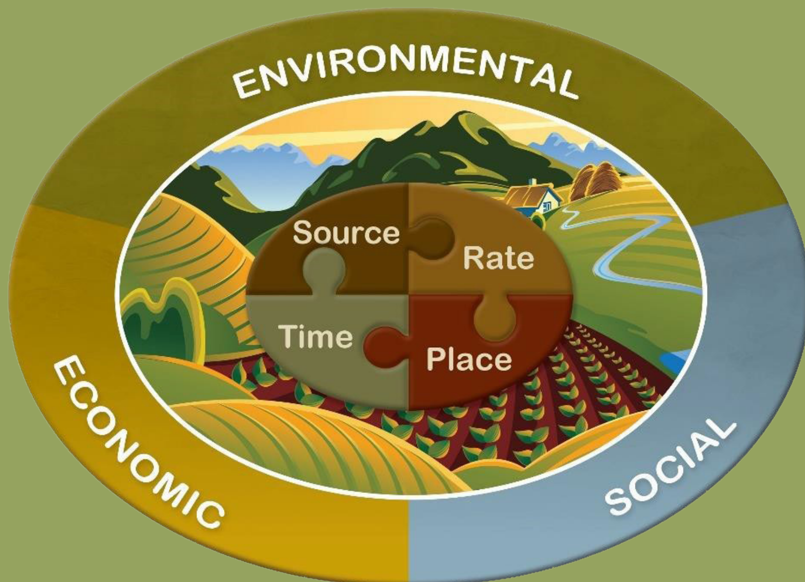
4R Management of Phosphorus Fertilizer in the Northern Great Plains: A Review of the Scientific Literature

Summary



July 3, 2019

Cynthia Grant and Don Flaten University of Manitoba

A project funded by:
Fertilizer Canada with the support of the North American 4R Research Fund

Front Cover Figure: The 4R nutrient stewardship concept defines the right source, rate, time, and place® for plant nutrient application as those producing the economic, social, and environmental outcomes desired by all stakeholders to the soil-plant ecosystem **(http://www.ipni.net/ipniweb/portal/4r.nsf/article/communicationsguide)**

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The overall purpose of this review is to assemble and summarize the existing science base for 4R management of P fertilizer ("right" source, "right" rate, "right" time and "right" place for fertilizer application) for crop production in the Northern Great Plains region of North America. In addition, this review identifies key gaps in knowledge and priorities for future research on this topic.

However, it's important to note that this review does not address management of livestock manures, composts, biochars, or other amendments that are not generally regarded as conventional fertilizers, even though these amendments may play important roles in management of P fertility in soil and P nutrition in crops. Furthermore, this review does not address soil and water management beneficial management practices, which complement nutrient management practices for maintaining soil and water quality.

In the full version of the review, each chapter provides five perspectives on the chapter's topic, including:

- a list of key messages
- a short, approximately 2 page overall summary of the chapter
- detailed information for the review
- a list of knowledge gaps
- a list of references for readers that want further information.

However, this summary version of the review does not include the detailed information and list of references.

Many of the aspects of P behaviour and management are highly interrelated and may be repeated within and between chapters, where those aspects are important to the understanding of the issue. This redundancy is intentional and it is included to provide readers who access only specific sections of the publication with the background material needed.

Input was provided from a wide range of contributors and the final product has been reviewed for content and accuracy by a technical review panel (see Acknowledgements), whose contributions are greatly appreciated.

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Introduction

Key Messages

- The cold soils at planting and short growing season of the Northern Great Plains affect P dynamics and 4R nutrient stewardship
- Changes in management practices such as widespread adoption of reduced tillage systems, introduction of new crops and high-yielding cultivars, intensification and extension of crop rotations and development of new fertilizer products affect P management
- The main purpose of this review is to provide a strong science base to ensure that “4R” management of P fertilizer (i.e., “right” source, “right” rate, “right” time and “right” place for fertilizer application) is agronomically, economically and environmentally sustainable

The Northern Great Plains includes the arable portions of the Canadian provinces of Manitoba, Saskatchewan, Alberta and northeastern British Columbia as well as the agricultural regions of South Dakota, North Dakota, and Montana; plus parts of northeastern Wyoming and northwestern Nebraska (Figure 1) (Barker and Whitman 1988; Padbury et al. 2002). According to Padbury et al. (2002), the northern boundary of this region is the northern limit for agriculture in North America, although the rich agricultural region of the Peace River district in northern British Columbia and Alberta technically lies outside of the Northern Great Plains. The climate of the northern Great Plains is continental, with long, cold winters and short, warm summers; insufficient moisture is often a major limiting factor for crop yield.

Over the past several decades there have been substantial changes in farming practices on the Northern Great Plains, including widespread adoption of reduced tillage systems, introduction of new crops and high-yielding cultivars, intensification and extension of crop rotations, development of new fertilizer products, increased appreciation of the role of microbial interactions in phosphorus dynamics, and growing concerns about climate change and the effects of P on water quality (Grant and Flaten 2019). As cropping systems, technology and societal demands evolve over time, nutrient management practices must also evolve to address concerns and take advantage of emerging opportunities.

In dryland farming systems on the Northern Great Plains, economically and environmentally sustainable agronomic management of phosphorus requires science-based application of “4R” nutrient stewardship principles (i.e., “right” source, “right” rate, “right” time and “right” place for fertilizer or manure application (Bruulsema 2017; Bruulsema et al. 2009; Flis 2018)). One of the challenges associated with the “4R” nutrient stewardship program is to ensure that farmers and agronomists have the “right” science-based information to make good decisions about their nutrient management practices. The last comprehensive literature review of P fertilizer management in the Prairies was published by the Canadian Society of Soil Science in 1993, as part of the “Impact of Macronutrients on the Crop Responses and Environmental Sustainability on the Canadian Prairies” … also known as “The Red Book” (Rennie et al. 1993). The Red Book has been a valuable source of scientific information on macronutrients for students, scientists and agronomists. Unfortunately, the P review in that book has historically been available only in hard copy and it does not include the substantial quantity of additional P fertility research that has been conducted over the last 25 years. The lack of inclusion of recent research is of a serious limitation because of the great changes in agronomic practices in western Canada over the last three decades.

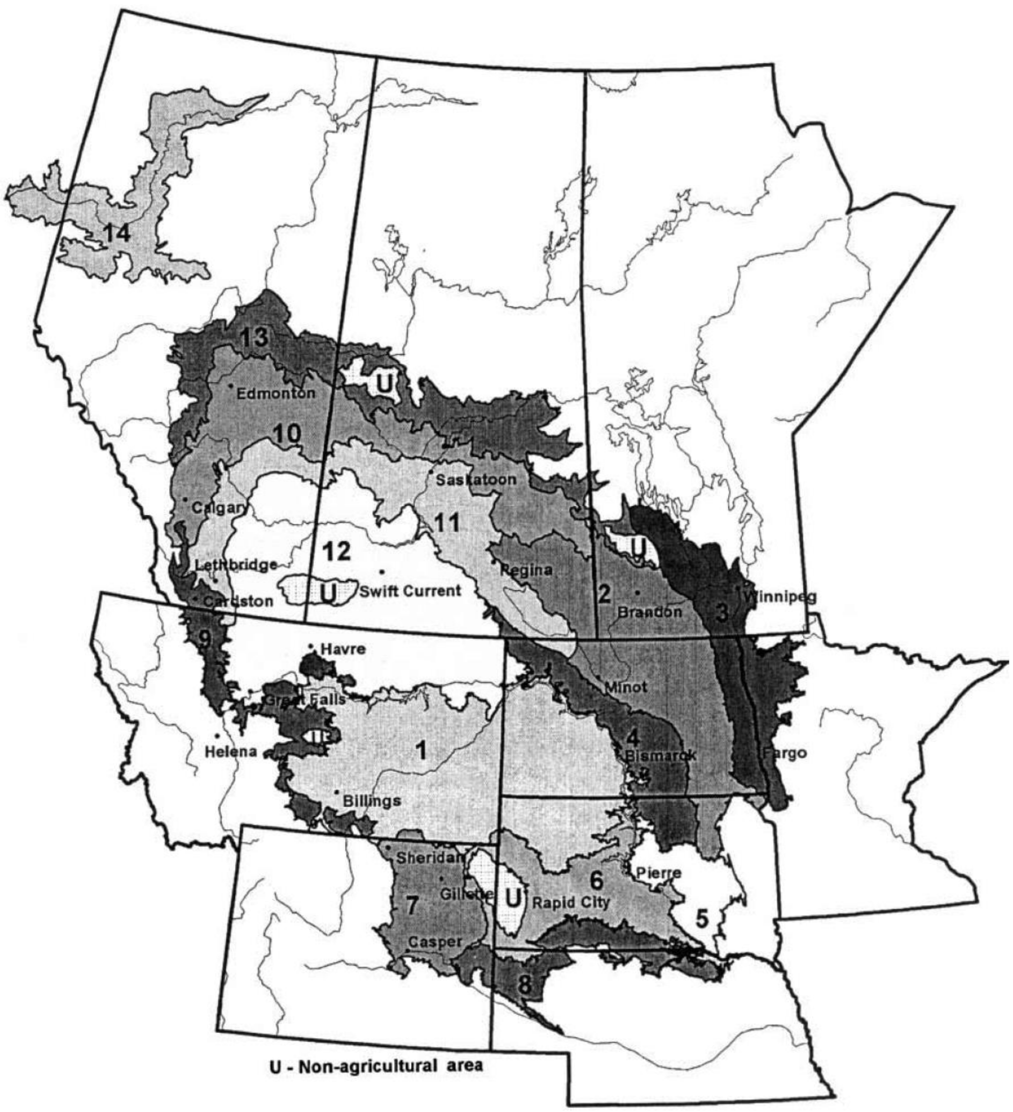

Figure 1. Agroecoregion of the Northern Great Plains (Padbury, G., Waltman, S., Caprio, J., Coen, G., McGinn, S., Mortensen, D., Nielsen, G. and Sinclair, R. 2002. Agroecosystems and land resources of the Northern Great Plains. Agronomy Journal 94:251-261.)

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Abbreviations

4R	applying the <u>right</u> nutrient source at the <u>right</u> rate, <u>right</u> time and in the <u>right</u> place
ADP	adenosine diphosphate
APP	ammonium polyphosphate liquid fertilizer (e.g., 10-34-0)
ATP	adenosine triphosphate
BMP	beneficial management practice
Cd	cadmium
DNA	deoxyribonucleic acid
DAP	diammonium phosphate granular fertilizer (e.g., 18-46-0)
MAP	monoammonium phosphate granular fertilizer (e.g., 11-52-0)
NADP	nicotinamide adenine dinucleotide phosphate
NADPH	reduced form of nicotinamide adenine dinucleotide phosphate
P	phosphorus
P_i	inorganic phosphorus
RNA	ribonucleic acid
SBU	seedbed utilization
SSP	single or "ordinary" superphosphate granular fertilizer (e.g., 0-20-0-10S)
TSP	triple super phosphate granular fertilizer (e.g., 0-45-0)

1.0 Background of 4R Nutrient Stewardship

Key Messages

- 4R nutrient stewardship aims to use the right nutrient source, rate, time and placement to optimize agronomic crop yield and quality, economics of production, environmental sustainability and social good on a site-specific basis.
- While multiple stakeholders with differing concerns may be affected by nutrient management, the farmer plays the key role in how nutrients are managed
- 4R nutrient management is a science-based, flexible and adaptive approach that will continue to evolve over time as new products, practices and information become available.

Summary

The 4R nutrient stewardship framework means applying the right nutrient source or product at the right rate, right time and right place to optimize agronomic crop yield and quality, economics of production, environmental sustainability and social good on a site-specific basis (Figure 1). Within the 4R framework, fertilizer beneficial management practices (BMPs) should be developed for each location considering all three of these areas of sustainable development.

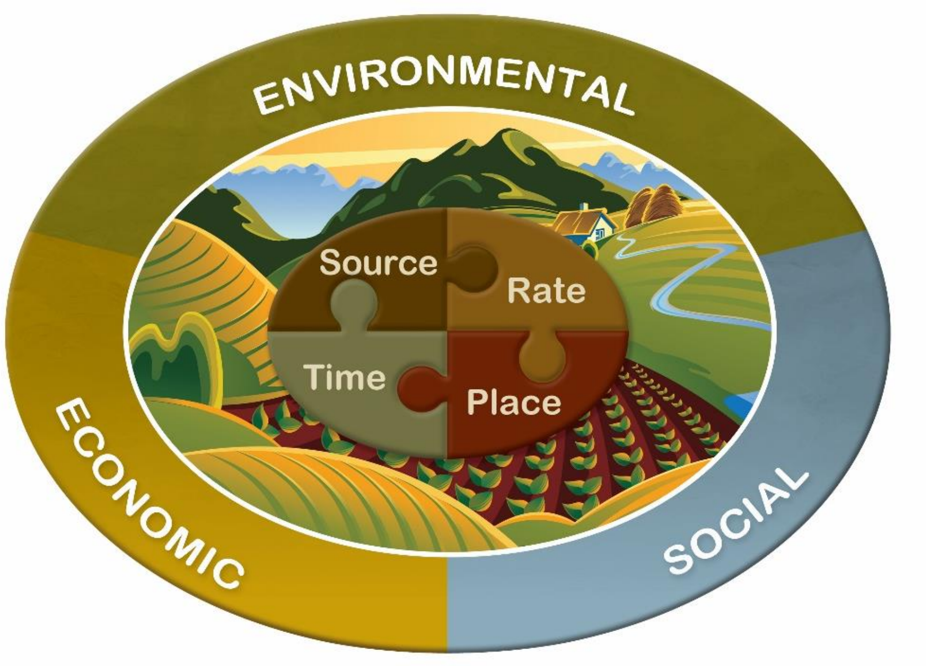

Figure 2. The 4R nutrient stewardship concept defines the right source, rate, time, and place for plant nutrient application as those producing the economic, social, and environmental outcomes desired by all stakeholders to the soil-plant ecosystem. Figure credit: http://www.ipni.net/ipniweb/portal/4r.nsf/article/communicationsguide)

The framework recognizes that there are multiple stakeholders affected by nutrient management practices and that they will frequently have differing concerns. Farmers may focus on the agronomic and economic aspects of production, as well as stewardship of their land. The public may be more concerned with safe, nutritious and affordable food, clean air and water, and habitat preservation. Policy makers may focus on food security and addressing the evolving needs of both current and future generations. Balancing the varying concerns of the different stakeholders is a major challenge and the "right" choices will depend on the environmental, economic and societal conditions of each situation. The desires of the various stakeholders are considered within the management goals of crop productivity, economic profitability, cropping system durability, and environmental health. However, ultimately, the farmer as the manager of the land has direct control on how nutrients are managed to meet these goals.

