increased P stratification in soils, and often very old data (based on a narrow range of traditional crops, excluding higher-yielding new varieties or hybrids and grown on less stratified/more intensely cultivated soils). Continued consideration of how variable moisture conditions will affect yield benefits of different P management approaches remains important. There may also be potential to manipulate our cropping systems in the future to use P more efficiently and address the rate dilemma.
- Industry, via crop input suppliers, certified crop advisors and agronomists, are the primary advisors for producers on P management. This means we need to more effectively network across government, industry, and academia to ensure we all understand the diverse needs, and effects of changing P management.
- Producers want to engage in solving environmental problems, which means building close networks of scientists, producers and advisors who can discuss workable solutions from farms to lakes. We need continuing conversations with industry and a sustained network for exchanging information.
- There is the need to increase awareness of environmental P management in making P recommendations, and in extension work more broadly, by being aware that a small agronomic P loss could have a big impact on downstream water quality.

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