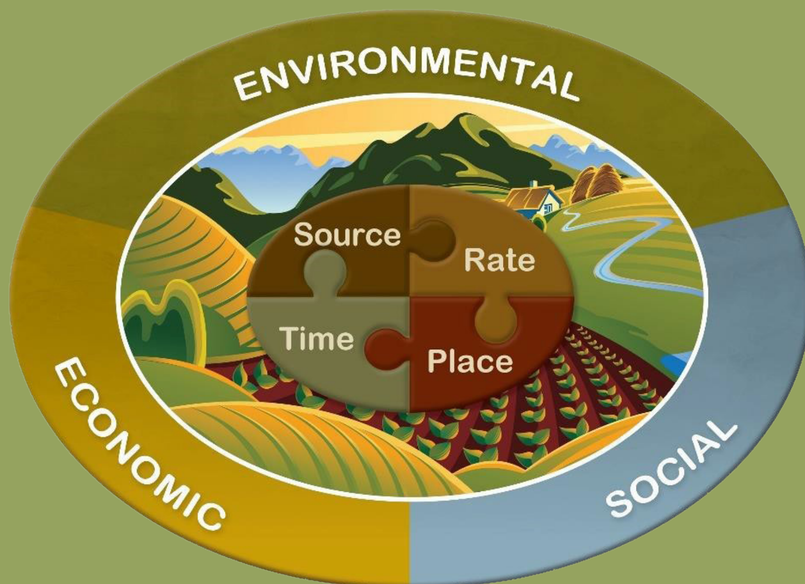
4R Management of Phosphorus Fertilizer in the Northern Great Plains: A Review of the Scientific Literature



July 3, 2019

Cynthia Grant and Don Flaten University of Manitoba

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Fertilizer Canada
Fertilisants Canada

nutrient stewardship

IPNI
International Plant Nutrition Institute

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 this 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.

There is also a summary version of the review that 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.

Outline of the Review

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.

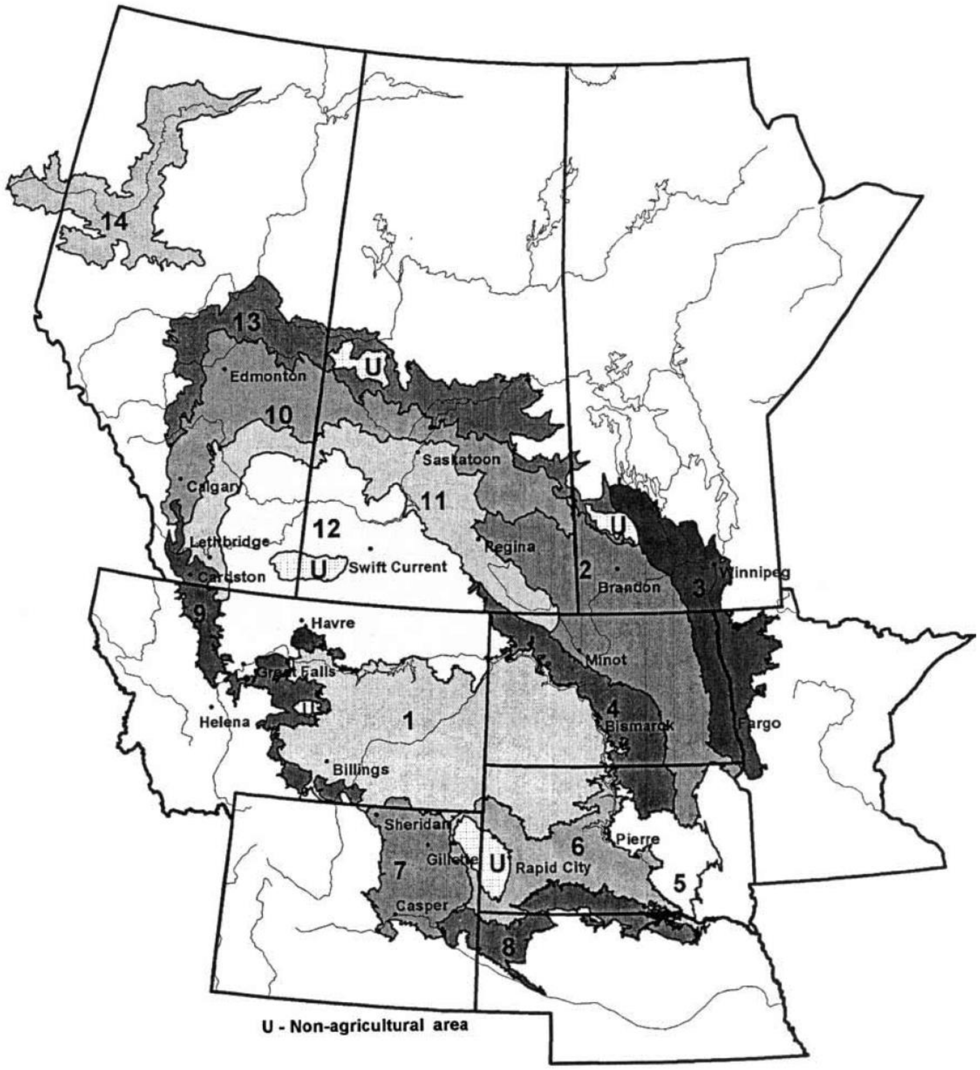

Figure 1. Agroecoregion of the Northern Great Plains (Padbury et al. 2002)

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In addition, the “review” was “reviewed” by a Technical Advisory Group, which included:

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Unit Conversions

Generally, within this document, the measurements are in imperial units (e.g., lbs or bushels per acre). However, most of the scientific literature used for this document report measurements in S.I. or metric units. The following factors can be used to convert between these types of units.

Convert	to	Multiply First Column by	Comments
Acres	Hectares	0.402	
Pounds	Kilograms	0.454	
Inches	Centimeters	2.54	
Pounds per acre	kg/ha	1.12	
Canola (bu/acre)	kg/ha	56.0	
Wheat (bu/acre)	kg/ha	67.3	
Barley (bu/acre) 48 lb bu	kg/ha	53.8	
Flax (bu/acre)	kg/ha	62.8	
ppm	lb/acre in six inches	2	Assumes that bulk density is uniform and high, at 1.33 g/cm^3
P	P_2O_5	2.29	
P_2O_5	P	0.44	

Definitions of Concentrations

ppm = $mg\ L^{-1}$ or mg/L if reported as concentration in solutions (e.g., in water) or
$mg\ kg^{-1}$ or mg/kg if reported as concentrations per unit of mass (e.g., in soil)

ppb = $\mu g\ L^{-1}$

Abbreviations

4R	applying the right nutrient source at the right rate, right time and in the right place
ADP	adenosine diphosphate
AMF	arbuscular mycorrhizal fungi
APP	ammonium polyphosphate liquid fertilizer (e.g., 10-34-0)
ATP	adenosine triphosphate
BMP	beneficial management practice
Cd	cadmium
DCP	dicalcium phosphate
DCPD	dicalcium phosphate dihydrate
DNA	deoxyribonucleic acid
DAP	diammonium phosphate granular fertilizer (e.g., 18-46-0)
FA	fulvic acid
HA	humic acid
HFA	mixture of humic and fulvic acid
KS	potassium sulphate granular fertilizer (e.g., 0-0-50-18S)
LDH	layered double hydroxide
MAP	monoammonium phosphate granular fertilizer (e.g., 11-52-0)
MCP	monocalcium phosphate
N	nitrogen
NADP	nicotinamide adenine dinucleotide phosphate
NADPH	reduced form of nicotinamide adenine dinucleotide phosphate
NMR	nuclear magnetic resonance (spectroscopy)
OCP	octacalcium phosphate
P	phosphorus
P_i	inorganic phosphorus
P_o	organic phosphorus
PUE	phosphorus fertilizer use efficiency
RNA	ribonucleic acid
SBU	seedbed utilization
SSP	single or "ordinary" superphosphate granular fertilizer (e.g., 0-20-0-10S)
STP	soil test phosphorus
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.

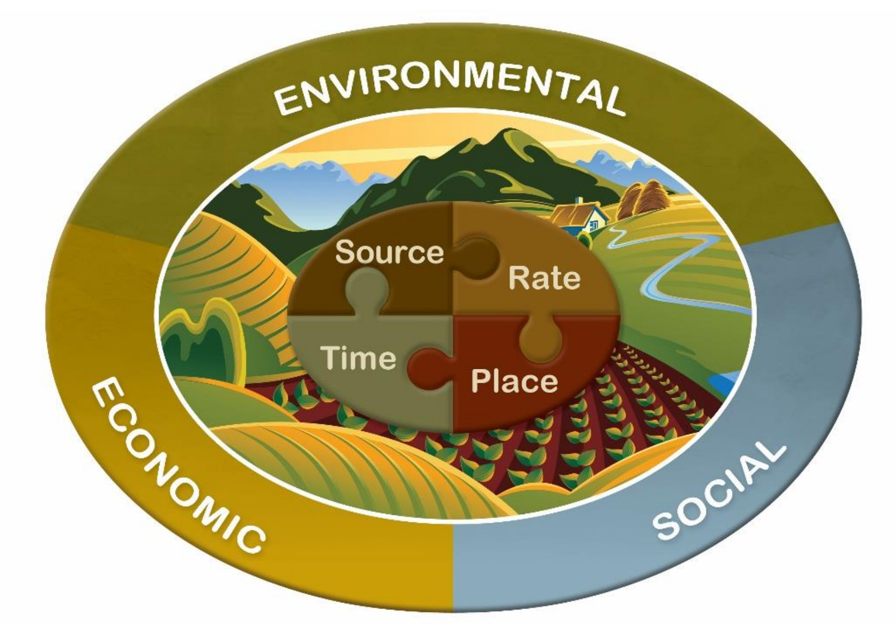

Figure 1 . The 4R nutrient stewardship concept defines the right source, rate, time, and place for plant nutrient application as those producing the economic, social, and environmental outcomes desired by all stakeholders to the soil-plant ecosystem (Roberts 2010) figure credit: http://www.ipni.net/ipniweb/portal/4r.nsf/article/communicationsguide

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.