Gaps in Knowledge

More information is needed on:

- comprehensive evaluation of 4R nutrient stewardship practices as packages, rather than individual practices. A greater emphasis on integration of 4R nutrient stewardship practices would be valuable, as well as more effort to integrate the environmental and production aspects of P management.
- how P management influences nutritional quality of food, especially as related to trace element concentration and bioavailabilty for human nutrition and health.

2.0 Role of P in Crop Production

Key Messages

- Phosphorus is required for energy transfers, photosynthesis, and cell division; it plays a critical role in all stages of crop growth
- Phosphorus is taken up from the soil solution as orthophosphate through an active uptake system in the plant root cell membrane
- The ability of the plant to absorb P from the soil will depend on the concentration of P ions in the soil solution at the root surface, the area of absorbing surface in contact with the solution and the rate of P ion movement through the soil to the root surface
- Plant-available soil P over the season will be affected by the concentration of P in the soil solution and the ability of the soil to replenish the soil solution from other organic and inorganic soil P pools
- Plants' mechanisms to improve their ability to access P when deficiencies occur include increased root growth, secretion of compounds to mobilize P in the solution and formation of associations with mycorrhizal fungi to increase soil exploration for P
- Phosphorus deficiency symptoms are often subtle, but plants may develop dark green or purple coloration of leaves and stems, and be shorter with delayed leaf emergence, slower develoment, reduced tillering, lower dry matter yield and reduced seed production.

Summary

Phosphorus is an essential plant nutrient and, after nitrogen, is the nutrient most frequently limiting to crop production in the Northern Great Plains. Phosphorus is required for photosynthesis as a component of ATP, ADP, NADP and NADPH, the molecules that capture the energy harvested from sunlight in the chloroplasts. The chemical energy stored in these phosphate-based molecules is used to convert CO_2 and water to carbohydrates and to drive other energy-requiring reactions of plant metabolism. Phosphorus is also a structural component of the nucleic acids of DNA, RNA, genes and chromosomes and of many coenzymes, phosphoproteins and phospholipids. Phosphate compounds are also intermediate products in a wide range of metabolic processes. The concentration of inorganic P present in the cell affects enzyme regulation and the control of starch synthesis. Dissociation of phosphoric acid plays a role in buffering of cellular pH and maintenance of homeostasis.

The importance of P in all energy transfers, photosynthesis, and cell division means that P plays a critical role from the initial reactions in the germinating seed, throughout plant growth, to formation of crop yield. Each time a cell divides, P is required to provide energy for reactions, to replicate the genetic material that is passed to the new cell, to form the phospholipids of the cell membranes, and to form a wide range of enzymes and other cellular components. Therefore, an adequate supply of P is essential from the earliest stages of plant growth. Early season limitations in P availability can result in restrictions in crop growth from which the plant will not recover, even when P supply is increased to adequate levels.

Phosphorus is taken up by the plant as the inorganic orthophosphate ion ($H_2PO_4^-$ or HPO_4^{2-}), with the greatest uptake rate occurring when the P is in the monovalent $H_2PO_4^-$ form. Therefore, plant uptake rates of P are greatest between soil pH levels of 5 and 6, where the monovalent form dominates. Uptake of P by the plant from the soil solution occurs mainly through actively growing cells just behind the root cap, where root hair density is high. A series of active carriers transports the P across the cell membranes of the various cells and organelles to move it into the root and distribute it throughout the plant to where it is needed. The concentration of phosphate ions in the soil solution is many times lower than that in the plant, so uptake of P from the soil to the plant requires energy to move the P against the concentration gradient.

The ability of the plant to absorb P from the soil will depend on the concentration of P ions in the soil solution at the root surface, the area of absorbing surface in contact with the solution, and the movement of P ions in the soil to the root surface. The P ions in solution are absorbed quickly by the active transporter system on the root cell membranes, leading to a depletion zone of low concentration at the root surface. Phosphorus ions will move through the soil water to the root surface by mass flow and diffusion, with diffusion along the concentration gradient being the most important mechanism. Movement of P will increase with increasing concentration of P in the soil solution, partly because there will be more P in the water moving towards the plant in mass flow, but mainly because the concentration gradient for diffusion will increase as the P concentration in the bulk soil solution increases.

Plant roots can directly take up only dissolved inorganic P (P_i) in the soil solution, but at any time the solution Pi contains only a small amount of the total soil P. Most of the soil P is present in a range of organic and inorganic forms that can be viewed as being “pools” of P that vary in availability. Phosphorus can move from pool to pool along concentration gradients that result

from P being added or removed from the soil solution. Labile P is the pool that will rapidly move in and out of the soil solution in the short-term, while non-labile P is more stable, slowly retaining and releasing P over the long-term. When plants remove P from solution, most of the P that is removed can be replenished from the labile pool of P. When fertilizer P is added to the soil solution, most of the added P will move out of solution and replenish the labile pool. The P will also move between the labile and non-labile pools, but these reactions take longer to occur.

Phosphorus supply to a crop will be influenced by the ability of the soil to replenish the P in the soil solution at the root surface from the P present in the other soil pools. Therefore, plant-available soil P over the season will be affected both by the concentration of P in the soil solution (the intensity factor, I) and the amount and rate of release P from other soil pools (the quantity factor, Q).

Phosphorus concentration in the plant will be affected by the amount of P that the plant can take up from the soil solution. Most of the P in the plant is present as inorganic phosphate with only a small portion being metabolically active. This small amount of active P remains relatively constant with changes in P supply while the concentrations of inorganic P may vary substantially, being stored or mobilized as external supplies increase or decrease. Surplus phosphate can be stored in the vacuoles of plant cells, to be used as a reserve source if P supplies become limited. Mobilization of the plant's "luxury" reserves of stored P helps to maintain the metabolically active P to support plant growth if external P becomes deficient.

The importance of P for plant growth has led plants to develop strategies to improve their ability to access P when deficiencies occur. The ability of the plant to take up P depends on the P in solution at the soil surface and the amount of root surface area. If P supply is low, plants will increase root development at the expense of shoot growth, producing finer and more abundant roots and root hairs to improve their ability to explore the soil and take up P. Deficient plants will also release organic acids and acid phosphatases that increase P availability in the rhizosphere. Low P concentrations in plant tissue will encourage mycorrhizal colonization in many plants, a symbiosis that increases the soil volume explored for P uptake.

Phosphorus deficiency symptoms are often subtle, and moderate P deficiency may not produce obvious symptoms ("hidden hunger"). Plants may develop dark green or purple coloration of leaves and stems. Plants may be shorter, leaf emergence and development can be delayed, and there can be less tillering and root development, lower dry matter yield and reduced seed production. Seed number will be reduced but usually the seed size will be maintained.

Deficiency generally occurs at P concentrations below approximately 0.2% in the plant tissue, depending on the crop stage and portion sampled, but the thresholds for sufficiency will vary with different crops. The P in plant tissue will usually decline as the plant ages and matures; therefore, the critical P concentrations required for optimum growth decrease as plants age. Phosphorus is generally mobile in the crop and will re-translocate from vegetative tissue to reproductive organs such as seeds. As a result, most of the P taken up by the crop will be removed in the harvested material (Table 1).

Table 1. Phosphorus uptake and removal (lbs per unit of yield) for a range of crops[a].

Crop	Unit for Yield	Uptake Min	Uptake Max	Uptake Prairies	Removal Min	Removal Max	Removal Prairies
		lb P_2O_5					
Spring wheat	Bushel	0.73	0.88	0.68	0.53	0.65	0.51
Barley	Bushel	0.50	0.61	0.33	0.38	0.46	0.29
Oats	Bushel	0.36	0.45	0.27	0.26	0.28	0.23
Canola	Bushel	1.31	1.63	0.87	0.94	1.14	0.68
Faba Beans	Bushel	1.78	2.19	-	1.10	1.34	-
Flax	Bushel	0.75	0.92	0.71	0.58	0.71	0.64
Lentil	Bushel	0.76	0.92	-	0.60	0.66	-
Peas	Bushel	0.76	0.92	0.53	0.62	0.76	0.44
Corn	Bushel	0.57	0.69	0.46	0.39	0.48	0.39
Sunflowers	CWT	1.15	1.40	1.90	0.70	0.90	1.20
Soybeans	Bushel	1.10	1.32	1.37	0.80	1.00	1.17
Dry Beans	CWT	-	-	1.39	1.40	1.40	1.12
Potatoes	CWT	0.15	0.18	0.18	0.08	0.10	0.16

[a] Low and high values are estimates from the Canadian Fertilizer Institute (CFI. 2001. Nutrient uptake and removal by field crops - western Canada. Canadian Fertilizer Institute, Ottawa, Ontario, Canada.) and values for Canadian Prairie crops are from Heard and Hay (Heard, J. and Hay, D. 2006. Typical nutrient content, uptake pattern and carbon: nitrogen ratios of prairie crops. Designing cropping systems that prosper in variable weather: Proceedings of the 7th Manitoba Agronomists Conference, Winnipeg). Values for lentils and faba bean are from https://saskpulse.com/files/general/160401_Phosphorus_management_for_pulses2.pdf, accessed March 25, 2019). It is important to note that these values are strongly affected by crop yield potential, genetics and environment. Much of the data contributing to this table was collected using older cultivars and management practices. Efforts are currently underway to update uptake and removal values using more current information.

Gaps in Knowledge

More information is needed on:

- nutrient requirements and removals for current high-yielding crop cultivars.
- the development of crop varieties and hybrids with the ability to mobilize P from the soil through rhizosphere modification or improved rooting. Such cultivars could be more productive than current cultivars, when grown on soils with low levels of P fertility. This would not necessarily save on crop inputs of P in the long term, since the rates of crop P removal must eventually be balanced with rates of P application. However, P-efficient cultivars could enable farmers to maintain crop productivity at lower levels of soil test P, which could reduce P loss to surface water due to runoff and erosion.
- more refined information on threshold tissue concentrations required for optimum yield in current, high-yielding crop cultivars.

3.0 Phosphorus Behaviour in the Soil

Key Messages

- Plants take up P as orthophosphate ions ($H_2PO_4^-$ or HPO_4^{-2}) from the soil solution at the root surface.
- Phosphorus is present in the soils as a variety of dynamic "pools" of organic and inorganic forms that range in availability and interact with each other through chemical reactions and biological transformations.
- Water-soluble P fertilizer undergoes a series of adsorption and precipitation reactions with calcium and magnesium in high pH (alkaline) soils and iron and aluminum in low pH (acid) soils that remove the P from the soil solution and transform it into adsorbed and less soluble forms.
- Plant uptake of orthophosphate from the soil solution shifts the equilibrium so that P moves from the less available pools towards plant-available solution P.
- Availability of P to the plant will depend on the concentration of P in the soil solution at the root surface and the ability of the soil to replenish the soil solution P from the less labile pools.
- Assessment of long-term P use efficiency must consider the accumulation of fertilizer P in soil pools that can be accessed by the plant over time.
- The short growing season and cold, frequently high pH, carbonated soils of the Northern Great Plains will affect P behaviour.

Summary

The native plant-available P in soils comes originally from the weathering of P-rich minerals such as apatite. Phosphorus can be added to the soil system through manures, crop residues, fertilizers, municipal wastes and by-products and can be lost from the soil system through crop removal, erosion and runoff and, under some conditions, through leaching and/or subsurface drainage (Figure 3).

Organic P in the form of growing plants and plant residues, animal waste, soil biota, soil organic matter, and soluble organic P present in the soil solution can make up as much as 25 to 60% of the total P content of surface soils. These forms vary in their lability or the ease with which they can be converted into plant-available orthophosphate. Organic phosphate can be mineralized into plant-available orthophosphates when soil microorganisms use the organic matter as an energy source and, conversely, mineral P can be immobilized when soil microorganisms incorporate it into their biomass. Immobilization and mineralization operate in a cyclical process with P being tied-up as the microorganisms grow and P being released as they die and decompose. Organic phosphorus can also be converted to orthophosphate by soil phosphatase operating outside of living organisms.

The inorganic forms of P in the soil include the phosphate ions in the soil solution, P that is adsorbed on the surface of soil particles, P that is precipitated as secondary P minerals such as Ca, Mg, Fe and Al phosphates, and the P that is present as primary P minerals such as apatite. These P pools vary in availability and P will move back and forth between the pools in a series of equilibrium reactions. The reactions of the labile pools are relatively rapid while reactions of the non-labile pools may take months to years.