Detailed Information

1.1 History

The idea of effectively managing nutrients for crop production is not a new one. Marcus Porcius Cato, the Elder in ancient Rome (234 to 149 B.C.E.) laid out principles for using manure and legume crops effectively to optimize crop yield and sustain soil fertility (Cato the Elder 2016). However, development and application of Beneficial Management Practices (BMPs) for fertilizer applications have evolved with increasing understanding of the impact of nutrient management on agronomic productivity and the environment. In 2007, the International Fertilizer Industry Association (IFA) initiated a program to define the principles of fertilizer BMPs and develop a strategy to encourage their international adoption. At an IFA workshop held in Brussels in 2007 to define and encourage the adoption of fertilizer BMPs, Paul Fixen described the idea of a global BMP framework that would be science-based, tested through farmer implementations, adaptable to local conditions and able to change and evolve as understanding of the system increased (Fixen 2007). The framework was based on economic, agronomic, environmental and social stewardship goals that could be addressed by fertilizer management objectives using the right rate, source, placement and timing of nutrient application, based on fundamental scientific principles on a site- and grower-specific basis. The concept of a global framework for sustainable nutrient management that could be applied on a local level was further developed by IFA and the International Plant Nutrition Institute and became the Global "4R" Nutrient Stewardship Framework (Bruulsema 2017; Bruulsema et al. 2009; Bruulsema et al. 2008; IFA 2009).

1.2 Background and principles

The 4R nutrient stewardship framework is a conceptual approach to optimize agronomic crop yield and quality, economics of production, environmental and social good on a site-specific basis (Bruulsema 2017; Bruulsema et al. 2009; Flis 2018; IPNI 2012). The initiative focusses on applying the right nutrient source or product at the right rate, right time and right place to achieve sustainability goals. The framework also 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 economic, environmental and social desires of the various stakeholders are considered within the cropping system 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.

The 4Rs are the tools that are used by the producer in the management system to address the sustainability goals. The basic principle is to apply the right source (or product) at the right rate, right time and right place. These four "rights" (4R) encompass the nutrient management options available to achieve the economic, social and environmental goals. The 4R framework is adaptable and allows a producer to make nutrient management decisions based on site-specific conditions such as soil characteristics, climate, cropping history, as well as the local sustainability imperatives (Bruulsema 2017; Bruulsema et al. 2009; Bruulsema et al. 2008; Flis 2018; IPNI 2012; Johnston and Bruulsema 2014). Therefore, within the 4R framework, these fertilizer BMPs should be developed for each location considering all three goals for sustainable development.

Right Rate - Choosing the right rate means matching the fertilizer applied to the crop demand. The rate required will be affected by crop type, yield potential, residual soil nutrient levels, crop sequence, and other management factors. Accurate assessment of nutrient supply is a first step to selection of the right rate. Optimum rate will reflect the balance between crop demand and soil supply. Rate is also affected by source, timing and placement methods and by short- and long-term sustainability goals.

Right Source - Using the right source means using a form that is suitable to the crop being grown, the management practices used and the environmental conditions occurring in the field. The source selected should provide plant-available nutrients to meet crop demand. Sources of P fertilizer include fluid fertilizers such as ammonium polyphosphates, dry granular products such as monoammonium or diammonium phosphate, triple superphosphate, rock phosphate, or compound fertilizer. Composts, manures and reclaimed materials such as struvite are also sources of P. Various additives, coatings and amendments may also be used to improve the effectiveness of applied fertilizer sources. Source selection will be affected by balance and interaction with other nutrients and the presence of other nutrients or contaminants in the fertilizer material. Selection of source must also consider factors such as soil characteristics, timing of application, method of placement, availability of P over time, compatibility issues, and cost per unit of "actual" nutrient.

Right Place – Applying fertilizer in the right place means that the nutrient must be in a position where the crop can access it when needed and where it will not be lost from the system. Phosphorus is not very mobile in the soil and should be placed in a position where the crop roots can access it early in the growing season. Seed-placement or side-banding P ensure that the crop roots reach the fertilizer early in the season to correct P deficiencies. Root geometry is an important factor in selecting proper placement. Surface applications of P, especially if not incorporated, are at risk for transport off-site to surface waters, so should not be used in environmentally sensitive areas.

Right Time - Applying fertilizer at the right time means making nutrients available to the crop when they are needed. Nutrient use efficiency can be increased significantly when availability is synchronized with crop demand. Early-season P supply is critical for optimum crop growth, so it is important that P be accessible by the crop early in the season. Placement and source will interact with timing, to ensure that a readily available form of P can be safely placed near the seedling for the plant to use early in the season. Timing of application may also influence risk of off-site movement of P, through snow-melt or rainfall events.

Although the "4R" title for this nutrient management framework is relatively new, most of the science-based fertilizer management principles within the framework have been developed and tested over many years. Nevertheless, these principles and practices are dynamic and will continue to change as knowledge and technology evolve. They are interdependent and must be developed as a package, rather than as individual practices; hence, the portrayal of them as interlocking pieces of a puzzle in Figure 1. They are also dependent on the other crop management practices being used in a cropping system. Tillage, cultivar selection, weather, pest management practices, land tenure, equipment and labour availability and a range of other factors will impact 4R choices. Therefore, the 4R framework is flexible and adaptable and allows a producer to make nutrient management decisions to address short- and long-term sustainability issues on a site-specific basis. Sound science provides the basis for current recommendations and for 4R practices to evolve and adapt to changing conditions and changing technology.

While application of 4R stewardship occurs at the farm level, development and evaluation of 4R stewardship will also occur at regional and policy levels (Figure 2). At a regional level, scientists work to provide locally tested, science-based tools for farmers, with recommendations for the right source, rate, time and place for local conditions. At a policy level, resources are allocated to support research and extension, regulations are made that will influence the practices that will be allowed on the farm, and subsidies or incentives may be provided to encourage adoption of BMPs. At each level, the success of 4R stewardship practices should be assessed based on the performance of the cropping system in addressing the sustainability goals and decisions made to continue, revise or discard the practices, based on their measured performance. Performance indicators on-farm will include crop yield and quality, nutrient use efficiency, change in soil nutrient reserves, improved operational efficiency and economic profitability. Other indicators such as long-term resource sustainability, environmental impact, or societal effect may be more difficult to measure directly in an individual field, but may be calculated based on estimate of aggregate risk. Successful 4R nutrient stewardship will address multiple and site-specific sustainability goals.

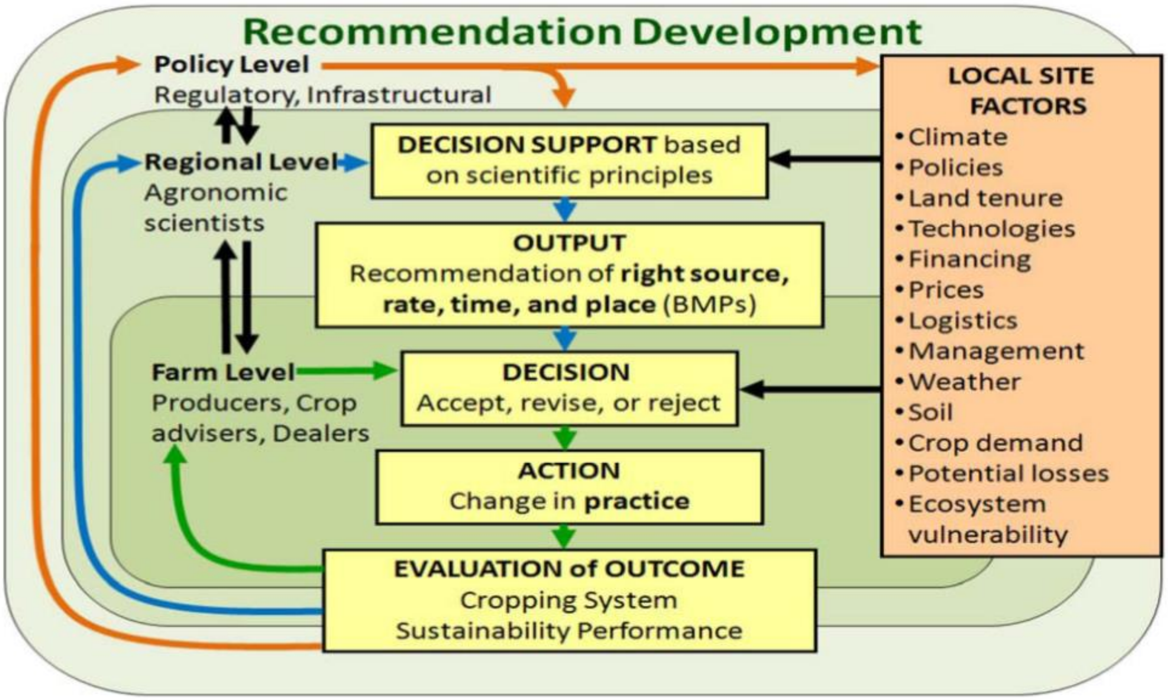

Figure 2. The 4R nutrient stewardship concept requires evaluation of sustainability performance, whether applied on-farm by producers and advisers, in recommendation development by agronomic scientists, or in consideration at the policy level. Practical decisions depend on close attention being paid to the full range of local site factors (Johnston and Bruulsema 2014).

The 4R Nutrient Stewardship Framework provides a flexible and adaptive method of selecting nutrient management practices to address short- and long-term economic, social and environmental sustainability issues on a site-specific basis. Sound science provides the basis for current recommendations and for 4R practices to evolve and adapt to changing conditions and changing technology. The following chapters will provide an outline of the 4R nutrient stewardship tools and the science behind their development in the Northern Great Plains.

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.

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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 metabolites 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.

Detailed Information

2.1 Functions of P in plants

Phosphorus is one of the 17 essential plant nutrients. It is critical for plant metabolism and an adequate amount of P is required for a plant to grow and reproduce. Phosphorus is needed in nearly all energetic reactions in a plant because of its role as a component of adenosine triphosphate (ATP), adenosine diphosphate (ADP), nicotinamide adenine dinucleotide phosphate (NADP) and NADPH (Glass et al. 1980; Hopkins 2015; Raven et al. 2005; Sultenfuss and Doyle 1999). The ATP molecule is composed of a unit of adenine, a sugar and three phosphate groups, with the last two phosphates linked to the molecule by a high-energy bond (Figure 1). The NADP and NADPH molecules also contain phosphate groups (Figure 2).

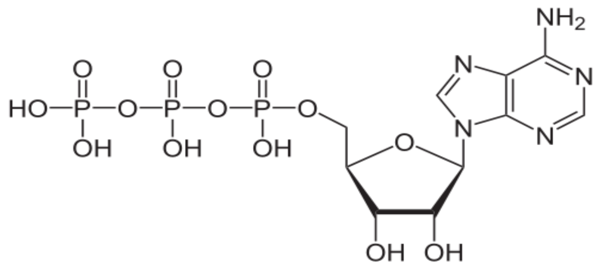

Figure 1. Structure of adenosine triphosphate (ATP)
https://en.wikibooks.org/wiki/Structural_Biochemistry/ATP#/media/File:Adenosintriphosphat_protoniert.svg

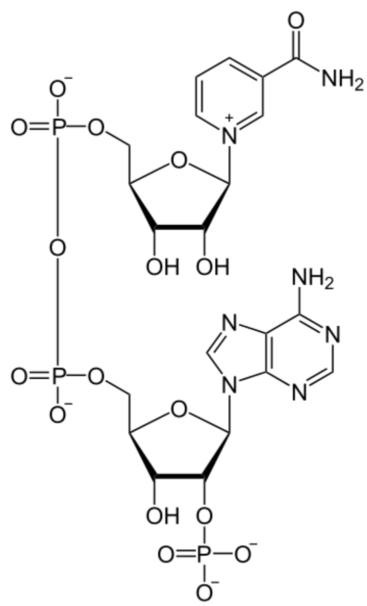

Figure 2. Structure of NADP (NEUROtiker - Own work, Public Domain, https://commons.wikimedia.org/w/index.php?curid=2326143).

Phosphorus plays a key role in photosynthesis. The light energy absorbed by chlorophyll during photosynthesis is stored in adenosine triphosphate (ATP) and serves as the primary source of energy for all energy-requiring biological processes. Light energy captured by the chlorophyll molecule during photosynthesis causes the chlorophyll to lose an electron. In non-cyclic reactions in photosystem II, the electron passes down an electron transport chain, reducing NADP to NADPH and creating an energy gradient across the chloroplast membrane that is used to synthesize ATP (Raven et al. 2005).

$$2\ H_2O + 2\ NADP^+ + 3\ ADP + 3\ P_i + \text{light} \rightarrow 2\ NADPH + 2\ H^+ + 3\ ATP + O_2$$

In the cyclic reaction, which takes place only in photosystem I, no NADPH is generated, and the displaced electron returns to photosystem I from which it was emitted. Through the action of these two photosystems, light energy is converted to stored chemical energy that can be used to power plant metabolism. The NADPH and ATP formed using the energy captured during the light reactions are used to reduce carbon dioxide to carbohydrates during the dark reactions of photosynthesis.

$$6\ CO_2 + 6\ H_2O \xrightarrow{\text{Light energy}} C_6H_{12}O_6 + 6\ O_2$$

When the phosphate is transferred from the ATP to another molecule by hydrolytic enzymes, the high energy bond is broken, and the energy is released. The ATP hydrolysis can be coupled with other energy-requiring reactions to power their progress.

Phosphorus is a structural component of the nucleic acids (e.g., DNA and RNA) of genes and chromosomes and of many coenzymes, phosphoproteins and phospholipids (Figure 3) (Raven et al. 2005). Phosphate compounds are also intermediate metabolites in a wide range of metabolic processes (Raven et al. 2005). The concentration of inorganic P present in the cell is involved in enzyme regulation and in the control of starch synthesis (Mills and Jones 1996). Dissociation of phosphoric acid plays a role in buffering cellular pH and maintenance of homeostasis (Mills and Jones 1996).

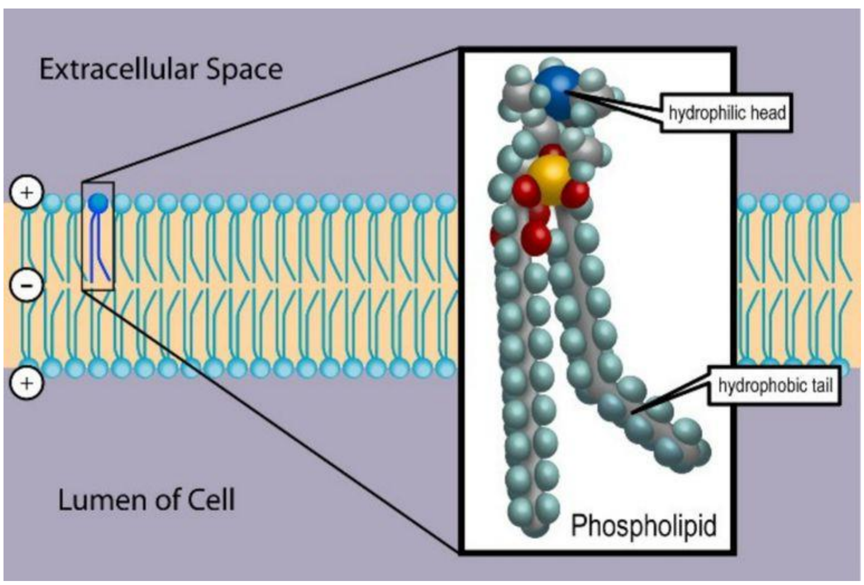

Figure 3. The phospholipid bilayer is an important component of cell membranes (https://www.thoughtco.com/phospholipids-373561)

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 P containing cellular components.

Therefore, an adequate supply of P is essential from the earliest stages of plant growth. Studies conducted at Melfort, SK showed that about half of the P accumulation in wheat occurred by about 41 days after emergence, with maximum uptake of P attained by full flowering to late milk or ripening, depending on the environmental conditions during the growing season (Malhi et al. 2006). The maximum rate of P accumulation and the maximum total P uptake occurred earlier than the corresponding values for biomass accumulation, a pattern similar to that of N and other macronutrients, indicating that P uptake preceded biomass accumulation and that the supply of nutrients must be adequate in early stages to support biomass production. However, P accumulation continued until as late as the early ripening stages. A similar pattern of nutrient accumulation preceding biomass accumulation occurred for pulse crops (Malhi et al. 2007b) and oilseed crops (Malhi et al. 2007a). The P present in the seed of cereal grains is largely provided by redistribution of nutrients accumulated in the vegetative tissue during the early stages of growth. As the plant develops, P is transported from leaves and stems to the grain until 75 to 80% of the plant P is present in the grain at maturity (Mohamed and Marshall 1979). Although uptake of P by the plant continues until as late as the ripening phase, the supply in the early growth stages has a great effect on plant response. 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 (Grant et al. 2001).

2.2 Phosphorus accumulation in plants

Phosphorus is taken up by the plant root as inorganic P (P_i). The major location for P uptake by plants is in the area of actively growing cells just behind the root cap, where root hair density is high (Hopkins 2015). Uptake of P_i requires energy since P_i concentration in the soil solution is as much as 1000-fold lower than that in the plant (Schachtman et al. 1998; Vance et al. 2003). The P_i is transported across the plasma membranes of the root cells and moved in the symplasm from the root surface to the xylem. The P_i travels in the xylem from the root and is distributed throughout the plant, again by passing through the membranes of other cells and organelles (Rouached et al. 2010; Schachtman et al. 1998). Movement from the xylem to the cell cytoplasm is also against a steep concentration gradient, so it requires active transport. The movement of P_i across cell membranes uses a suite of primary orthophosphate transporter proteins, with both low- and high-affinity transporters involved in phosphate uptake (Schroeder et al. 2013). The high affinity system tends to function when P_i concentrations are low, improving the plant's ability to transport the orthophosphate across the root membranes when P supply is restricted. Phosphate transporters also function in the distribution of P_i throughout the plant and from source to sink tissues and in regulating phosphate homoeostasis within the plant. Since P is transported as an anion, co-transport requires a counterion. The cytoplasm is acidified when P is added to deficient cells, indicating that H^+ is likely the counterion (Vance et al. 2003). Surplus P_i will be stored in the vacuole, where it can be a reserve for future deficiencies (see Section 2.4). The concentration in the vacuole tends to be lower than that in the cytoplasm, so movement from the cytoplasm to the vacuole does not need an input of energy, although there is evidence of active transport in some cases (Yang et al. 2017). Phosphorus deficiency can trigger an active movement of P_i from the vacuole to the cytoplasm to meet the metabolic requirements of the plant (Yang et al. 2017).