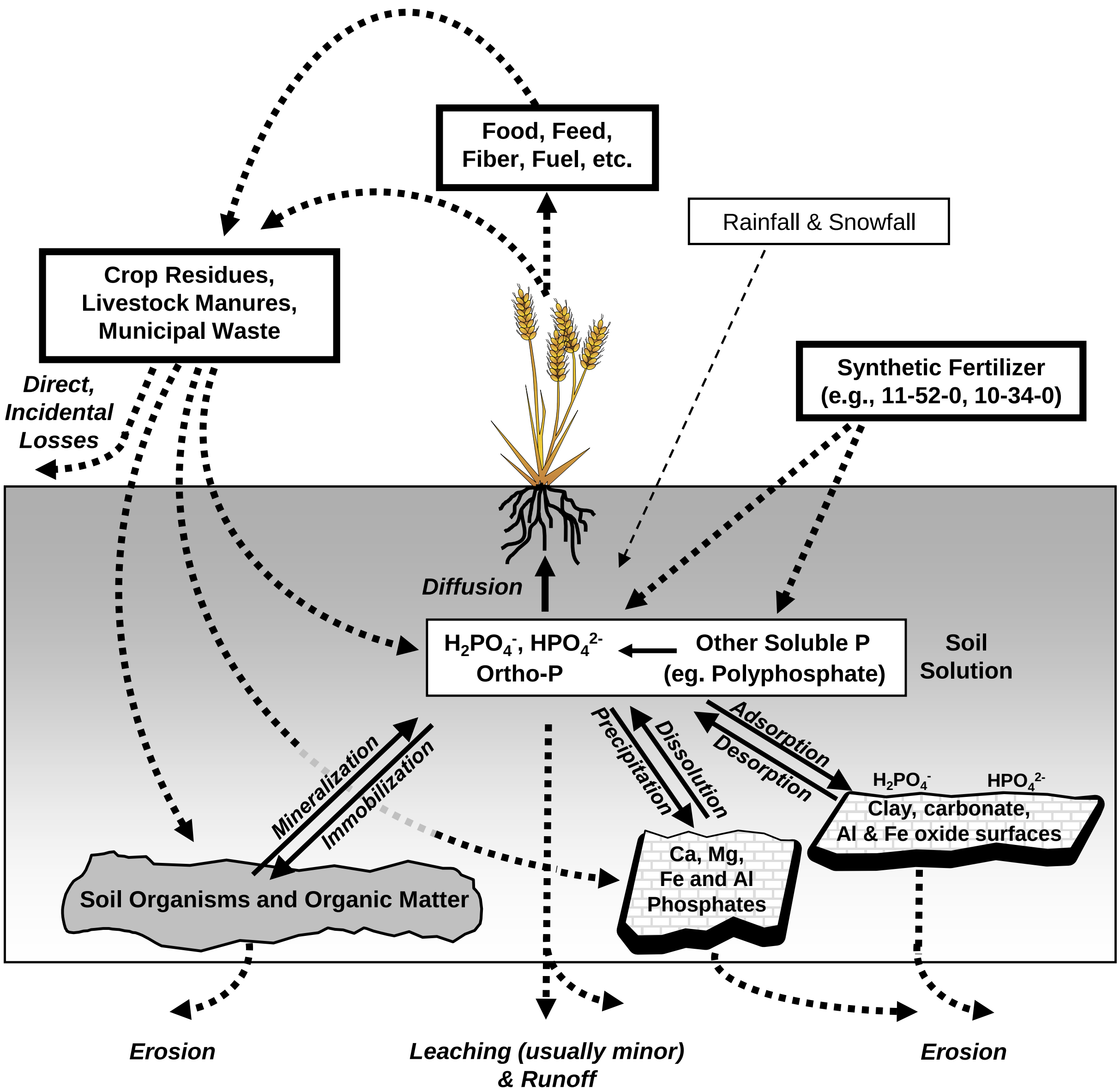

Figure 3. Simplified phosphorus cycle. Dashed lines represent phosphorus gains or losses in the soil system; solid lines represent internal transformations within the soil system (https://www.gov.mb.ca/agriculture/environment/nutrient-management/pubs/effects-of-manure%20-fertilizer-on%20soil%20fertility-quality.pdf, accessed April 30, 2019).

Plants take up P as orthophosphate ions ($H_2PO_4^-$ or HPO_4^{2-}) from the soil solution at the root surface. The soil solution normally contains very low P concentrations, typically much less than 0.1% of the total quantity of P in the soils. Even with a moderate P concentration, the soil solution will contain substantially less than 1 lb/acre of plant-available P to the 6-inch depth at any time, far less than the crop requires for growth. Roots will intercept P as they grow into new soil that has not been depleted, but they contact only a small part of the soil and P that is directly intercepted by the root is only a small fraction of the P requirements. Most plant P is supplied by replenishment of the very low concentration of P in the rhizosphere surrounding the plant root through diffusion along the concentration gradient created by active uptake of P by plant roots. Diffusion through the soil solution is very slow and the path of movement through the soil moisture films around the soil particles is long and winding. Therefore, the net movement of P though the soil is small, in the range of 0.13 mm per day.

Availability of P to the plant will depend on the concentration of P in the soil solution at the root surface and the ability of the soil to replace the P removed by the root. The concentration of P in the soil solution is called the intensity factor (I) and the ability of the soil to replenish the P in the soil solution is call the quantity factor (Q) or the P buffering capacity. Replenishment occurs from the pool of labile P that will rapidly equilibrate with the soil solution and become available in the short-term. Non-labile forms will equilibrate more slowly and are a longer-term source of replenishment for the labile reserves and the soil solution. The labile forms include easily mineralizable organic P, the relatively soluble forms of precipitated P and the adsorbed P that is readily exchangeable. The non-labile P forms include the more strongly adsorbed forms and more sparingly soluble forms. Soil P will move among solution, labile and non-labile forms in response to changes in the relative concentration of P in the various pools driven by plant uptake and phosphorus applications.

When water-soluble P fertilizer is applied to the soil, the P in solution undergoes a series of adsorption and precipitation reactions that remove it from the soil solution and move it into the labile and non-labile pools. On low pH (acid) soils, P retention is dominated by reactions with Fe and Al, while on high pH (alkaline) soils, Ca and Mg reactions dominate. These retention reactions reduce the availability of P fertilizers over time, but the process is reversible and the retained P forms can become available in response to P removal from the soil solution. Phosphate precipitation increases with increasing concentration of the reacting ions, so high concentrations of Ca, Mg or phosphate will increase precipitation on high pH soils while increasing concentrations of Fe, Al or phosphate will increase precipitation on low pH soils.

When a droplet or granule of water-soluble fertilizer is applied to the soil, it will attract liquid water and water vapour from the soil, dissolving the granule within a few days. As the water moves toward the fertilizer, highly concentrated P solution will diffuse away from the granule or droplet, along the osmotic concentration gradient towards areas of lower concentration outside of the fertilizer reaction zone. The highly concentrated solution may dissolve soil minerals and release cations such as Al, Fe, Ca and Mg that precipitate the P in solution. The residual granule or droplet and the immediate area around contain insoluble P compounds from the original fertilizer and the compounds that have precipitated from the fertilizer P and the reacting cations. Beyond this is a zone of soil next to the granule where the capacity of the soil to adsorb P has been saturated, and precipitates have formed from the reaction of the fertilizer solution with the metal ions and organic matter released from the soil. As distance from the granule increases, the solution becomes more dilute and the soil will be able to adsorb the P without being saturated.

Mass flow of reacting cations in the soil water moving towards the granule may increase the precipitation of phosphate, particularly on calcareous soils, reducing the movement of phosphate away from the granule and reducing the volume of the fertilizer reaction zone. Blending ammonium-based fertilizers with phosphate can reduce the retention of P fertilizer and increase its availability. In some soils, when P fertilizer is applied as a solution rather than as a granule there is less movement of water carrying reacting ions towards the fertilizer, so precipitation is reduced, and P will move further away from the site of application. Use of solution P has provided large increases in P use efficiency on dry, highly calcareous soils in Australia, but the same benefits have not been demonstrated on the Northern Great Plains.

Although retention reactions will reduce P fertilizer's immediate availability, a large proportion of the P that is not used by the crop in the year of application will remain in the soil as residual P that can be used by the crop in subsequent years. Residual P can be increased in the soil by large, one-time applications of P fertilizer or built up gradually over time if P applied in fertilizers or manures is greater than that removed through crop uptake. If P removal is greater than P addition, the residual P will often remain in labile P forms for several years and serve as a long-term source for plant uptake. However, the residual P compounds in soil tend to slowly decrease in availability over time (e.g., several years), due to changes in chemical form that reduces their solubility. Changes in soil P over time will be a function of the balance between P input and removal. Where P input exceeds P removal, soil P fractions can increase and where removal is greater than input, P reserves will decline. Consideration of fertilizer P use efficiency should consider both the immediate and the long-term, residual benefits of the fertilizer applied. Many long-term studies have shown that recovery of applied P can be very high if P balance is considered over the long-term.

Gaps in Knowledge

More information is needed on:

- the dynamics of organic soil P and its contribution to plant-available P and to environmental P losses on the Northern Great Plains.
- evaluation of varying formulations, additives and coatings of P fertilizer, to improve short-term availability for crops. In particular, fertilizer products, additives or coatings that match the release of P into the soil solution with the rate of depletion by root uptake could reduce retention of P by soil and increase fertilizer use efficiency.
- the long-term efficiency of fertilizer P applications on different soils and environments, as well as the soil test P levels that indicate the agronomic, economic and environmental optimum overall, background P fertility in various cropping systems. Further information from new or continuing long-term experiments would help to clarify these issues.

4.0 Environmental and Sustainability Concerns Related to Phosphorus Fertilizer

Key Messages

- Small amounts of P moving into surface water can have a large effect on water quality, so losses of P that are not agronomically significant can be environmentally damaging, particularly with respect to algae growth in freshwater (eutrophication).
- Most of the P loss on the Northern Great Plains is driven by movement of dissolved P during the snowmelt period.
- Phosphorus runoff is a function of the concentration of P in soil and vegetation at the soil surface and the amount of runoff that occurs, so management should focus on reducing the concentration of P at the soil surface during runoff periods.
- While very high P concentrations at the soil surface are most frequently caused by excessive applications of manure P, fertilizer P can also be a contributor, especially if the fertilizer is broadcast.
- Soil fertility may be impaired through nutrient depletion if P removed in the harvested crop is not replaced.
- Accumulation of cadmium (Cd) in the soil from long-term application of Cd-containing P fertilizer may be a concern for human and soil health.
- Banding P fertilizer under the soil surface, near the seed-row during seeding at rates based on an effective soil test and an accurate prediction of crop requirements will reduce the risk of excess P in runoff, P depletion and excess Cd accumulation in soils and crops.

Summary

Small amounts of P moving into surface water can have a large effect on water quality, so losses of P that are not agronomically significant can be environmentally damaging. Phosphorus is an essential nutrient for the growth of aquatic plants and algae. Small increases in plant and algae growth can be beneficial by increasing the food supply for fish. But, as P concentrations in the water increase, dense algal blooms can occur and degrade the water quality for fisheries, recreation, drinking and industrial uses. Excessive plant growth and decomposition can use up the oxygen from the water, leading to fish kills. Lakes and other surface water bodies on the Northern Great Plains are often at risk for eutrophication because they are commonly shallow and fed by large, fertile agricultural watersheds that can supply high amounts of nutrients.

Phosphorus loss from a field is a function of the amount of P in the surface soil and the degree of transport (Figure 4). Risk of water contamination by P from agricultural land will be high in areas where soil test P is high, the ability of the soil to retain P is low, susceptibility to runoff is high, soil erosion risk is high, and water from the field can easily move offsite to sensitive waters through natural or artificial drainage. Most of the P risk indicators that have been developed worldwide concentrate on risk of loss from fields where the main mechanism for P loss is rainfall-induced erosion, which carries particulate P from sloping land into water bodies. Such indicators do not work well in the Northern Great Plans, where P losses are mainly from spring snowmelt runoff over relatively level landscapes and across frozen ground. Under these conditions in the Northern Great Plain there is very little erosion-driven loss of particulate P. However, soluble P in the soil or crop residues at the soil surface is easily dissolved in the melting snow and moved with the runoff. Since approximately 80% of annual runoff in the

Northern Great Plains occurs during snowmelt, the dissolved P in snowmelt runoff is a major source of P movement into water bodies in this region.

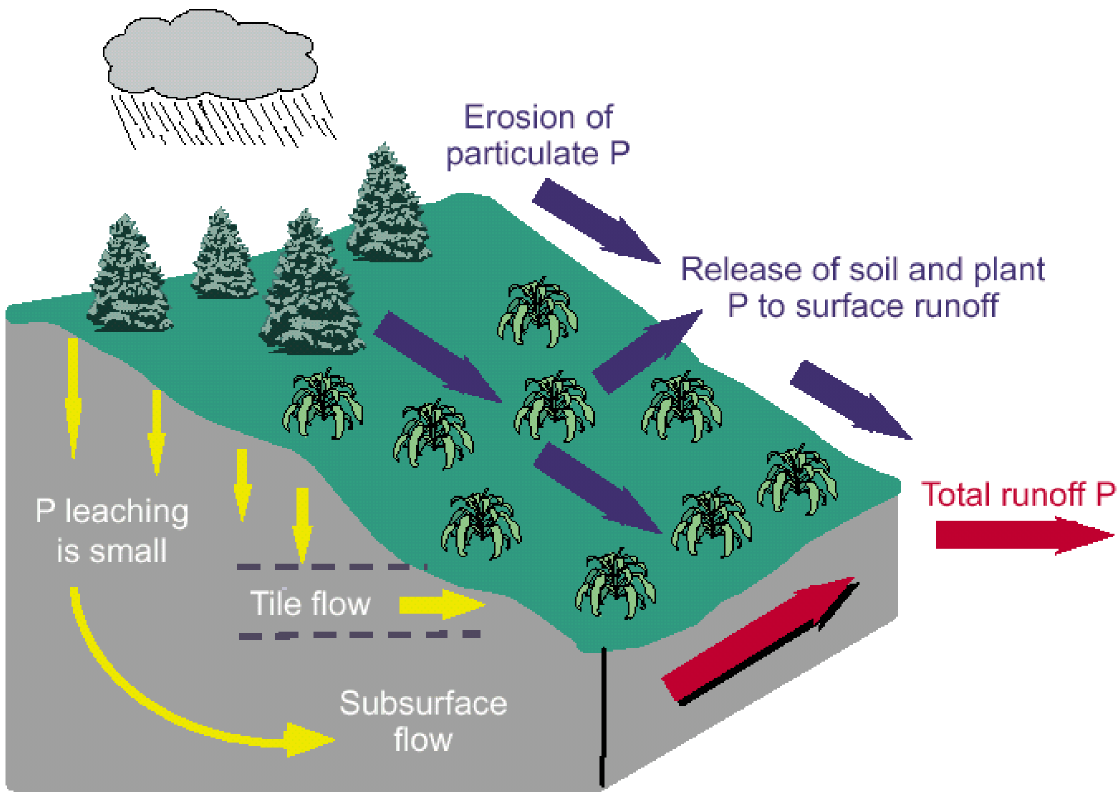

Figure 4. Processes that transport phosphorus to water from agricultural land (Sharpley, A. N., Daniel, T., Sims, T., Lemunyon, J., Stevens, R., and Parry, R. 2003. Agricultural phosphorus and eutrophication. ARS-149, USDA-ARS. https://www.ars.usda.gov/oc/np/phoseutro2/phoseutrointro2ed/

Many of the beneficial management practices (BMPs) to reduce P movement to waterways have been developed to reduce nutrient loss from erosion. Erosion-focused BMPs concentrate on practices such as vegetative buffer strips to trap eroded particles before they enter water bodies, maintenance of vegetative cover in place of bare soils, and reduction in tillage or the adoption of no-till to reduce the movement of soil particles. On gently sloping landscapes on the Northern Great Plains, where most nutrient transport is during snowmelt and in the dissolved form, vegetation is less effective in trapping nutrients and may contribute nutrients to snowmelt runoff. Living plant material contains high concentrations of soluble P that can be released during freezing and thawing. In addition, crop residues left on the soil surface under no-till management also contain soluble P, although the concentration is lower than in living plant material. Slow snowmelt leaves the water in contact with the residues and the surface P for a long time, allowing the soluble P to leach out of the residues and into the surface water, especially when soils are frozen and impermeable.

Effective 4R nutrient stewardship practices to reduce P runoff on the Northern Great Plains must focus on reducing the concentration of various sources of P in contact with the snowmelt runoff water. Research in Alberta and Manitoba demonstrates that the amount of dissolved P in runoff water increases as the soil test P concentration at the soil surface increases, just as it does elsewhere. However, those relationships are consistently linear, with no obvious "change point" to indicate substantial increases in runoff losses of P above a specific concentration of soil test P. Phosphorus fertilizer rates that are closely matched to crop demand should be used to reduce accumulation of P at the soil surface.

Broadcast P applications, particularly if not incorporated, will increase the amount of soluble P near the soil surface and can increase the risk of P movement in runoff. In-soil banding of P will reduce the risk of P loss by placing the P below the soil surface, where it is not in contact with the runoff water. Placing the P in a concentrated band near the seed-row can also increase fertilizer use efficiency and reduce the amount of P required for optimum crop yield.

Large P losses can occur where rainfall or runoff in general follows quickly after surface P application, before the soluble P fertilizer has reacted with the soil to reduce its availability. Since the risk of P loss is greatest immediately after application, P fertilization, especially broadcast applications, should be timed to avoid periods of high runoff. Fall broadcast P applications should be avoided because the fertilizer can remain near the surface over the winter in a soluble form that can move with the spring runoff. Applying fertilizer after snowmelt, just prior to or during seeding can avoid movement in spring runoff and reduce the risk of P loss.

Therefore, optimum 4R nutrient stewardship practices to reduce P runoff in the Northern Great Plains should concentrate on matching P application rates to crop demand, ensuring that soil test P concentrations in the surface soil are managed to avoid excess accumulation, placing P fertilizers below the soil surface and timing applications to avoid P fertilizer remaining at the soil surface during the snowmelt period or prior to rainfall events. It is also important to consider that most of the P loss will occur from a small area of the watershed and practices that reduce risk of P movement is those sites will probably have the greatest benefit on water quality.

Excess accumulation of P in the soil, especially near the soil surface, can increase the risk of P movement to water bodies. However, P depletion should also be avoided as it can reduce the productivity of the soil, because crops on very low testing soils may not be able to attain optimum yields even with high rates of fertilizer P. Accumulation or depletion of P in the soil will reflect the balance between P applied in fertilizers or other soil amendments and P that is removed in the harvested crop. As a result, depletion of soil P may be particularly problematic in organic production systems where synthetic fertilizer inputs are not permitted. A long-term sustainability approach to P fertilizer management is desirable, where fertilizer is managed through the rotation to maintain reasonable concentrations of available soil P to optimize soil productivity while avoiding increased risk of P movement to water.

Another environmental concern related to P fertilizer management is the accumulation of cadmium (Cd) in the soil over time. Long-term consumption of large amounts of Cd in the human diet, particularly in subsistence diets low in zinc and iron, has been linked to chronic toxicity and adverse health effects. Soil organisms may also be negatively affected by excess Cd exposure, affecting soil ecology and health. Therefore, it is desirable to ensure that concentrations of Cd in soils remain low enough to avoid adverse effects on soil or crop quality. The amount of Cd added to soils from P fertilizer application is a function of the rate of application, the frequency of application and the concentration of Cd in the fertilizer material. Cadmium is removed from the soil primarily through crop harvest, with erosion, bioturbation and leaching also being minor potential pathways of loss. Therefore, over the long-term, changes in Cd concentration in soils reflects the balance between Cd input and removal. However, because addition of Cd in phosphate fertilizer at normal agronomic rates of application is low relative to background concentrations, major changes is soil background concentrations will take many years to develop. In Canada, the concentrations in the soil after 100 years of application at current rates are not predicted to represent an increased risk relative to the current soil quality guidelines. Nevertheless, accumulations of Cd in the soil can be minimized by avoiding excess applications of P fertilizer and by using fertilizer BMPs that optimize fertilizer use efficiency.

On the Northern Great Plains, in-soil banding near the seed-row during seeding at rates based on an effective soil test and predicted crop requirements are BMPs for optimum P use efficiency that will reduce the risk of excess Cd accumulation in soils.

Gaps in Knowledge

More information is needed on:

- landform effects on P losses to surface water for relatively level landscapes, since most studies have concentrated on more variable landscapes. Questions remain on how much P is moving off the field in level landscapes. Research into the benefit of improved fertilizer management practices targeted to depressional portions of the field where most runoff flows would be beneficial, especially on more level landforms where minor changes in elevation can channel the runoff. This would help in quantification of the potential benefits of variable rate P management for reducing P movement off field.
- the interaction between fertilizer source and the time of application on snowmelt P runoff and crop yield response would be useful, since some retailers of sparingly soluble P products are suggesting that they are suitable for fall application.
- long-term changes in Cd and P availability on a wide range of soils, to determine the impact of Cd and P loading over time as affected by soil characteristics. This type of information for P across a range of soils would help our understanding of the influence of soil characteristics and environment on long-term P availability as a function of P fertilizer deficits or surpluses.

5.0 Phosphorus Fertilizer Rates

Key Messages

- Phosphorus fertilization rate should be selected to ensure that the crop can access the P that it requires as it is needed to optimize crop growth.
- Phosphorus fertilizer rate should be based on a suitable soil test and a prediction of crop requirement for P for the specific crop type and yield potential.
- Rates of P application can be managed for short-term sufficiency or long-term sustainability, depending on the crop rotation, land tenure, relative cost of P fertilizer, risk of P movement to water systems, and the P status of the soil.
- Rate of P application will interact with source, timing and placement.
- Crops differ in quantity of P removed, efficiency of P use, sensitivity to seed-placed P and response to P application, so P fertilizer rate will differ with crop species.
- In the long-term, rate of P application should be matched to P removal to avoid excessive accumulation or depletion of soil P over time.
- Site-specific management (e.g., varying P applications within a field based on soil variability in available P or in risk of P movement to waterbodies) may be beneficial to optimize P inputs, increase fertilizer use efficiency and reduce the potential environmental impact of P applications.

Summary

Phosphorus fertilization rate should be selected to ensure that the crop can access the P that it requires as it is needed to optimize crop growth. However, different strategies exist for phosphorus management, depending on the time scale of production that is considered in the management program. Phosphorus may be managed to optimize production for a single production year, over a rotational cycle or for long-term sustainability. The management strategy selected will be influenced by crop rotation, land tenure, relative cost of P fertilizer, risk of P movement to water systems, and the P status of the soil.

Recommendations for P fertilizer applications based on a **short-term sufficiency strategy** aim to supply just enough P to produce good yield of the current crop. Fertilization is based on applying a rate where the net returns are maximized in the year of application. Economic value of the residual benefits of P fertilizer is not considered. This strategy tends to be most suitable on land with short-term tenure, where cash flow is limited, or in years where fertilizer price is high relative to crop values. Raising or maintaining the soil test P value is not a goal in the sufficiency method and this strategy tends to keep soil test levels in the low to medium range. Phosphorus application rate is based on the critical threshold, soil test values and the probability of response to P by the crop in the current year. In the Northern Great Plains, the fertilizer P would normally be applied as starter or in band placement near the seed to improve efficiency.

A long-term sustainability strategy aims to manage the soil test P level in the soil towards a specific critical range to ensure that the background level of P in the soil is not limiting to crop production (Figure 5). If the soil test is below a critical level, fertilization would **build** the soil P level by adding more P than is removed by the crop until the target soil level is reached. If the soil test P level is higher than desirable, no P or only a minimal amount of starter P would be applied, to **deplete** the soil P reserves. After that, a **balance** or **maintenance** approach would be followed, to apply the amount of P that is removed by the crop, perhaps plus some extra P to account for retention and other losses, and maintain a target level of soil P. In this approach, application rates are designed to maintain soil test values and eliminate nutrient deficiency, but not necessarily to maximize profit from fertilization of one crop in a single year. The long-term sustainability strategy assumes that P applied to the soil will not be lost from the system in appreciable amounts except through crop removal. It is suited to land that has a long tenure arrangement and where capital is available to carry the operation through the P fertility building phases. It is also attractive if the present cost of P fertilizer is lower than anticipated future cost or if low cost fertilizer sources such as livestock manure are readily available.

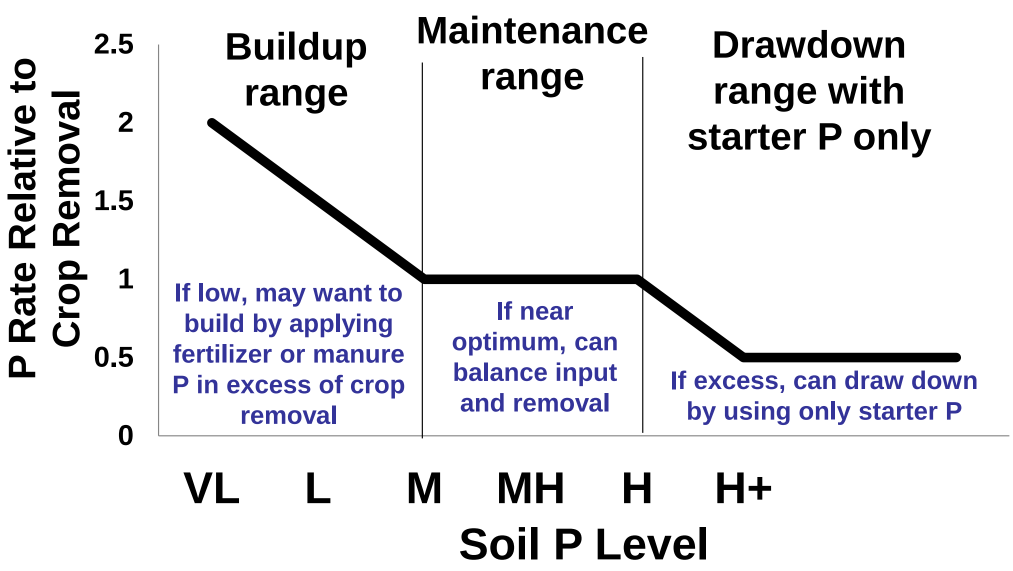

Figure 5. The long-term sustainability strategy for P management relies on building, maintaining or depleting soil P, based on soil test P concentration.

Soil testing plays an important part in the selection of P fertilization rate, regardless of whether a short-term sufficiency or long-term sustainability strategy is used. Therefore, an effective soil test to determine the plant-available P in the soil is essential to determine the need for fertilizer application and an estimation of the appropriate fertilizer application rate. The type of soil test used should be suited to the soil characteristics and calibrated for the area. The Olsen test is commonly used in the Northern Great Plains, because it is effective across a broad range of soils, including high pH, calcareous soils (Figure 6). However, the Olsen test may be less reliable on acid soils, while the Bray test is effective only in neutral to low pH, non-calcareous soils. Kelowna and modified Kelowna tests are also considered effective on many of the soils in the Northern Great Plains. Resin-based tests are also available and can provide a measurement of both plant-available P concentration in the soil and rate of replenishment of solution P at the adsorbing surface.