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 intensity factor or I), the area of absorbing surface in contact with the solution, and the movement of P ions through the soil. The inorganic P in the soil solution is present as orthophosphate P ions, usually $H_2PO_4^-$ and HPO_4^{2-}, with most P_i being present as $H_2PO_4^-$ if the pH is below 6 (Figure 4). Uptake rates of P_i by plants tend to be greatest between pH of 5 and 6, indicating that P_i is primarily taken up by the plant in the monovalent form, $H_2PO_4^-$ (Schachtman et al. 1998). 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 (Bagshaw et al. 1972). Phosphorus ions will move through the soil water to the root surface by mass flow and diffusion (Barber 1980; Barber et al. 1963). However, because the concentration of P in the soil solution is very low, the total amount of P that will move to the plant root via mass flow will also be very low, in the order of 2-3% of the total amount required for optimum crop growth (Johnston et al. 2014). Therefore, most P movement towards the root surface occurs through diffusion down the concentration gradient created by the active uptake of P by plant roots (Barber 1995). Movement of P will increase with increasing concentration of P in the soil solution, partly because there will be more P_i in the water moving towards the plant in mass flow and mainly because the concentration gradient for diffusion will increase as the P_i concentrate in the bulk soil increases. However, the speed of diffusion of phosphate ions though the soil solution is very slow and the path of movement through the soil moisture films around the soil particles is long and crooked, or “tortuous”. Therefore, the net movement of P though the soil is small, in the range of 0.13 mm per day.

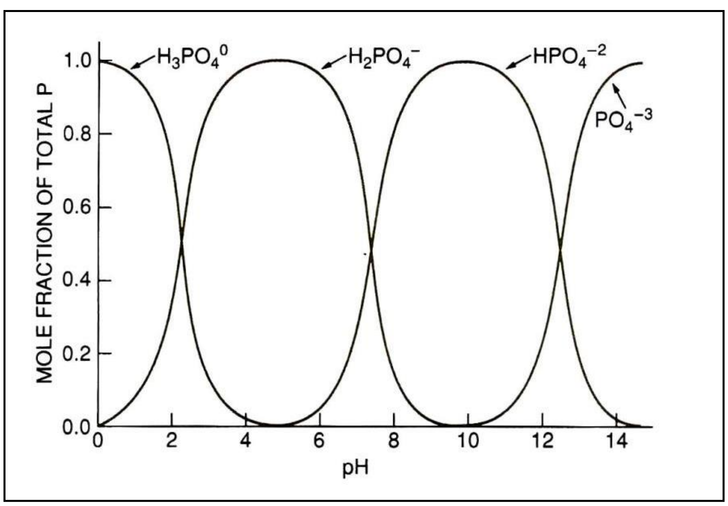

Figure 4. Influence of pH on the distribution of orthophosphate forms in solution (Havlin et al. 2014).

While the P ions in soil solution are the immediate source for uptake by the plant, the soluble P_i in solution at any given time generally represents less than 1% of P taken up by crops during a growing season, with approximately 99% of P that plants use over time being bound to soil constituents prior to uptake. Phosphorus in the soil is present in organic and inorganic forms of varying availability (Figure 5). As the phosphate ions in the soil solution are depleted they are replenished from the organic and inorganic reserves of P that are present in soil solids or on soil surfaces. These reserves are broadly divided into "Labile" and "Non-Labile" forms. Labile P will rapidly equilibrate with the soil solution and become available in the short-term, while non-labile P equilibrates more slowly and will replenish the labile reserves and the soil solution in the long-term (Figure 5) (Johnston et al. 2014; Syers et al. 2008).

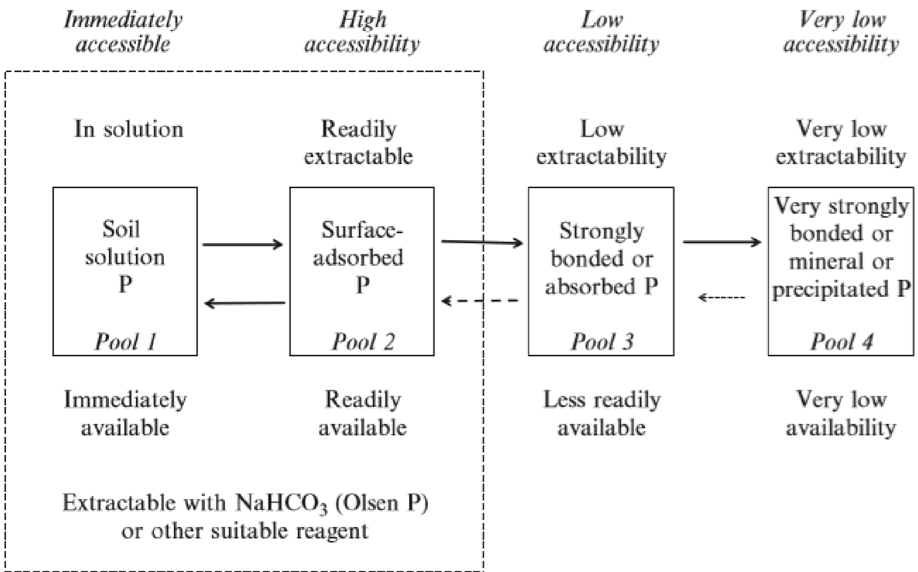

Figure 5. Conceptual diagram for the forms of inorganic P in soils categorized in terms of accessibility, extractability and plant availability (Johnston et al. 2014)

The ability of the soil to replenish the P in the soil solution is referred to as the quantity factor (Q) or the P buffering capacity. The depletion of the P ion concentration of the solution at the root surface though plant uptake will drive the movement of P by diffusion to the root surface and the movement of inorganic P into solution from the labile pools. Conversely, addition of soluble forms of P such as fertilizers will shift the equilibria towards the less available pools. The movement of P among the various phases varies with time and the gradient of P ion concentration (Morel and Plenchette 1994; Morel et al. 2000; Schneider and Morel 2000). Phosphorus supply to a crop will be influenced by the ability of the soil to replenish the depletion zone at the root surface from the P present in the soil in the other pools, especially the labile P pool. During periods of peak P demand, the P in the soil solution at the root hair surface must be replenished at least 10 to 20 times per day (Syers et al. 2008). 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) (Morel et al. 2000).

2.3 Effects of phosphorus deficiency

In tissues of most of the higher plants, phosphate is mainly present as inorganic phosphate. More than 75% of the P moving in the xylem is inorganic phosphate, while that moving in the phloem is generally present as proteins, RNA, enzymes and ATP (Bieleski 1973; Glass et al. 1980; Lefebvre and Glass 1982). With an adequate supply of P, much of the inorganic P is stored in cell vacuoles as orthophosphate or present in storage compounds such as phytic acid or polyphosphate. In seeds, P is stored in a myoinositol-P form, for example as a Mg or K salt of phytic acid in cereals and legumes. For the first few days of growth, a plant will rely on its seed reserves and external P supply will have little effect on growth. Only a small amount of the P in plants is metabolically active and much of the metabolically active portion is involved in cyclical processes such as the cycle between ATP and ADP. The metabolically active P will be held relatively constant by the plant and so will vary much less with changing external P supply than will the concentration of stored inorganic P. When the external P supply falls, the plant remobilizes the stored inorganic reserves while the metabolically active forms are maintained (Ozanne 1980). Therefore, luxury uptake of P early in the season, or high P concentration from the seed can help the plant to maintain metabolic activity when external P supply becomes restricted.

Plants respond to P deficiency by implementing strategies to increase their ability to access P from the soil. One strategy used by plants to increase access to P is enlargement of the root surface area. Plants preferentially retain P in the root, over moving it to the shoot when P supply is limited to meet the metabolic requirements for root growth to access soil P (Loneragan and Asher 1967; Schjørring and Jensén 1984; Sutton et al. 1983). With P deficiency, many plants will also allocate more carbohydrate to roots than shoots (Marschner et al. 1996), increasing the root:shoot ratio to improve their ability to access P from the soil (Brenchley 1929; Schjørring and Jensén 1984). Under low-P conditions, plants develop enlarged root systems, with highly branched roots, numerous and long root hairs, and a greater root length per unit mass to increase the soil volume explored (Barber 1977; Brenchley 1929; Hodge 2004; Ozanne 1980; Schjørring and Jensén 1984; Tomasiewicz 2000; Vance et al. 2003). In addition, many plants such as canola and 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 extract P from that area (Drew and Saker 1978; Foehse and Jungk 1983; Strong and Soper 1974a; Strong and Soper 1974b). Uptake of P by roots is proportional to both the concentration of the P at the root surface and the area of absorbing root surface that contacts the P, so root proliferation in a zone of high P concentration increases the ability of the plant to take up P. Other plants, such as flax and soybean, are less able to proliferate roots in a high-P zone and are more reliant on P in the bulk soil.

Plants can also implement physiological changes in response to P deficiency to enhance the ability of the root to absorb P from the solution (Hodge 2004). Uptake rate per unit of root can be increased in P-deficient plants (Anghinoni and Barber 1980; Borkert and Barber 1983; Drew et al. 1984; Green et al. 1973; Hodge 2004; Jungk and Barber 1974). Many plants will secrete low molecular weight amino acids that acidify the rhizosphere, compete with phosphate ions for sorption sites, and complex cations bound to phosphate ions, thus increasing P availability (Hinsinger 1998; Hinsinger 2001; Hinsinger and Gilkes 1995; Hoffland et al. 1989; Jungk et al. 1993). Some plants can also excrete phosphatases into the rhizosphere to release P from organic forms (Ashworth and Mrazek 1995; Hinsinger 2001; Lefebvre and Glass 1982). Plants can also excrete compounds that encourage development of P-solubilizing microorganisms in the rhizosphere (Kucey et al. 1989; Richardson 2001; Richardson et al. 2009).