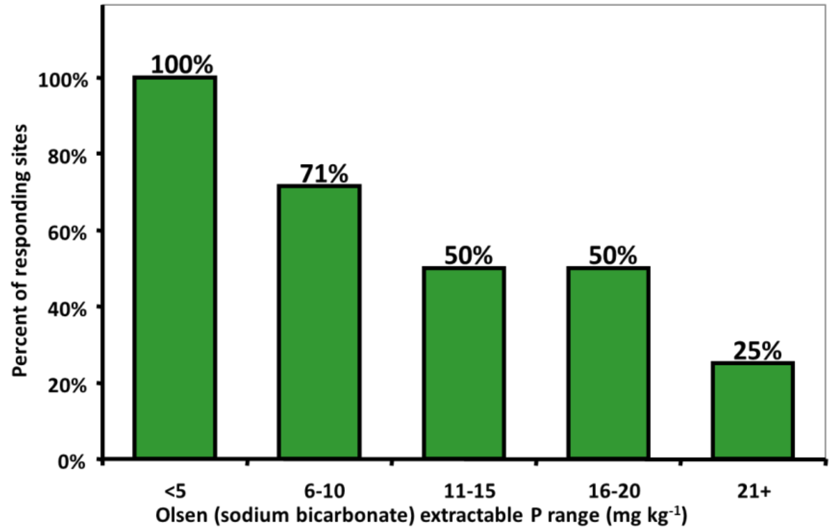

Figure 6. Percentage of sites responding to phosphorus application at various Olsen-P soil test ranges. Of the 47 sites, 5 sites tested less than 5 ppm, 14 sites tested between 6 and 10 ppm, 20 sites tested between 11 and 15 ppm, 4 sites tested between 16 and 20 ppm and 4 sites tested 21 ppm or more. (Karamanos, R. E., Flore, N. A. and Harapiak, J. T. 2010. Re-visiting use of Penicillium bilaii with phosphorus fertilization of hard red spring wheat. Canadian Journal of Plant Science 90(3):265-277)

While soil testing is an important guide to P requirements, the response of crops to fertilizer P addition varies with environmental conditions (i.e., from one year to another) and is often not precisely related to the P concentration of the soil (Figures 6 and 7). Therefore, soil testing will not predict exactly how much to apply, nor will it assure that a response will be attained every year. Nevertheless, soil test P information is good for estimating the average probability of response to P application and assessing the accumulation or depletion of P from a field over a long period of time. It is fair for estimating the average relative yield response to P across similar fields and yields and for estimating the probability of response in a given field and year. However, soil tests for P are relatively poor at predicting if a specific response will occur in a specific field and a specific year.

In the long-term sustainability strategy, the soil test P level is an important part of the decision to build, replace or draw down the P in the soil. The level of soil P below which a yield response to fertilizer P application is likely to occur is often referred to as the critical level or critical threshold. A long-term sustainability strategy would target a soil P level near the critical threshold, which ranges from approximately 15 ppm to over 30 ppm for Olsen soil test P on the Northern Great Plains.

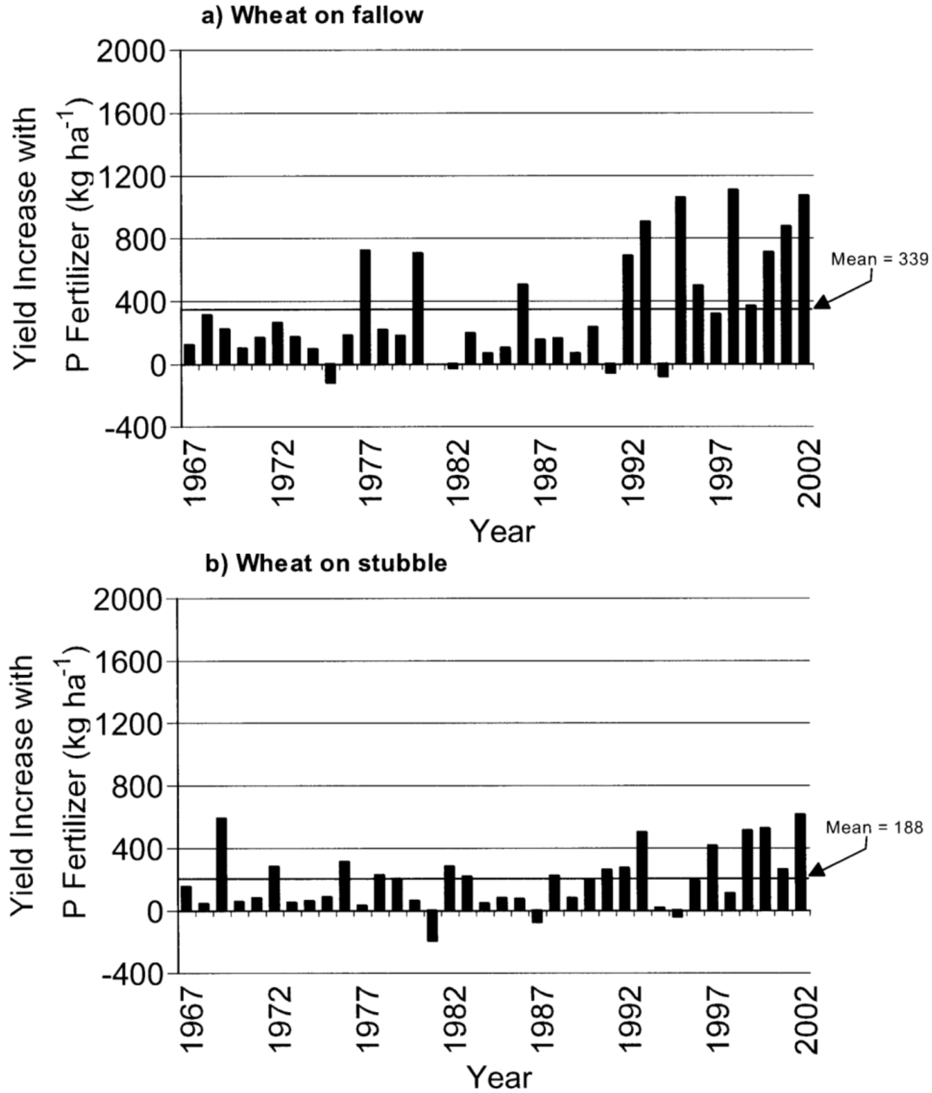

Figure 7. Spring wheat response to annual applications of seed-placed P fertilizer at a rate of 20 lb P_2O_5/acre on stubble and fallow in a fallow-wheat-wheat rotation at Swift Current, SK from 1967 to 1998 (Campbell, C. A., Zentner, R. P., Selles, F., Jefferson, P. G., McConkey, B. G., Lemke, R. and Blomert, B. J. 2005. Long-term effect of cropping system and nitrogen and phosphorus fertilizer on production and nitrogen economy of grain crops in a Brown Chernozem. Canadian Journal of Plant Science 85(1):81-93.)

With very low levels in the soil, building of soil test P may be desirable to ensure that the crop's supply of P is optimized. The P can be built up slowly over time, with small surplus applications of P fertilizer applied annually or through the crop rotation. The approach of slowly building up a low soil P status soil to a satisfactory level will usually be economically viable over the long term, since the applied P is eventually used efficiently. The rate of fertilizer required to build soil test P will depend on the amount of crop removal and the P buffering capacity of the soil. The P fertilizer in a gradual building program should be managed to optimize efficiency by seed-placing or banding near the seed-row. In a crop rotation that includes crops with high sensitivity to seed-placed fertilizer, it may not be possible to apply enough P with the seed to both optimize crop yield and replace or increase background soil P.

Alternatively, if low cost sources of P are available, it may be desirable to add a large amount of P to more quickly increase the soil test P level. This would be especially attractive if the price of P fertilizer is low relative to crop values or if low-cost forms of P, such as livestock manures, are available. Application of manure to satisfy crop N requirements will usually apply enough P for several years of crop removal and increase soil P over time. Situations occur across the Northern Great Plains where long-term annual applications of manures to satisfy N requirements have led to excess concentrations of P in the soil. With excess concentrations in the soil it may be desirable to deplete the soil reserves, to reduce P fertilizer costs, as well as environmental risks such as excess P in runoff. Once the critical level is established, maintaining soils near the critical value for the soil type and farming system is done primarily by replacing the P removed in the harvested crop.

If the short-term sufficiency strategy is selected, a soil test will indicate the likelihood of a response to P application and an estimate of the rate of P required to optimize crop yield in the year of application. The rate of fertilizer application will depend on the ability of the plant to access P from the soil, especially during the early stages of growth. If the soil supply of P is high enough to provide an adequate supply of P to the plant throughout the growing season, P application can be reduced or eliminated. If the soil is deficient in P, fertilizer applications can be used to provide P to the plant as it is required, particularly early in the growing season. Likelihood and magnitude of a response to P will tend to increase with the yield potential of the crop but will also vary with environmental conditions. The rate of P required to optimize crop yield is usually within a narrow range, from about 10 to 50 lb P_2O_5 per acre for small grains, oilseed and pulse crops. A minimum rate of P application will be required to ensure that individual plants have access to fertilizer granules or droplets in a timely fashion, based on the physical distribution of the fertilizer. Reducing the rate of application to extremely low levels limits the number of granules applied and reduces the probability of a seedling root contacting the fertilizer.

If a short-term sufficiency strategy is used for selecting P application rates, differences among crops in their responsiveness to P application must be considered. Different crops have different requirements for P and different strategies that affect their ability to use soil P and their response to fertilizer P. Phosphorus fertilization requirement and yield response of a crop depend both on the total amount of P needed by the plant and its ability to access it from the soil at the time it is required. Cereal crops tend to be moderately effective while canola is highly effective at using both fertilizer and soil P. Flax is relatively poor at using fertilizer P and is highly dependent on mycorrhizal associations to help it access P from the soil. Soybean and other pulse crops appear to be able to use soil P very effectively and therefore do not respond well to fertilizer P applications in Northern Great Plains soils.

Crops such as canola, flax and pulses are sensitive to seed-placed P and yield may be reduced if high rates of P are placed too close to the seed-row. If the rate of P needed for optimum yield is greater than can be safely placed with the seed, it may be applied away from the seed-row or to other, more tolerant crops in the rotation.

Available P differs substantially across a field, so uniform fertilizer application based on an average soil test P value for the field may result in over- and under-fertilization in different areas of the field, reducing fertilizer use efficiency. As well, P runoff may be concentrated in specific areas of the field and ignoring differences across the field would reduce the effectiveness of environmental P management practices. Use of more detailed site-specific information to vary P applications within a field based on soil variability in available P or in risk of P movement to waterbodies could help to optimize P inputs, increase fertilizer use efficiency and reduce the potential environmental impact of P applications.

Fertilizer applications may be adjusted based on grid sampling to identify high and low-testing zones in the field. Optical sensors linked to variable rate applicators are being tested to measure soil P and adjust fertilizer rate on the go. Available P tends to be highly correlated to topography, being greater in depressional areas and less on knolls, so sampling may be based on topographical zones to identify high and low-testing areas. Application of high rates of P to correct deficiencies on upper slope positions may be used to remediate eroded knolls and make the P levels more uniform across the field. Manure is particularly beneficial for correction of P deficiency on eroded knolls because the organic matter it provides can also improve soil structure and water-holding capacity. The benefits from large applications of P would persist for many years.

In a long-term sustainability system, where P removal is balanced by P inputs, variable P inputs could be based on a yield map. Phosphorus removal is highly driven by crop yield. In soils with a long-term history of uniform P application, P may have accumulated in low-yielding areas and may be depleted in high-yielding areas. Using variable P application rates based on crop yields would correct the rate for crop removal, if lower yields were not caused by P deficiencies.

Gaps in Knowledge

More information is required on:

- soil test P calibration data for probability and magnitude of P response for new crop varieties/hybrids, as well as new crops grown under field conditions for the Northern Great Plains
- the appropriate target "background" soil test P concentration for long term agronomically, economically and environmentally sustainable P management in the soils and cropping systems of the Northern Great Plains.
- changes in soil P concentrations with P surpluses or deficits on different soil types with more modern diversified and extended rotations.
- the impact of in-soil banding as compared to broadcast applications of large amounts of P fertilizer on eroded and/or carbonated knolls.
- the long-term benefits of variable rate P application, from agronomic, economic and environmental perspectives.
- crop demand and removal for P by improved cultivars with high yield potential.

Consideration should be given to collecting information from field experiments in a web-based database similar to the Better Fertiliser Decisions for Cropping Systems (BFDC) National Database from Australia (Watmuff et al. 2013) to improve decision support systems and fertilizer recommendations.

6.0 Phosphorus Fertilizer Sources, Additives, and Microbial Products

Key Messages

- Phosphorus fertilizer sources must provide available orthophosphate ions in the solution for plant uptake as required to optimize crop growth.
- Phosphorus fertilizers will react with soil constituents to influence the availability of the fertilizer P to the plant.
- Monoammonium phosphate (MAP, e.g., 11-52-0) is the most popular source of P fertilizer used on the Northern Great Plains, due to its high availability under high pH conditions, while ammonium polyphosphate (APP, e.g., 10-34-0) is a common and readily available fluid P source. Both sources capitalize on the benefits of modest amounts of ammonium-N in their formulation, which increases P crop uptake of P, without a high risk of toxicity when placed in the seed-row.
- Novel P fertilizer formulations, additives, coatings or use of microbial products have generally not shown increased effectiveness over MAP and APP under field conditions on the Northern Great Plains.
- Use of reclaimed P from wastewater streams as fertilizer products is beneficial for "closing the loop" to recycle P within the food system, lengthen the lifespan of P reserves and reduce negative environmental impacts of wastewater P loading to surface water.

Summary

Phosphorus fertilizer sources should provide available phosphate to the plant as required to optimize growth. Plants use orthophosphate ions from the soil solution, so fertilizer materials must dissolve before they become plant-available. As the fertilizer P dissolves and moves into the soil solution, it initiates a series of reactions with calcium and magnesium in neutral to alkaline soils and with iron and aluminum in more acid soils to form increasingly less soluble compounds. The reaction of phosphate with soil constituents will influence the volume and nature of the reaction zone around the fertilizer granule and the ability of the plant to access the fertilizer P. Fertilizer source will also interact with the plant to affect rooting and rhizosphere chemistry. The effectiveness of various fertilizer sources will be affected by the initial content and release of plant-available P, by the type and speed of reactions of the soluble P with soil constituents, and by interactions with the plant rhizosphere.

Phosphate rock is the original source for production of most agricultural fertilizers and contains a range of apatite minerals. Phosphate rock is relatively insoluble, but its solubility and effectiveness as a fertilizer varies, depending on its composition and particle size. Sedimentary forms of phosphate rock tend to be more soluble than igneous sources, due to their chemical composition and finer particle size. Solubility of rock phosphate decreases with increasing soil pH and calcium content, so its availability is particularly low on the high pH, calcareous soils that commonly occur on the Northern Great Plains and it is rarely used as a fertilizer in conventional farming in this region. Rock phosphate use is more common in organic farming because it is considered a permissible fertilizer source, while other more soluble phosphate fertilizers are prohibited.

The common commercial phosphorus fertilizers are produced from rock phosphate that is treated with acid to increase its solubility. Impurities are removed through beneficiation and the ore is ground and reacted with acid to form phosphoric acid that is used directly or more commonly as a step in the production of other less corrosive products. The first improved phosphate fertilizer produced was single superphosphate (SSP), which dates to a patent issued in 1845. Both SSP and triple superphosphate (TSP) are soluble and contain monocalcium phosphate but TSP has a higher phosphate analysis of approximately 40 to 46%, as compared to 18 to 20% for SSP.

Monoammonium phosphate (MAP, e.g., 11-52-0) is the most common form of phosphorus fertilizer used on the Northern Great Plains. The chemical analysis is $NH_4H_2PO_4$, with the P present as orthophosphate. MAP is a highly water-soluble, granular form of P that provides both ammonium and phosphate ions for plant uptake, containing about 10-12% N and 48 to 61% phosphate. The solution around the fertilizer granule is moderately acidic, which will increase the availability of the phosphate on neutral to high pH soils. MAP also contains ammonium ions that increase crop uptake of phosphate by decreasing pH in the rhizosphere and reducing precipitation of phosphate, as well as by encouraging root proliferation in the fertilizer reaction zone.

Diammonium phosphate (DAP, e.g., 18-46-0) contains from 18 to 21% N and from 46 to 53% phosphate with the chemical analysis $(NH_4)_2HPO_4$. As with MAP, the phosphate in DAP is in the form of orthophosphate and it contains ammonium that can improve P uptake by plants. While DAP has a higher concentration of N than does MAP, it has a disadvantage on calcareous soils because its solution pH is higher than that of MAP. The high pH of DAP and its high ammonium content create a high solution concentration of ammonia that can lead to toxicity if too high a rate is placed too close to the seed-row. The higher pH of DAP as compared to MAP may also make it less plant-available on calcareous soils but more available on acid soils. Movement of DAP away from the fertilizer granule is less than with MAP making it a less effective fertilizer source especially on calcareous soils.

The most common fluid phosphate fertilizer on the Northern Great Plains is **ammonium polyphosphate (APP)**, which provides both polyphosphate and orthophosphate forms of P. The analysis of ammonium polyphosphate is usually 10-34-0 or 11-37-0. As with MAP and DAP, the presence of ammonium in the fertilizer will increase the P availability. Plants take up P as orthophosphate but because enzymes in the soil rapidly convert polyphosphates to orthophosphate, the polyphosphate in APP is quickly available to the crop. In some situations, the efficacy of APP may be greater than granular fertilizer forms because it is applied in a fluid form. Research in Australia has shown greatly improved efficiency by using fluid formulations such as APP or even dissolved MAP solutions instead of dry granular fertilizer. With fluid sources, the fertilizer was not precipitated as rapidly as with granular forms, and the size of the reaction zone was larger, increasing the fertilizer availability. However, this benefit has not been observed consistently in trials in the Northern Great Plains (Figure 8) and may be greater on the very dry, highly calcareous soils in Australia than on the soils in this region.

Fertilizer formulation can influence P availability. Blending phosphate with ammonium and sulphate can increase the solubility and mobility of phosphate in calcareous soils. A homogenous blend of monoammonium phosphate, ammonium sulphate and elemental sulphur formulated in a single granule is marketed with the idea that acidification of the reaction zone during oxidation of the elemental sulphate and the presence of sulphate ions may increase the availability of the MAP, although field studies have not shown a significant benefit in P availability over traditional MAP.

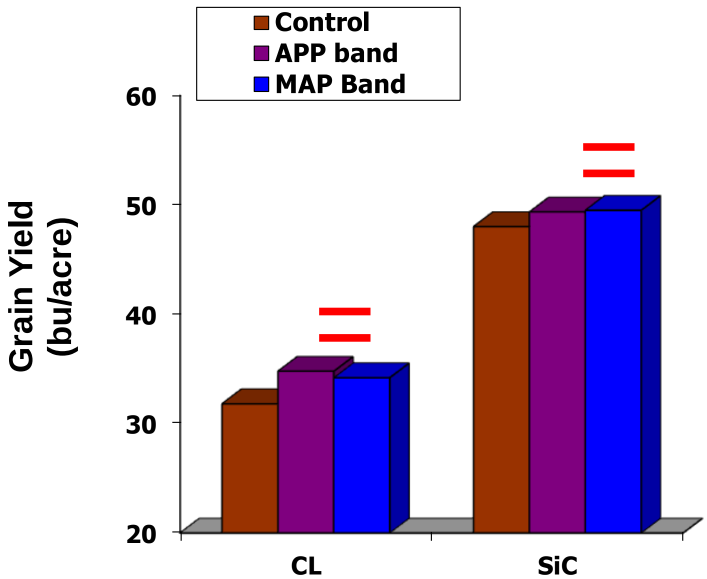

Figure 8. Wheat grain yield response to granular MAP and fluid APP fertilizer was similar over three years at two sites near Brandon (Grant, C., Clayton, G., Monreal, M., Lupwayi, N., Turkington, K. and McLaren, D. 2007. Improving phosphorus nutrition in wheat. Pages 15 pp. Agriculture and Agri-Food Canada, Brandon Research Centre, Brandon, MB.)

Fertilizer coatings and additives are being marketed to improve the effectiveness of fertilizer P. A maleic-itaconic co-polymer additive can be applied to either granular or liquid P fertilizer with the aim of sequestering antagonistic metals in the soil around the fertilizer granule to reduce the tie-up of phosphorus. However, field studies in the Northern Great Plains have not generally shown a benefit from this mechanism.

Polymer coatings on granules may control the release of P into the soil solution to slow the formation of sparingly soluble P compounds and increase the supply of crop-available P. Polymer-coated P compounds are not commercially available, but in field trials they performed similarly to uncoated products in promoting yield, with the benefit of producing significantly lower risk of seedling damage.

A range of reclaimed and by-product P compounds, including struvite, have been evaluated as fertilizer sources. These are attractive because use as a fertilizer can recycle P that would otherwise end up in the waste stream. Most of these compounds would serve as a slow-release P source, with effectiveness depending on the long-term solubility.

Humic acids are not direct sources of P but have been investigated for their ability to slow the precipitation of phosphate on calcareous soils. While humic acid supplements have shown promise in laboratory incubation studies, benefits have not been as consistent in pot or field studies, possibly because very high rates are needed to be effective.

Two major types of microbial products are marketed in the Northern Great Plains to improve P availability. ***Penicillium bilaiae*** has been sold as an inoculant to improve the availability of soil P. This organism is a fungus that occurs naturally in agricultural soils and is said to improve P availability by secreting organic acids that can solubilize P. Benefits of *Penicillium bilaiae* have been erratic under field conditions and it seems to be unreliable as a method for improving P nutritional status of crops on the Northern Great Plains. **Mycorrhizae** are associations between fungi and the plant root that play a key role in the soil microbial community and are of great importance to a wide range of crop and wild plant species. Mycorrhizal fungi are naturally present in soils and their ability to colonize crops is affected by crop type, tillage, cropping system and P status of the plant. Crops differ in their response to mycorrhizae with canola being non-mycorrhizal while corn and flax are highly mycorrhizal. Mycorrhizal inoculants are commercially used in horticulture and forestry as well as in organic production systems; however, their effectiveness in commercial cropping systems on the Northern Great Plains has been limited. Although mycorrhizae clearly aid in P uptake for many crops the mycorrhizal populations provided in currently available inoculants may not be an improvement over a well-established native population.

Gaps in Knowledge

More information is required on:

- agronomic value of varying formulations, additives and coatings for P fertilizers. For example, development of more cost-effective coated P products would be beneficial, particularly for use as seed-placed starters in today's high yielding, diversified cropping systems.
- performance of fluid P forms on highly calcareous soils on the Northern Great Plains. While it appears that fluid and granular sources behave similarly on the Northern Great Plains, it would be interesting to determine if there are situations where fluids are more effective than granular products, as has been seen in Australia.
- recycled and by-product sources of P would be highly beneficial, so investigation of methods of increasing the solubility and availability of these products as fertilizer sources is worthwhile.
- performance of mycorrhizal inoculants for field crops. While the importance of mycorrhizae for plant growth is clear, performance of inoculants has been disappointing. It is not apparent whether native inoculants are adequate or if the commercial inoculants used have either been suboptimal or not competitive with local microbiota. So, it would be worthwhile to determine if more effective inoculants could be found. This would not necessarily save on crop inputs of P in the long term, since the rates of crop P removal must eventually be balanced with rates of P application. However, P-efficient mycorrhizal associations could enable farmers to maintain lower levels of soil test P, which could reduce P loss to surface water due to runoff and erosion.
- influence of biochar amendments on prairie soils.

7.0 Phosphorus Fertilizer Placement

Key Messages

- Banding P fertilizer in or near the seed-row is agronomically and environmentally beneficial for P applications on the Northern Great Plains.
    - Phosphorus fertilizer does not move easily in soil and should be placed in a position where the crop can access it early in the growing season and where root density and activity are high.
    - Placing fertilizer in a concentrated band slows or reduces soil reactions that retain P, which keeps the fertilizer an available form for longer than with broadcast applications.
    - Broadcast applications, especially if left at the soil surface, are agronomically less efficient than in-soil bands and increase the risk of P runoff.
- Increasing farm size may create logistical challenges that make some producers reluctant to band fertilizer at the time of seeding, leading them to select broadcast application or application in the fall, instead of more agronomically and environmentally beneficial options.
- Risk of seedling toxicity should be considered when selecting the rate of seed-placed P fertilizer, especially for sensitive crops such as legumes and canola.

Summary

Phosphorus fertilizer should be applied in a position where the nutrient is available to the plant early in the season, when it is needed to ensure optimum yield. Placement choice will depend on the rate of application being used, the type of crop being grown, the soil and environmental conditions and logistical considerations in the farming operation.

Broadcast P is spread on the soil surface and may or may not be incorporated through a tillage operation. Broadcast and incorporation of P fertilizer distributes the P relatively uniformly through the surface soil, providing a large zone of fertilized soil with a high fertilizer-soil contact. There is little chance of significant P fertilizer injury to the seedling from broadcast, incorporated P fertilizer, but the high degree of contact between the fertilizer and the soil increases P retention, reducing fertilizer use efficiency and does not place the fertilizer in the optimum position for early season access by the crop. However, broadcasting with incorporation is an effective method of managing high rates of P fertilizer to build the background level of P in the soil, particularly prior to establishment of perennial crops such as forages. It is a less effective method of managing lower rates of application for annual crops, especially on low-P soils and/or soils that are cold at planting. Broadcasting P, especially without incorporation, may also be environmentally harmful because it leaves soluble P at the soil surface, increasing the risk of runoff of P into water-bodies.

Band applications place the fertilizer in narrow zones, usually below the soil surface, that provide a concentrated source of P. Band applications may be placed any time before planting, at the time of planting, or after planting. Fluid sources may also be dribble-banded on the soil surface. Unless the bands of P are disturbed by tillage, they remain intact through the growing season. Under no-till systems or with perennial crops, the bands may remain intact over several years because of the lack of soil disturbance. The contact between the banded fertilizer and the soil is low, which reduces the retention of P through soil-fertilizer reactions, so the fertilizer P

remains in a plant-available form for longer than with a broadcast, incorporated application, particularly on soils with a high capacity for P retention. The volume of soil fertilized in a band is smaller than with broadcast applications, so there is a smaller region of high-P soil where the plant roots can grow. However, many plants can intensify root development when they contact a high P zone, increasing their ability to use the banded fertilizer P.

In a one-pass seeding and fertilizing operation, phosphorus fertilizer can be precisely applied in bands in the seed-row, near the seed-row, or in a mid-row band. Phosphorus can also be applied in a separate operation in random bands alone or dual banded with nitrogen fertilizer. The bands can be placed deep in the soil or on the soil surface. With precision GPS technology, bands applied in a separate operation from seeding may be positioned at a specific distance from the seed-row. The precise position of the band may be especially important on soils that are low in P or cold, because these are situations where the seedling needs to reach the P fertilizer early in the season to avoid deficiency. Placing the fertilizer in or near the seed-row allows the plant roots to contact it early in the growing season, when P is required to optimize growth. Positioning the fertilizer in or near the seed-row is particularly important for crops such as flax, which have poorly developed root systems. Placing the fertilizer below the soil surface also keeps the fertilizer in moist soil for longer than with surface applications, reducing the risk of “surface stranding” the fertilizer in dry soil. Banding below the soil surface reduces environmental risk from movement of P to water bodies. In addition, placing the fertilizer in or near the seed-row and below the soil surface can give the crop a competitive advantage over weeds for accessing the fertilizer. Band placement in or near the seed-row is especially important in regions such as the Northern Great Plains because crops are often seeded into cold soils where root growth and P availability are lower than in warm soils (Figure 9). Furthermore, seed-row placement of “starter P” fertilizer can advance crop maturity, an important issue in this region, where the growing season is short. Where soil P levels are moderate to high and the soils are warm, the soil’s reserves of P may be sufficient to support early plant growth and deep- or mid-row banding may be just as effective as seed-placement.