Another strategy used by most plant species to improve access to soil P is to form mycorrhizal associations (Bolan 1991; Grant et al. 2005; Hamel and Strullu 2006; Jakobsen 1986; McGonigle et al. 2011; Miller 2000; Monreal et al. 2011; Ryan and Graham 2002; Ryan et al. 2000; Smith et al. 2011). In return for fixed carbon from the host, mycorrhizal fungi capture P, water and some other nutrients from the soil and transfer it to the plant. The mycorrhizal hyphae are finer than plant root hairs and will extend both further from the root and into finer soil pores, greatly increasing the effective volume of soil that can be accessed by the mycorrhizal association. Plants vary substantially in their reliance on mycorrhizal colonization for P access, with some crops such as flax relying heavily on mycorrhizal associations and other crops such as canola, having no mycorrhizal associations.

Phosphorus deficiency symptoms are often subtle, and moderate P deficiency may not produce obvious symptoms. If P deficiency becomes severe, the plant may develop dark green or purple coloration of leaves and stems (Hopkins 2015; Hoppo et al. 1999). Both photosynthesis and respiration can decline with P deficiency, but if respiration falls more than photosynthesis, carbohydrates will accumulate producing a dark green colour. Anthocyanins may accumulate because of a blockage in metabolic pathways, leading to purpling or reddening of the tissue (Close and Beadle 2003). With severe P deficiency, nitrate reduction may proceed normally but the synthesis of proteins and nucleic acids may be restricted, so that soluble N compounds accumulate in the tissue. Metabolic processes in the cell will be slowed because of the lack of protein catalysts, so cell growth can be impaired by P deficiency (Elliott et al. 1997a; Glass et al. 1980). Restrictions in cell growth leads to shorter plants, delayed leaf emergence, delayed development, reduced tillering and secondary root development, decreased dry matter yield and reduced seed production (Elliott et al. 1997a; Glass et al. 1980; Grant et al. 2001; Hoppo et al. 1999; Konesky et al. 1989). Plants will respond to P deficiency in a way that will increase the probability of producing viable seed. For example, in cereal crops, P stress will reduce seed number by reducing the number of fertile tillers and the number of grains per tiller, but seed size will be maintained. (Hoppo et al. 1999). In soybean, P deficiency will reduce the number of pods and seeds, but will not decrease seed size (Crafts-Brandner 1992). The restricted plant resources are distributed among fewer seeds, increasing the likelihood that the remaining seeds will be viable.

Deficiency generally occurs at P concentrations in plant tissue below 0.2%, but the sufficiency thresholds will vary with crop stage and with different crops (Table 1). The P in plant tissue will usually decline as the plant ages and matures because of a declining proportion of metabolically active tissue and an increasing proportion of low-P structural and storage tissue (Bélanger and Richards 1999; Elliott et al. 1997a; Racz et al. 1965). Therefore, the critical P concentration required for optimum growth decreases as plants age (Elliott et al. 1997a; Elliott et al. 1997b; Tomasiewicz 2000). Phosphorus is generally mobile in the crop and will re-translocate from vegetative tissue to storage organs such as seeds. As a result, most of the P taken up by the crop will be removed in the harvested material (Table 2).

Table 1. Sufficiency ranges for phosphorus tissue concentrations in selected crops of the Northern Great Plains. (Adapted from Mills and Jones (1996)).

Species	Latin Name	Plant Part Sampled	Timing	P Concentration %
Alfalfa	*Medicago sativa* L.	12 tops 15 cm new growth	Prior to flowering	0.26 to 0.70
Barley	*Hordeum vulgare* L.	25 whole tops	emergence of head from boot	0.20 to 0.50
Beans	*Vicia faba L.*	50 leaf blades without petiole from uppermost mature leaves	summer	0.32 to 0.42
Brome	*Bromus inermis L.*	25 fully developed stems with leaves	Summer, midway between mowings	0.25 to 0.35
Canola	*Brassica napus* L.	50 mature leaves (5th from the top) without petioles	Rosette to pod development	0.28 to 0.69
Corn	*Zea mays* L.	15 whole tops	Plants 30 cm tall	0.30 to 0.5
Oats	*Avena sativa* L.	25 whole tops	Head emerging from boot	0.20 to 0.50
Potato	*Solanum tuberosum* L.	25 most recent fully-developed leaves	Plants 30 cm tall	0.20 to 0.50
Rye	*Secale cereale* L.	25 whole tops	Panicle initiation	0.52 to 0.65
Sorghum	*Sorghum bicolor* L.	25 whole tops	seedlings < 30 cm tall, 23 to 39 days old	0.30 to 0.60
Soybean	*Glycine max* Merr.	25 mature leaves from new growth	Prior to pod set	0.25 to 0.50
Spring wheat	*Triticum aestivum* L.	25 whole tops	As head emerges from boot	0.20 to 0.50
Sugar Beet	*Beta vulgaris L.*	25 leaves	50 to 80 days after planting	0.45 to 1.10
Sunflower	*Helianthus annus* L	25 mature leaves from new growth	summer	0.25 to 0.60
Winter Wheat	*Triticum aestivum* L.	50 leaves, top two leaves	Just before heading	0.20 to 0.50

Table 2. 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) and values for Canadian Prairie crops are from Heard and Hay (2006). 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.

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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.

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.

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.

Detailed Information

3.1 The phosphorus cycle

The phosphorus cycle is the biogeochemical cycle in which P moves through soil, water and organisms. Unlike several other biogeochemical cycles, the atmosphere is not involved substantially in the P cycle, because P and P compounds rarely move through a gaseous phase under normal conditions, especially in terrestrial environments. However, there can be small amounts of atmospheric movement of P in air-borne dust particles moving through wind erosion. In natural systems, soils contain phosphate that originated from the weathering of P-rich minerals such as apatite ($Ca_{10}(X)(PO_4)_6$,where X represents F^-, Cl^-, OH^-, or CO_3^{2-} (Pierzynski and McDowell 2005). As soils weather and develop over time, soil pH decreases and the Ca phosphates will change to amorphous and crystalline Al phosphate and then to Fe phosphate (Sample et al. 1980). Phosphorus can be added to the system through manures, crop residues, fertilizers, municipal wastes and by-products and will be lost from the systems through crop removal, erosion and runoff, and under some conditions through leaching or drainage (Figure 1).

The organic forms of P can comprise as much as 25 to 60% or more of the total P content of soils and include growing plants and plant residues, animal waste, soil biota, soil organic matter, and soluble organic P present in the soil solution (Doyle and Cowell 1993; Liu et al. 2015). The amount of organic P in the soil may vary seasonally, reflecting the dynamic nature of mineralization-immobilization reactions that affect both P_o and P_i (Dormaar 1972). Factors that decrease the total amount of organic matter in the soil, such as excess cultivation and summer fallowing will lead to a reduction in total organic P. Most naturally occurring organic P is in the form of esters of orthophosphoric acid . The organic phosphate forms in the soil include inositol phosphates, nucleic acids, nucleotides, phospholipids and sugar phosphates (Stewart et al. 1980; Stewart and Tiessen 1987). In Chernozemic soils, about 10-30% of the organic P is in the form of inositol phosphate; phospholipids make up 1-2%; less than 1% are nucleic acids and about 70% are unidentified (Stewart et al. 1980). Studies using ^{31}P NMR spectroscopy to characterize soils from a long-term P study in Swift Current found P_o species in the phosphonate, orthophosphate monoester and orthophosphate diester compound classes (Liu et al. 2015) Identified monoesters included various stereoisomers of inositol hexakisphosphate, choline phosphate, glucose 6-phosphate diester degradation products including glycerophosphates and mononucleotides. Orthophosphate diesters occurred as DNA and two types of unknown diesters. There was also a range of unidentified monoesters. However, only a small portion of the soil organic phosphorus is biologically active and much of the organic P in the soil has accumulated as chemically resistant and aggregate-protected forms (Stewart and Tiessen 1987). Procedures that fractionate P_o using sequential extractants of increasing strength that remove P fractions of varying availability can be used to characterize the bioavailable P pools in the soil (Bowman and Cole 1978; Hedley and Stewart 1982; Hedley et al. 1982).