All crops experience seedling toxicity if too much fertilizer is placed too near the seed. Legumes and small seeded crops such as flax or canola tend to be very sensitive to seed-placed fertilizer while cereal crops such as wheat or barley are more tolerant. The damage from P fertilizer is related to salt damage from the fertilizer salt in the soil solution and to ammonia toxicity from the ammonium applied with the phosphate. Increasing N in the fertilizer increases the risk of seedling toxicity. Triple super phosphate (TSP, 0-45-0) has a low salt index and does not contain ammonium, and so it is less damaging than either monoammonium phosphate (MAP, 11-52-0) or diammonium phosphate (DAP, 18-46-0). Coated, controlled release products can be less damaging that uncoated products at the same rate of application; however, these products are not commercially available. Diammonium phosphate is more damaging than MAP because it has a higher N concentration and because it produces a high pH reaction zone, which leads to a higher ammonia to ammonium ratio. Risk of seedling damage is higher on coarse-textured (e.g., sandy) soils because they are less able to adsorb ammonium and ammonia from the soil solution. Moisture will dilute the fertilizer, lowering the concentration in soil solution. Therefore, moist soils or rainfall received after seeding will decrease the degree of seedling damage.

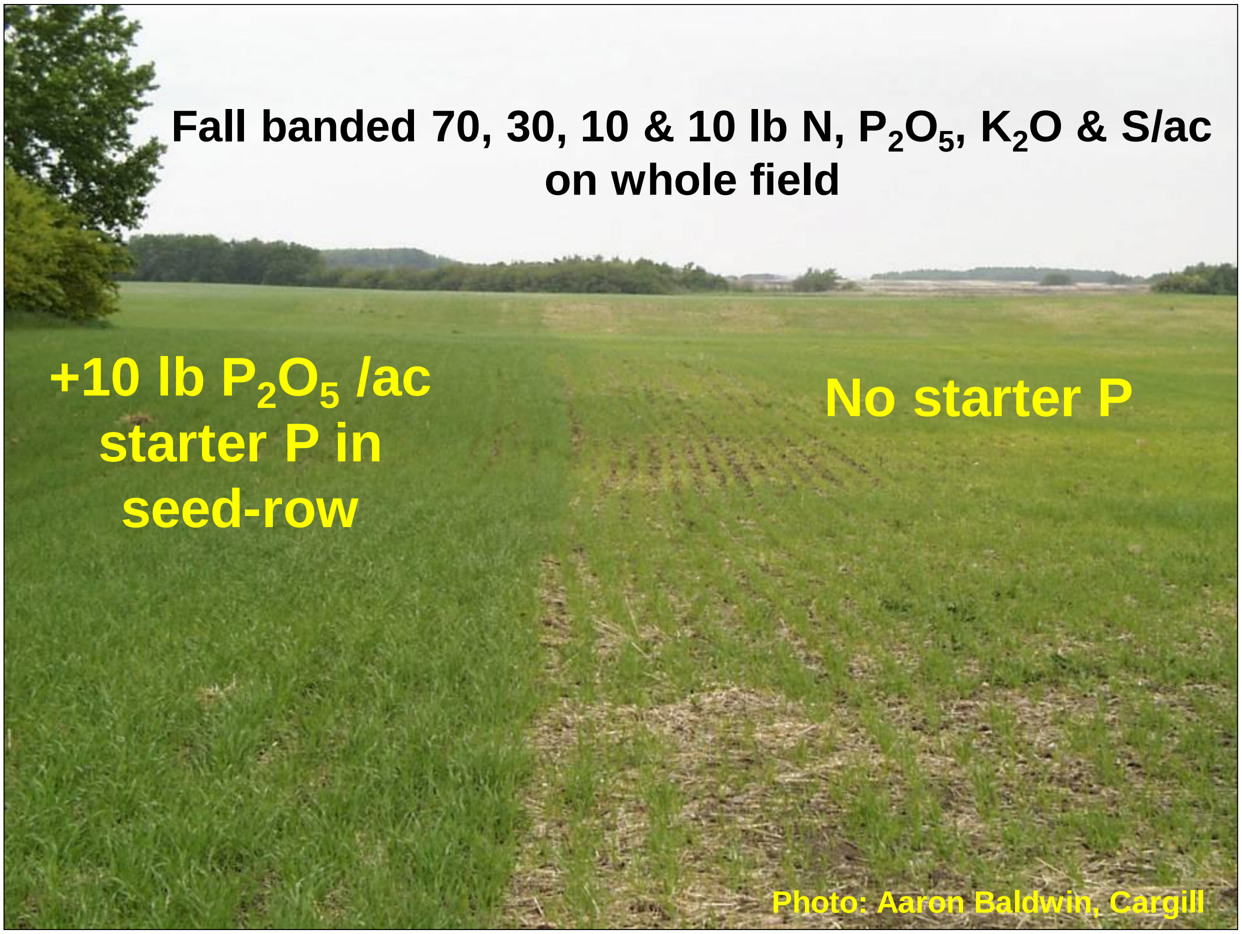

Figure 9. Placement of P in or near the seed-row can improve early growth on cold soils, as shown in this picture of starter P response in Saskatchewan. On the left, a low rate of starter P was applied in the seed-row during spring seeding; both areas of the field received a fall banded application of 30 lbs P_2O_5/acre.

For seed-row placed fertilizer, seedbed utilization (SBU) is the degree of dispersion of the fertilizer and seed and is calculated as the percentage of the total soil area over which the fertilizer and seed are spread. A higher SBU means that the fertilizer is diluted more than with a lower SBU, reducing the concentration of the fertilizer in the solution and decreasing the risk of seedling damage. The SBU can be increased by increasing the width of the fertilizer band or by reducing the row spacing. Recommendations for safe rates of seed-placed P should consider the type of crop grown, soil and moisture characteristics, type of fertilizer and the seed-bed utilization of the seeding equipment being used. While the specific recommendations vary from region to region, recommended safe rates are higher for cereal crops than oilseed crops, higher for fine- than coarse-textured soils, and higher for wide openers and narrow row spacings than for seeders that have lower SBU (Figure 10).

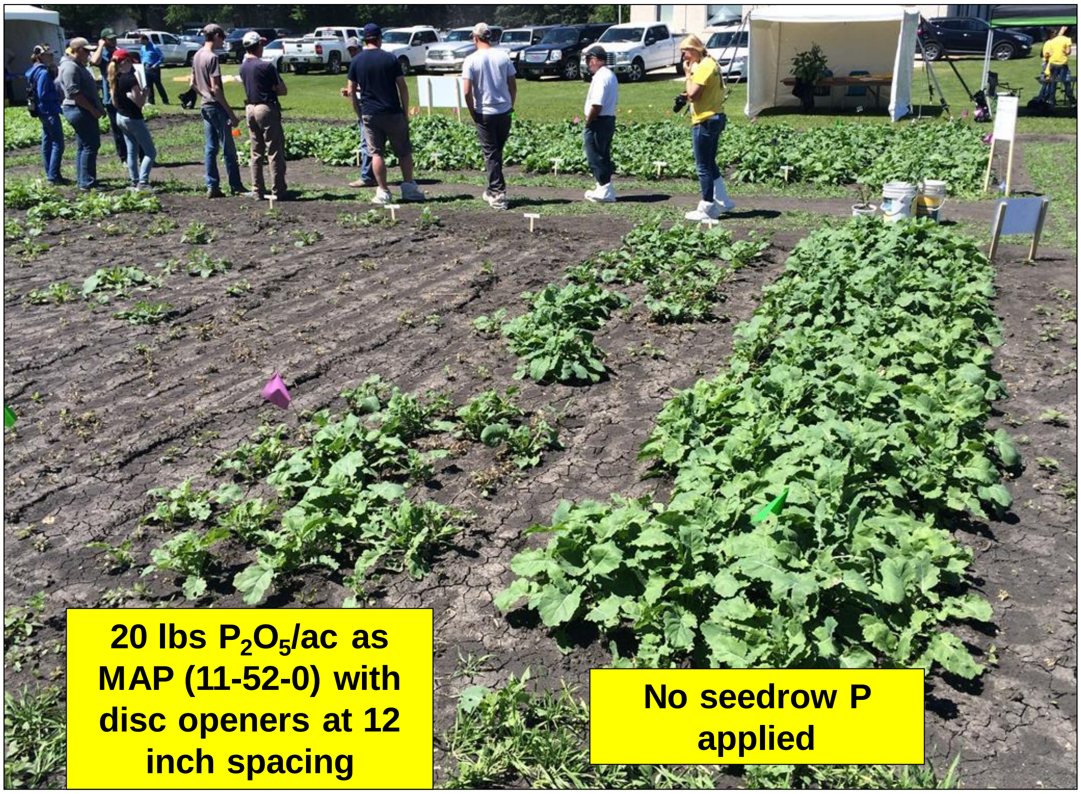

Figure 10. Seed-placed phosphorus fertilizer can lead to seedling damage in sensitive crops (e.g., canola) and low seedbed utilization (e.g, wide row spacings and narrow openers) as shown at the Portage la Prairie AAFC research station in Manitoba (Photo credit: Don Flaten).

Under conditions where a risk of seedling damage exists from rates of P required to support crop yield, the fertilizer may be moved away from the seed-row with side-banding or mid-row banding. Side-banding or mid-row banding effectively reduces the concentration of P in contact with the seed and can produce higher yields by avoiding seedling damage and allowing higher rates of P to optimize crop yield. While some studies have shown that under very P-deficient situations, yield may be reduced by moving the P away from the seed-row, it appears that side-banding of P will be as effective as seed-row placement in increasing crop yield under most conditions experienced in the Northern Great Plains. However, applying all the fertilizer P requirements in mid-row bands may compromise early season access of crops to fertilizer P if the row spacing is wide and/or if large amounts of N are also applied in the mid-row band.

Dual banding is the application of N and P fertilizer in a single band, often placed deep in the soil prior to seeding or in side- or mid-row bands during seeding. The deep dual bands are positioned far enough from the seed that damage will not occur and deep enough in the soil that they are not disrupted during the seeding operation. Deep placement can also position the fertilizer where the soil stays moist long into the growing season and where shallow-rooted weeds are slow to contact it. Placement of the phosphate with ammonium-based or urea fertilizers can increase the availability of the P for plant uptake. Ammonium can increase root proliferation in the fertilizer reaction zone which increases the ability of the plant to absorb the applied P. However, banding P with high rates of urea or anhydrous ammonia may delay fertilizer P uptake because the high concentration of ammonia, ammonium, nitrate, nitrite and salt can prevent root penetration and proliferation in the band (Figure 11). Generally, on highly P-deficient soils, phosphate should not be banded with high rates of N fertilizer, to avoid reduced early-season uptake of the P fertilizer. Alternately, a portion of the P may be seed-placed to provide P to the young seedlings.

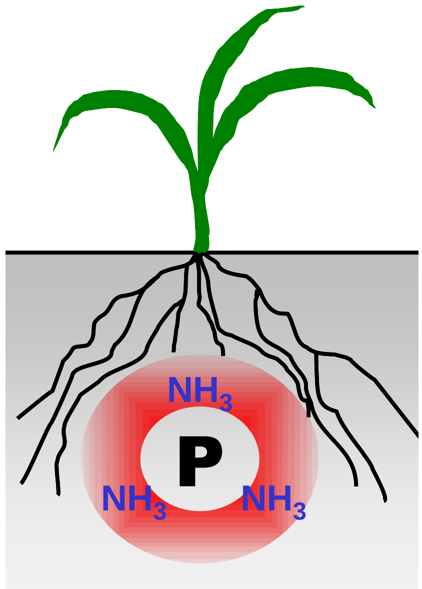

Figure 11. High rates of N fertilizer may delay fertilizer P uptake in "dual" bands, because the high concentration of N delays root penetration and proliferation in the band.

Gaps in Knowledge

More information is required on:

- the long-term persistence of band applications, especially under reduced tillage or where high rates of application are banded.
- the agronomic, economic and environmental benefits of banding rather than broadcasting large application rates in a soil building or maintenance program.
- the interaction between soil temperature and seedling toxicity with different plant species.
- the benefit from in-soil banding of starter P for seeds with a low P concentration compared to seeds with a high P concentration.
- ideal soil volume or combination of band and broadcast P for typical NGP crops

8.0 Phosphorus Fertilizer Timing

Key Messages

- An early supply of phosphorus is critical for optimum crop growth. Therefore, P fertilizer should be applied at a time and in a position where the crop can access it early in the season.
- On the Northern Great Plains, cold soils in the early spring can restrict root growth and P availability, increasing the need for starter P fertilizer applied in or near the seed-row at planting.
- Subsurface band application in or near the seed-row at planting will place the fertilizer in a position where the crop can access it early in the season when it is required for optimum yield.
- Most P movement from fields in the Northern Great Plains occurs during spring snowmelt runoff, so subsurface banding after snowmelt, in or near the seed-row at planting will minimize the risk of P loss.
- Residual fertilizer P that is not used by the current crop often remains available for use by future crops.

Summary

Phosphorus must be available for crop uptake very early in growth because it is needed by the crop from the first stages of germination for energy reactions, cell division and growth. Phosphorus deficiency early in the growing season can reduce crop productivity more than P restrictions later in the season. Therefore, effective 4R management must provide an adequate amount of P in an available form when and where the plant can access it early in the growing season.