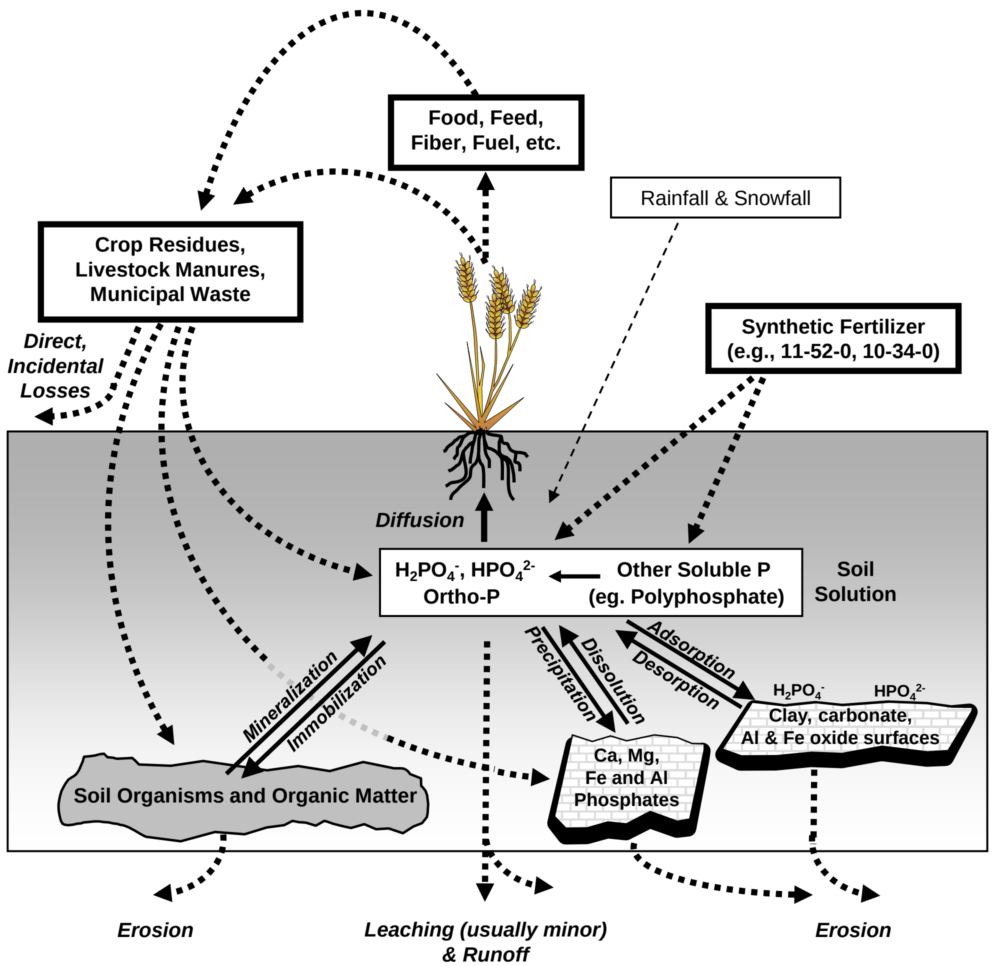

Figure 1. Simplified phosphorus cycle. Dashed lines represent phosphorus gains or losses in the soil system; solid lines represent internal transformations within the soil system (https://www.gov.mb.ca/agriculture/environment/nutrient-management/pubs/effects-of-manure%20-fertilizer-on%20soil%20fertility-quality.pdf, accessed April 30, 2019).

The organic forms of P in the soil can be converted to inorganic orthophosphates by mineralization, when microbes in the soil release orthophosphates as they metabolize organic matter as an energy source (Stewart and Tiessen 1987). Phosphatase enzymes in living cells cleave a phosphate group from a substrate to convert organic matter P into plant-available phosphate (Margalef et al. 2017). Mineralization of soil organic P can also be catalysed by phosphatase enzymes that are produced by bacteria, fungi and plants roots and released into the soil through excretion or cell lysis (Gould and Bole 1980; Margalef et al. 2017; Stewart and Tiessen 1987). Phosphatase activity is usually greater in the rhizosphere than in the surrounding soil because of the high biological activity in the vicinity of the root (Stewart and Tiessen 1987). Some organic phosphate esters are quickly broken down while others are more stable and may accumulate in the soil over time, depending on the balance between production and decomposition. Mineralization of organic P is important for providing plant-available inorganic P especially on highly weathered soils where available mineral forms have been depleted. Labile forms of organic P may move more readily through the soil than do labile inorganic P ions

(Stewart and Tiessen 1987). The high mobility of labile organic P can therefore potentially affect both movement of P to plant roots and environmental risk of P movement to water.

Inorganic phosphate can be immobilized by soil microorganisms that require it for their metabolism and incorporate it into their biomass (Figure 1). Immobilization and mineralization operate in a cyclical process with P being tied-up as the microorganism grow and released as they die and decompose.

The inorganic forms of P in the soil include the phosphate ions in the soil solution, P that is adsorbed on the 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 the various forms of apatite. Apatite can slowly weather over time and release orthophosphate into the soil solution. The secondary P minerals are also involved in equilibrium reactions where they dissolve to release orthophosphate or are precipitated by retention of solution orthophosphate with Ca, Mg, Fe and Al (Figure 1). Phosphate ions can be adsorbed onto the soil particles in a chemical binding process that is reversed through desorption, where the ions are released into the soil solution.

The soil solution will contain some soluble organic phosphates, pyrophosphate and polyphosphate; however, because plants take up P as orthophosphate, this is the main form of solution P that is of interest for crop production. The concentration of plant available orthophosphate in the soil solution is referred to as the intensity factor (I). The dominant form of orthophosphate in the soil solution depends on the soil pH (Figure 2). Within the normal range of soil pH, HPO_4^{-2} dominates if pH is greater than 7.2 and $H_2PO_4^-$ dominates at pH levels below 7.2 (Pierzynski and McDowell 2005). Uptake rates of orthophosphate by plants tend to be greatest between pH of 5 and 6, indicating that orthophosphate is primarily taken up by the plant in the monovalent form (Schachtman et al. 1998).

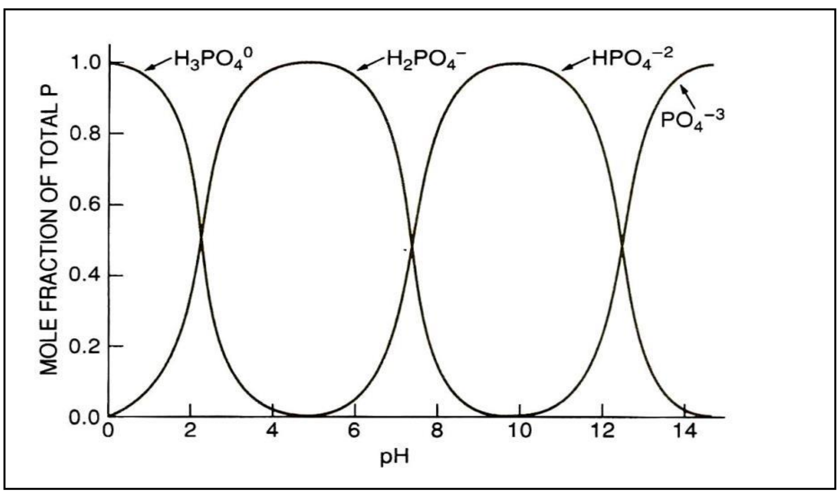

Figure 2. Influence of pH on the distribution of orthophosphate species in solution (Havlin et al. 2014).

The soil solution normally contains very low concentrations of P, typically ranging from as low as 10^{-8} M in very low fertility tropical soil, 10^{-6} M in deficient soils and as high as 10^{-4} M in high P soils (Syers et al. 2008). The amount of P in the soil solution will normally be less than 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 dissolved P to the 6-inch depth at any time, far less than the crop requires for growth.

Roots will intercept nutrients as they grow into new soil that has not been depleted, but roots contact only a small proportion of the soil surfaces in any particular growing season. While root volume and architecture will vary substantially among plants due to genetic and environmental conditions, the P accessed by direct root interception will make up only a very small percentage of the crop requirements (Barber 1995; Gahoonia and Nielsen 2004; Marschner and Rengel 2012). Barber (1995) calculated that corn grown on a silt loam soil would obtain only 1% of its P requirement through direct interception.

The majority of P is supplied by replenishment of the very low concentration of P in the rhizosphere surrounding the plant root. The movement of P to the root surface through the soil occurs by mass flow or diffusion. Mass flow refers to the movement of dissolved nutrients with water as it moves to the roots to meet the plant's transpirational water demand, while diffusion is the movement of nutrients through the soil solution from an area of high concentration to an area of low concentration, without any water movement. Because the concentration of P in the soil solution is very low, the total amount of P that will move to the plant root via mass flow will also be very low, in the order of 2-3% of the total amount required for optimum crop growth (Johnston et al. 2014). Most P movement to the rhizosphere occurs through diffusion, driven by the concentration gradient created by the active uptake of P by plant roots. However, the speed of diffusion of phosphate ions though the soil solution is very slow and the path of movement through the soil moisture films around the soil particles is long and crooked, or "tortuous". Therefore, the net movement of P though the soil is small, in the range of 0.13 mm per day. To support optimum crop growth, there must be a supply of P in the soil surrounding the root that can replenish the soil solution in contact with the root surface. During periods of peak P demand, the P in the soil solution at the root hair surface must be replenished at least 10 to 20 times per day (Syers et al. 2008). Therefore, the ability of the soil to replenish the soil solution P as it is extracted by crop roots is critical for ensuring an adequate P supply to the growing crop.

The ability of the soil's reserves of P to replenish the P in the soil solution is referred to as the quantity factor (Q) or the P buffering capacity. The P in the soil solution is replenished from the organic and inorganic reserves of P that are present as solids or on soil surfaces. These reserves are broadly divided into "labile" and "non-labile" forms. Labile P describe the forms of P in the soil that will rapidly equilibrate with the soil solution and become available in the short-term, while 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. Conversely, the non-labile P includes the more stable organic P, the strongly adsorbed forms and more sparingly soluble forms.

Conceptually, this gives a series of pools of various P forms that will shift with changes in relative concentration (Johnston et al. 2014; Syers et al. 2008) (Figure 3). The first of the soil reserves of inorganic P is the pool of soluble P in the soil solution that is immediately available for plant uptake. The second pool is P that adsorbed on the surface of the soil constituents. It can be readily desorbed to replenish the soil solution as it is depleted by plant uptake. The third pool is P that is adsorbed more strongly to surface constituents or possibly adsorbed on internal surfaces on the soil components but will become plant available over a slightly longer timescale of months to years. The fourth pool is strongly bonded to soil components or is precipitated as slightly soluble P compounds or may be poorly available due to its position deep in the soil matrix. It has a low availability but may be released for plant uptake over many years. Transfer of P from one pool to another is reversible with the time-frame for reaction reflecting the availability of the pools.

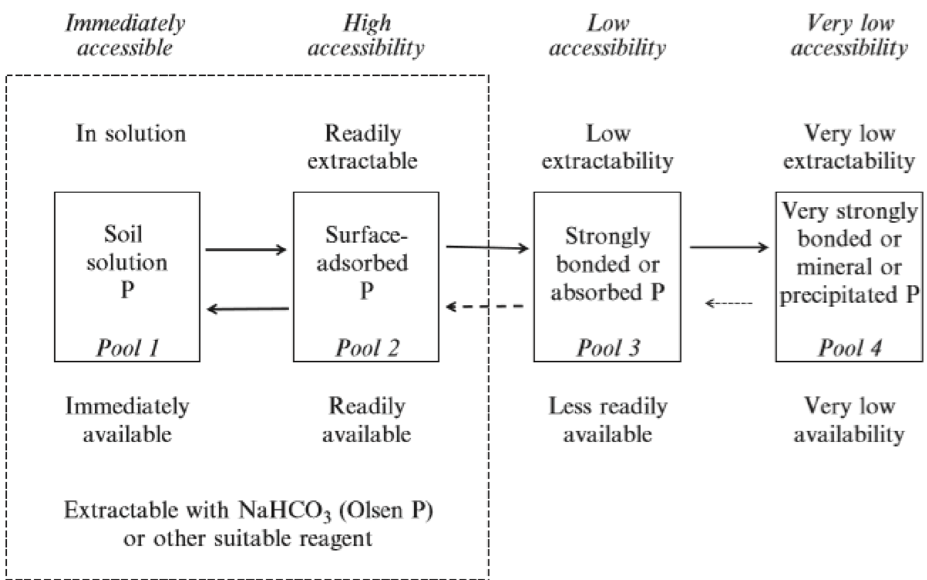

Figure 3. Conceptual diagram for the forms of inorganic P in soils categorized in terms of accessibility, extractability and plant availability (Johnston et al. 2014)

Adsorption/desorption and precipitation/dissolution reactions are concentration dependent, so addition or depletion of P in the soil solution will shift the direction of the equilibria and lead to movement of P along the availability gradient. In natural ecosystems, with limited external inputs of P, the P removed by plant uptake system will be ultimately replenished by the slow weathering of naturally occurring primary P minerals such as apatite. In managed ecosystems, such as cropland, external inputs of P and plant uptake from the soil solution will influence the direction of soil reactions.

3.2 What happens when P fertilizer is added to the soil?

When water-soluble P fertilizer is applied to the soil, only a small proportion of it remains in solution. The solution P undergoes a series of reactions that move the inorganic P from the solute phase and reduce its bioavailability (Hedley and McLaughlin 2005; McLaughlin et al. 2011; Sample et al. 1980). The reactions include adsorption on the surface of the soil particles, diffusion (absorption) where the P adsorbed on the soil particle moves to inner surfaces of the particles where it is less accessible, and precipitation of new sparingly soluble solid phase P with most of the P initially precipitating as high solubility reaction products. These are transient forms of P that are subsequently distributed between the readily and less readily available pools by adsorption and then absorption (Johnston et al. 2014). Phosphorus retention is by both precipitation and adsorption that often occur simultaneously (Ajiboye et al. 2007; Ajiboye et al. 2008).

Adsorption reactions include quickly reversible adsorption reactions at the surface of soil particles and slower reactions that occur when the P moves onto adsorbing surfaces in the interior of soil particles (McLaughlin et al. 2011; Sample et al. 1980). On alkaline soils, calcium carbonate or mixtures of calcium carbonate and Fe oxides are important while in acidic and neutral soils, Al and Fe oxides dominate. Adsorption reactions are important where the concentration of P is less than the P adsorption maximum of the soil and the concentration of reacting ions such as Al, Fe, Ca, Mg, Si or other trace elements in the soil solution are too low to cause precipitation of their phosphate mineral products (Hedley and McLaughlin 2005; McLaughlin et al. 2011; Pierzynski and McDowell 2005). The amount and form of Al and Fe minerals in the soil will determine the extent of adsorption reactions, especially in acidic and neutral pH soils, although Ca may play a role even in acid soils (Beauchemin et al. 2003; Holford and Mattingly 1975; Khatiwada et al. 2014; Luo et al. 2017). Aluminum and Fe hydrous oxides in soil can occur as discrete compounds, as coatings on other soil particles, or as amorphous Al hydroxy compounds in the interlayers of Al silicates (Sample et al. 1980). Because of their abundance in soils and their large specific surface area, amorphous hydrous oxides of Fe and Al adsorb more P than crystalline forms of Al and Fe. The H^+ present in orthophosphate allows a 2-step ligand exchange process in negatively charged soils, leading to inner sphere surface complexes, with P bonded to one metal atom being labile and P bonded to 2 metal atoms being non-labile (Figure 4).

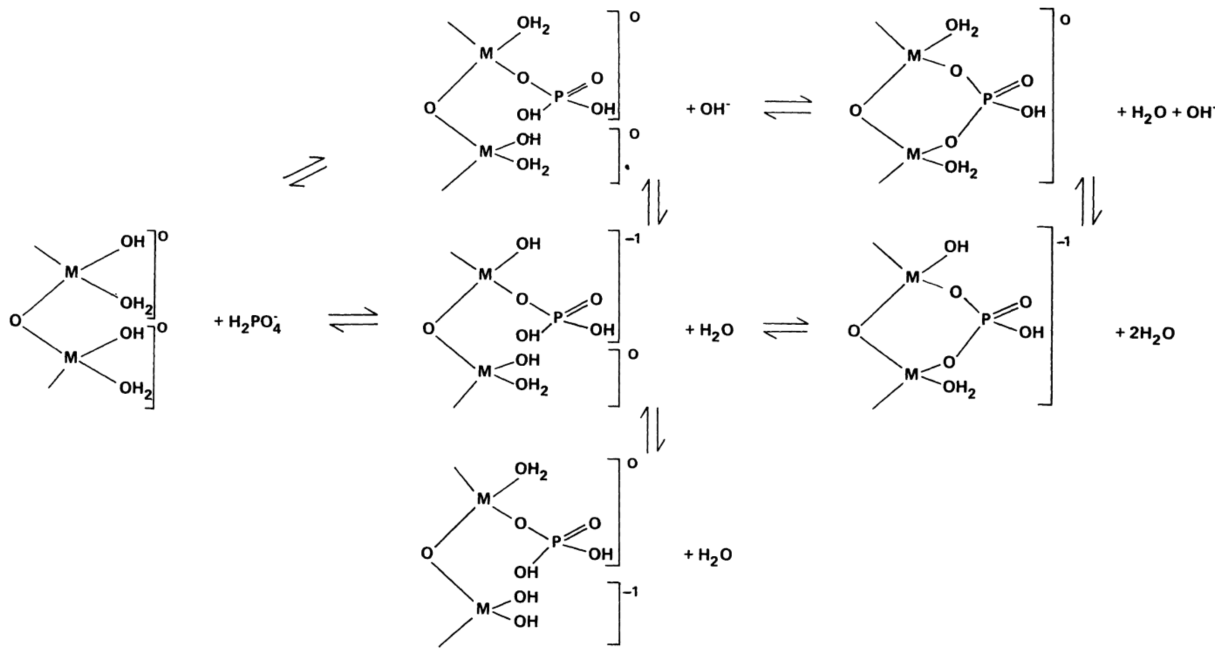

Figure 4. Phosphorus adsorption reactions on metal oxide surfaces (Barrow 1980). Mononuclear ligands with 1 P bonded to 1 metal atom are labile while binuclear or bridging ligands with 1 P bonded to 2 metal atoms are non-labile.

In calcareous soils, $CaCO_3$ will dominate the soil chemistry, although Al and Fe oxides may also be important (Holford and Mattingly 1975; McLaughlin et al. 2011; Sample et al. 1980; Weir and Soper 1962; Zhang et al. 2014). Phosphate can be adsorbed on free $CaCO_3$ at relatively low concentrations and held in a form that is less strongly bound and hence more plant-available than that adsorbed to hydrous oxides. During adsorption by $CaCO_3$, the phosphate ion replaces adsorbed water molecules, bicarbonate ions and hydroxy ions (McLaughlin et al. 2011; Sample et al. 1980). The adsorbing strength depends on the solubility of the compound formed with the surface Ca ions while the amount of adsorption is controlled by the area of adsorbing surface.

Soluble phosphorus can also be removed from solution through precipitation of new solid phases from the ions present in the soil solution when the concentration is high enough to exceed the solubility product of the precipitating substance. If the pH is 7 or lower, hydrous oxides of aluminum and iron will react with phosphate to form various Al- or Fe-P minerals, likely including amorphous analogs of variscite, as well as crystalline variscite ($AlPO_4 \bullet 2H_2O$) or strengite ($FePO_4 \bullet 2H_2O$) (Hedley and McLaughlin 2005; McLaughlin et al. 2011; Pierzynski et al. 1990a; Pierzynski et al. 1990b; Pierzynski and McDowell 2005; Sample et al. 1980). If the soil pH is above 7, phosphate will precipitate with Ca and Mg to produce minerals with lower solubility and decreasing proportions of P.

In calcareous soils, the dominant initial reaction product is dicalcium phosphate dihydrate (DCPD or $CaHPO_4 \bullet 2H_2O$) (Kar et al. 2017; Racz and Soper 1967; Sample et al. 1980). On soils containing high concentrations of Mg, dimagnesium phosphate trihydrate may also form.

Over time, reactions with Ca and/or Mg will continue, leading to formation of compounds with increasing ratios of Ca and/or Mg to P and decreasing solubility (Beauchemin et al. 2003; Doyle and Cowell 1993; Lombi et al. 2006; Sample et al. 1980; Zhang et al. 2014). The retention process reduces the availability of P over time; however, the process is reversible, and the retained or "fixed" P minerals can slowly become available as the crop removes P from the soil solution.