Early in the growing season, the roots of the young seedling are small and can explore only a small amount of soil. This is especially true for spring-planted crops in the Northern Great Plains, where cold soil conditions during the early spring can slow root growth. Cold soils will also reduce the solubility and mobility of soil P. The combination of lower P availability and reduced root growth will limit the plant's ability to take up P from the soil when temperatures are low and increase the need for placement of fertilizer P in or near the seed-row.

The optimum timing and placement of P fertilizer are strongly interconnected. The ability of the plant to access fertilizer P early in the growing season will be improved by placing the fertilizer in a position where the roots will contact it soon after germination. Phosphorus is relatively immobile in soil and will remain close to the site of application. Placing the fertilizer in or near the seed-row puts the P in a position where the plant root will contact the fertilizer reaction zone early in growth. Placing the fertilizer in a concentrated band will reduce the contact between the soil and the fertilizer, reducing retention and keeping the fertilizer in an available form for longer in the season. Many crops can increase root density when they contact an area of high P concentration such as a fertilizer band, increasing the ability to take up the nutrient. For crops with the ability to proliferate their roots in the band, a high proportion of the P they accumulate early in growth will come from a fertilizer band. Later in the season, as the plant roots grow, a greater proportion of the P that the plant takes up will come from the bulk soil.

Placing the P in or near the seed-row at planting may be especially important for crops that have limited early-season root development, such as flax. However, soluble fertilizer may lead to seedling damage if excess amounts are placed in or too near to the seed-row. Damage is more likely with ammonia-forming sources such as diammonium phosphate, as the ammonia contributes to seedling toxicity. Banding the fertilizer below or below and slightly to the side of the seed-row may reduce the risk of seedling damage in sensitive crops while maintaining the benefit of banding for early-season crop access to P.

Placement in or near the seed-row at planting is most important in low-P soils where the plant cannot access enough P from the soil to meet its early-season growth requirements. Therefore, benefits from starter P are greatest and most frequent where soil test P concentrations are low. Reduced tillage may also increase response to P applied in or near the seed-row at planting, because soils may be slightly denser and cooler in the spring when undisturbed rather than cultivated. If soils are not extremely deficient in P, application of P as a dual band, deep-placed away from the seed-row with N fertilizer may be effective.

If the soil test P concentration in the soil is high, the plant may be able to access enough P from the soil early in the season to satisfy its P demand. Building the soil P reserves through large applications of fertilizer P or manure can increase both early-season and late-season P supplies and satisfy crop requirements. However, yield responses due to starter applications in or near the seed-row may still occur even when soil P is high, especially with early seeding into cold soils.

An early supply of P can have long-lasting impacts of final crop yield potential, but a supplemental supply of P later in crop growth may also be important, particularly if the plant has not had the opportunity to store surplus P reserves. As the plant root system grows, it will access more P from the bulk soil and less from a fertilizer band. Uptake of P from the soil will continue during later growth stages if environmental conditions permit, and this late-season P supply may be important, depending on the initial P status of the plant. On severely depleted soils, the inability to take up adequate P later in the season may mean that maximum yield will not be obtained, even with high rates of seed-placed P.

Some studies indicate that foliar-applied P fertilizer may provide a benefit as a top-up treatment for wheat or corn if P from seed-placed P applications or uptake from the soil is severely restricted because of moisture stress or low soil P levels. However, benefits of foliar application appear to be rare under conditions experienced on the Northern Great Plains.

In summary, under cold soil conditions as are often experienced in the Northern Great Plains during early plant growth, plant access to soil P tends to be reduced because of slower diffusion, less root growth, and lower availability of native soil P. Under these conditions, fertilizer P may be more necessary to ensure adequate crop growth and may be more available for crop uptake because of slower retention reactions. Band application in or near the seed-row at planting will place the fertilizer in a position where the crop can access it early in the season and when it is required for optimum yield.

Gaps in Knowledge

More information is needed on the potential for improving early-season P nutrition of crops, for example:

- increased seed concentration of P to enhance P supply during germination and early growth.
- genetic selection or modification to produce crops with an enhanced ability for early season uptake of P from both soil and fertilizer sources, especially in cold soils.
- soil testing methods or improved modelling methods that more accurately predict early-season P supply from the soil, and hence crop requirements for P fertilizer additions in or near the seed-row.

9.0 Creating a Cohesive 4R Management Package for Phosphorus Fertilization

Key Messages

- The 4Rs of source, rate, time and place interact and, therefore, must fit with one another and with other agronomic management practices, as well as economic, environmental and social goals.
- Under conventional or reduced tillage systems, subsurface banding in or near the seed-row, at time of seeding, at rates based on suitable soil testing practices and reasonable yield goals will normally provide the most environmentally and economically sustainable results.
- Crops differ in their P demand, sensitivity to seed-placed fertilizer and ability to access P from fertilizer bands or the soil, so management practices must be selected to suit the individual crop.
- Phosphorus supply should be balanced with phosphorus removal over the long term to avoid excess depletion or accumulation.
- 4R management of P fertilizer will provide maximum benefits only if other agronomic management practices are in place to produce a healthy, vigorous crop.
- All nutrients, including N, K, S and trace elements must be available in an adequate supply either from the soil reserve or fertilizer applications to ensure optimum crop yield and P use efficiency.
- Efficient methods of P fertilizer management will improve agronomic, economic and environmental sustainability.

Summary

The basic principle of 4R nutrient stewardship is to apply the right source at the right rate, right time and right place to achieve economic, social and environmental goals for each location. The challenge for 4R management is to develop an effective management package that works cohesively within a dynamic and complex system. As mentioned at the beginning of this review, a 4R management program for P fertilization will deliver maximum overall benefits only if the rest of the "pieces" in the management system "puzzle" are optimized to fit properly with each other (Figure 2).

The 4R principles and practices are science-based and have been developed and tested over time but can be further refined as knowledge and technology evolve. No matter how traditional or novel, the 4R tools will interact with one another and will be affected by the agronomic, environmental, economic and logistical considerations on a given field and farm, and a given year. Therefore, the 4R framework is adaptable and allows a farmer to make nutrient management decisions based on site-specific conditions such as soil type, climate, cropping history, as well as the local sustainability goals.

The overall goal of 4R management of P fertilization is to provide the right amount of P to the growing crop at the time it is required, in the most cost-efficient manner, with the least environmental risk. An effective soil test provides the foundation for 4R management by estimating the rate of P application required, which will be affected by crop type, yield potential, residual soil nutrient levels, crop sequence, and other management factors. Efficiency of P fertilizer use for low rates of application is much higher with banded than broadcast fertilizers, so if low rates of P targeted to optimize short-term yield are being used, band application is preferable. When higher rates of fertilizer P are being applied, e.g., to build soil P, fertilizer can be either broadcast or banded, with banding preferred in areas where there is a substantial risk of P loss with surface runoff.

In the Northern Great Plains, cold soil temperatures in the spring may restrict root growth and P supply, so band placement of P in or near the seed-row is especially important with early seeding into cold soils that are low in P. Similarly, the lower the plant-available P in the soil, the greater the potential benefit of placing the fertilizer near or in the seed-row. With higher soil P levels or later seeding into warmer soils, placement of P in bands further away from the seed-row may be effective. Therefore, optimal placement can also be affected by time of seeding and weather conditions as well as by soil test P and other factors.

Building a 4R management program on the farm must consider a wide range of factors that can affect fertilizer management decisions including tillage system, crop rotation and intensity of production, interactions between P and other nutrients, pest management, risk of off-site P loss and economic, mechanical and logistical constraints. A healthy, vigorous crop is an important factor for effective 4R nutrient stewardship because if crop growth is restricted due to any of these other factors, nutrient use efficiency will decline.

One of the key agronomic management factors that interacts with 4R P fertilizer management is the tillage system. Adoption of reduced tillage over the past thirty years has had a large effect on cropping on the Northern Great Plains. Under reduced tillage, residues are retained at the soil surface where decomposition is slowed, so organic matter accumulates near the surface over time. While reduced tillage can decrease the risk of P transport in soil particles moved via wind and water erosion, stratification of crop residues and nutrients at the soil surface may increase the risk of dissolved P movement in snowmelt, which is the major mechanism of P loss in the Northern Great Plains. On the other hand, reduced tillage may encourage greater mycorrhizal colonization, which will improve soil P availability for mycorrhizal-dependent crops. Reduced tillage will increase moisture conservation and moderate changes in soil temperature influencing organic matter cycling and P dynamics. The greater moisture retention under reduced tillage can allow extended and intensified rotations in areas where water is limiting, increasing P removal and fertilizer requirements. Under no-till or conservation tillage, subsurface banding near the time of seeding, at rates based on suitable soil testing practices and reasonable yield goals will normally provide the most agronomically, environmentally and economically sustainable results.

Continuous cropping, production of high-yielding cultivars, use of balanced fertility to encourage high yields, and rotations including crops with high rates of P removal will increase the demand for P fertilizer to optimize yield and avoid long-term nutrient depletion. Specific crops may have additional effects on P management decisions. Crops differ in their sensitivity to seed-placed fertilizer, with canola, flax and some legume crops being more sensitive than cereal crops such as wheat or barley. Placement of high rates of monoammonium phosphate (MAP, e.g., 11-52-0) or ammonium polyphosphate (APP, e.g., 10-34-0) in or too close to the seed-row of sensitive crops can reduce stand and limit yield response. In these crops, the amount of fertilizer P that can safely be seed-placed may be less than crop removal at harvest, leading to a P deficit. In rotations with high proportions of crops such as soybean, field pea, flax or canola that are sensitive to seed-placed fertilizer, rates of application may be increased by using broadcast, side-band or mid-row band placement or an opener system with higher seed-bed utilization, or by building background soil P with large applications, or by applying higher rates of P to other crops in the rotation, or by choosing a fertilizer source with less risk of toxicity.

Crops such as canola or buckwheat will increase root density when they encounter a region of high P concentration, such as a fertilizer reaction zone, increasing the ability of the plant to use fertilizers effectively. Other crops such as flax, soybean or pulse crops are more effective at using P from the bulk soil and are unlikely to respond to fertilizer applications unless soil levels of P are very low. Therefore, the probability of an economic response to P fertilizer in the year of application will be greater in crops such as wheat or canola than in crops such as flax or soybean. In addition, growth of non-mycorrhizal crops such canola can reduce mycorrhizal colonization of a subsequent mycorrhizal crop such as flax or corn that follows in rotation. Therefore, P management through a rotation should consider the ability of the crop to use P applications, the sensitivity of the crop to fertilizer placement, the balance of input and removal and effects of sequence on P supply to following crops.

Weed competition is a major limiting factor for crop yield on the Northern Great Plains and effective weed control is a key step in optimizing crop yield and profitability. Weeds will compete with the crop for fertilizer P applications, and for light, water and other nutrients. Subsurface band application of P fertilizers near or at the time of seeding at rates matched to crop demand will provide the crop with a competitive advantage over the weeds in accessing P fertilizer. In addition, because weed competition can reduce crop growth and ability to use fertilizer P, effective weed management practices will improve crop yield and fertilizer use efficiency.

Liebig's law of the minimum states that crop growth will be limited by the nutrient in the shortest supply. If other nutrients are limiting for crop production, the crop will not be able to effectively use the P that is applied, and both crop yield and P use efficiency will decline. Similarly, P deficiency will reduce crop yield and efficiency of use of water and other nutrients. Therefore, balanced fertilizer management through identification and correction of nutrient deficiencies will contribute to overall agronomic efficiency. Nitrogen is the nutrient commonly limiting for yield of non-legume crops on the Northern Great Plains and correction of N deficiency will lead to higher crop yields and increased P use efficiency. Potassium is not often deficient on the Northern Great Plains, due to the high native K content in most prairie soils, but may limit crop yield in some instances, particularly on coarse-textured soils, because of their low clay content. Canola is especially subject to S deficiency, so S applications may be necessary when canola is grown on low-S soils to ensure optimum crop yield and efficient use of P. On soils that are low or marginal in available Zn, P fertilization may induce Zn deficiency in sensitive crops and lead to the requirement for Zn fertilization for optimum yield. Zinc deficiency is relatively rare on the Northern Great Plains, but may occur on soils low in organic matter, on sandy soils, on calcareous and high pH soils, on soils with exposed subsoil due to erosion or land-levelling, or on soils where P has accumulated to extremely high levels. Under these conditions, P fertilization will increase the risk of Zn deficiency and application of an effective Zn fertilizer source may be required to optimize crop yield.

In addition to these agronomic issues, 4R management must also address environmental issues, particularly the risk of P movement to water bodies. The 4R fertilizer management practices that increase the amount of P taken up by the crop and/or retained within the field will improve P use efficiency and reduce the risk of P losses from the field to water bodies. Therefore, efficient methods of P fertilizer management will improve agronomic, economic and environmental sustainability.

Gaps in Knowledge

More information is required on the effects of integrated 4R management of P fertilizer in modern, high-yielding, diversified cropping systems over the short and long term. Questions include:

- What are the optimal economic combinations of P fertilizer rates and placements for short term P sufficiency for current crops, varieties (e.g., much higher yielding) and cultural practices (e.g., conservation tillage, fungicides, plant growth regulators)?
- Are there ways to improve P nutrition for crops such as flax or soybean that do not seem to respond well to P fertilizer?
- Are mycorrhizal associations beneficial or harmful to crops such as wheat that do not appear to be as reliant on mycorrhizae as are flax or corn? And how does the frequency of canola in rotations affect this benefit?
- Are high-yielding crops more effective than lower-yielding crops at extracting P from the soil or using P fertilizers?
- Can seed concentration of P be manipulated to improve early season seedling vigour and P supply without negative effects on crop yield?
- Are current soil test methods and recommendations adequate for new crops and the higher target yields farmers are aiming for?
- How should P fertilizer rates be modified on Variable Rate Fertilizer fields?