Table 1. Reaction products of P fertilizers in calcareous soils

Compound & Sequence	Ca/P ratio	pK_{sp}[1]
Orthophosphate P	0/1	--
($H_2PO_4^-$ or HPO_4^{2-} eg. MAP)		(v. soluble)
↓		
Dicalcium phosphate dihydrate	1/1	6.56
(DCPD, $CaHPO_4 \bullet 2H_2O$)		(sl. soluble)
↓		
Octacalcium phosphate	8/6	93.81
(OCP, $Ca_8H_2(PO_4)_6 \bullet 5H_2O$)		(low solubility)
↓		
Hydroxyapatite	10/6	111.82
(HA, $Ca_{10}(PO_4)_6(OH)_2$)		
or Fluorapatite	10/6	120.86
(FA, $Ca_{10}(PO_4)_6F_2$)		(v. insoluble)

[1]The pKsp is the negative log of the solubility product constant (K_{sp}) which describes the equilibrium relationship between a solid and its respective ions in a saturated solution. Generically, K_{sp} = (Cation activity) x (Anion activity) in a saturated solution (that is, the product of the activity of each ion in solution). The higher the value of K_{sp}, the more soluble the compound while the higher the pKsp is, the less soluble the compound.

The soil's pH affects the solubility of the various phosphate compounds. In a high pH soil, H^+ is an ingredient in the dissolution reactions for calcium and magnesium phosphates, so low pH <u>increases</u> dissolution, e.g., for dissolution of dicalcium phosphate dihydrate (DCPD):

$$CaHPO_4 \cdot 2H_2O + \mathbf{H^+} \leftrightarrow H_2PO_4^- + Ca^{2+} + 2H_2O$$

In acid soils, H^+ is a product of the dissolution reactions for iron phosphates, so low pH <u>decreases</u> dissolution, e.g., for dissolution of strengite:

$$FePO_4 \cdot 2H_2O + H_2O \leftrightarrow H_2PO_4^- + \mathbf{H^+} + Fe(OH)_3$$

Precipitation of phosphate will increase with increasing concentration of the reacting ions. So, in high pH soils, increasing concentration of Ca, Mg or phosphate will increase precipitation. On low pH soils, increasing concentrations of Fe, Al or phosphate will increase precipitation.

Speed of reaction will increase with increasing temperature, whether it is precipitation or dissolution (Sheppard and Racz 1980). So, increasing temperature will increase the rate of dissolution of residual or native P or secondary minerals that are present in the soil, increasing the rate of release of orthophosphate into the soil solution. At the same time, increasing temperature will also increase the rate of precipitation of soluble P to less soluble forms, hastening the retention of recently applied P into less available forms.

When fertilizer P is added to the soil, there is an extreme change in the concentration of P in the immediate vicinity of the application site that initiates a series of adsorption and precipitation reactions that affect both the short- and long-term availability of the P in the reaction zone. If a solid fertilizer granule is added to the soil, it must dissolve before the phosphate enters the soil solution and becomes available. The release of phosphate from water-soluble fertilizers is rapid, with the initial dissolution and movement of P out of the granule occurring within a few days (Hedley and McLaughlin 2005; Lombi et al. 2004; McLaughlin et al. 2011). Phosphate fertilizers are hygroscopic, so will attract water vapour from the soil air-filled space, as well as soil porewater that will move towards the fertilizer through mass flow and capillary flow, dissolving the granule (Hettiarachchi et al. 2006; McLaughlin et al. 2011). At the same time, highly concentrated P solution will diffuse along the osmotic gradient, away from the granule, towards areas of lower concentration outside of the fertilizer reaction zone. The reactions of the fertilizer granule or droplet and the outward movement of the P solution result in a series of zones where P concentration decreases with increasing distance from the application point. The residual granule or droplet and the immediate surrounding area contain insoluble P compounds from the original fertilizer and the compounds that have precipitated from the highly concentrated fertilizer solution (Hedley and McLaughlin 2005; Kar et al. 2012). 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. Beyond this is an area where the P adsorption capacity of the soil has not been saturated.

The formation of compounds in the residual granule and the fertilizer-soil interface immediately surrounding it is affected primarily by the type of solution formed by the applied fertilizer and the available moisture from the soil (Hedley and McLaughlin 2005; Sample et al. 1980). The properties of the water-soluble P compounds most commonly contained in phosphate fertilizers are given in Table 2. The highly concentrated saturated solution may dissolve soil minerals and release cations such as Al, Fe, Ca and Mg. The high concentration of phosphate ions and reacting cations in the solution will lead to the precipitation of Al, Fe, and Ca phosphates (Hedley and McLaughlin 2005; Hettiarachchi et al. 2006; McLaughlin et al. 2011; Sample et al. 1980). The types of precipitates that have been identified during the reactions of various phosphate fertilizers in soils has been reviewed by Sample et al. (1980) and by Hedley and McLaughlin (2005). Mass flow of reacting cations in the soil water moving towards the granule may increase the precipitation of phosphate at the granule application site, particularly on calcareous soils, reducing the movement of phosphate away from the granule and reducing the volume of the fertilizer reaction zone.

Table 2. Phosphate compounds commonly found in fertilizers and composition of their saturated solutions (Sample et al. 1980)

Compound	Formula	Composition of saturated solution					Reference†
		Solution symbol	pH	P, moles/liter	Accompanying cation, moles/liter		
Highly water-soluble compounds							
Monocalcium phosphate	$Ca(H_2PO_4)_2 \cdot H_2O$	TPS	1.0	4.5	Ca	1.3	A
		MTPS	1.5	4.0	Ca	1.4	A
Monoammonium phosphate	$NH_4H_2PO_4$	MAP	3.5	2.9	NH_4	2.9	A
Monopotassium phosphate	KH_2PO_4	MKP	4.0	1.7	K	1.7	A
Triammonium pyrophosphate	$(NH_4)_3HP_2O_7 \cdot H_2O$	TPP	6.0	6.8 (3.4 P_2O_7)	NH_4	10.2	B
Diammonium phosphate	$(NH_4)_2HPO_4$	DAP	8.0	3.8	NH_4	7.6	A
Dipotassium phosphate	K_2HPO_4	DKP	10.1	6.1	K	12.2	A
Sparingly soluble compounds							
Dicalcium phosphate	$CaHPO_4$ $CaHPO_4 \cdot 2H_2O$	DCP	6.5	~0.002	Ca	0.001	C
Hydroxyapatite	$Ca_{10}(PO_4)_6(OH)_2$	HAP	6.5	$\sim 10^{-5}$	Ca	0.001	C

† A: Lindsay et al. (1962); B: unpublished TVA data; C: based on Farr (1950), assuming pH = 6.5 and Ca = 0.001*M*.

Evidence from Australian studies indicates that if the fertilizers are applied in a solution or dissolved form, there is less movement of water carrying reacting ions towards the fertilizer, thus precipitation is reduced and P will move further away from the site of application (Bertrand et al. 2006; Hettiarachchi et al. 2006; Holloway et al. 2001; Lombi et al. 2004; Lombi et al. 2005). Evaluation of reaction products formed from granular as compared to fluid sources on a highly calcareous soil showed that P lability decreased near granules because of precipitation of octacalcium phosphate or apatite-like compounds while with fluid applications more P remained in a plant-available form similar to monocalcium phosphate (Lombi et al. 2004; Lombi et al. 2005; Lombi et al. 2006).

Use of solution P fertilizer has provided large increases in P use efficiency on dry, highly calcareous soils in Australia (Holloway et al. 2001), but the same benefits have not been demonstrated consistently on the Northern Great Plains. Field studies near Brandon, MB showed that monoammonium phosphate granular fertilizer (MAP) increased both dry matter yield and P uptake more than ammonium polyphosphate liquid fertilizer (APP) early in the growing season, but that APP had a greater benefit on final grain yield (Spratt 1973). Dry matter production and the uptake of P continued after the dough stage with APP but not with MAP. The author suggested that the hydrolysis of polyphosphate by roots later in the season may encourage later-season responses. However, later field studies in Manitoba and Alberta showed no difference in response of spring wheat yield to APP or MAP (Grant et al. 2007). Other field studies in Manitoba also showed that durum wheat (Grant et al. 2008) and canola (Grant and Relf-Eckstein 2009) showed similar responses to APP and MAP, while soybean did not respond significantly to either P source (Grant et al. 2008).

Blending soluble salts such as ammonium nitrate, ammonium sulphate, potassium nitrate, potassium chloride or potassium sulphate with the phosphate fertilizer can lead to the formation of structural analogues for the calcium phosphate during the reaction process. The analogues where K or NH_4 replace some of the Ca are more soluble than the unsubstituted calcium phosphates and so will move more quickly away from the granule, reducing the amount of P that remains in the granule residue (Hedley and McLaughlin 2005; Sample et al. 1980; Takagi et al. 1980). In contrast, adding $CaCO_3$ will increase the precipitation of relatively insoluble octacalcium phosphate or dicalcium phosphate dihydrate and increase the amount of P remaining near the granule.

The zone of soil immediately surrounding the fertilizer granule or droplet will contain a saturated P solution, characteristic of the type of fertilizer applied, that will saturate the P adsorption capacity of the soil. The greater the ability of the soil to retain P, the smaller will be the extent of the P-saturated zone. In the zone nearest the granule, precipitation reactions dominate, rather than adsorption. As P diffuses away from the granule, the concentration in the solution decreases to the point where it is no longer saturated and adsorption reactions become more important. In this region, P movement will be mainly by diffusion via the tortuous route through the soil water film around soil particles and through micropores (Figure 5).

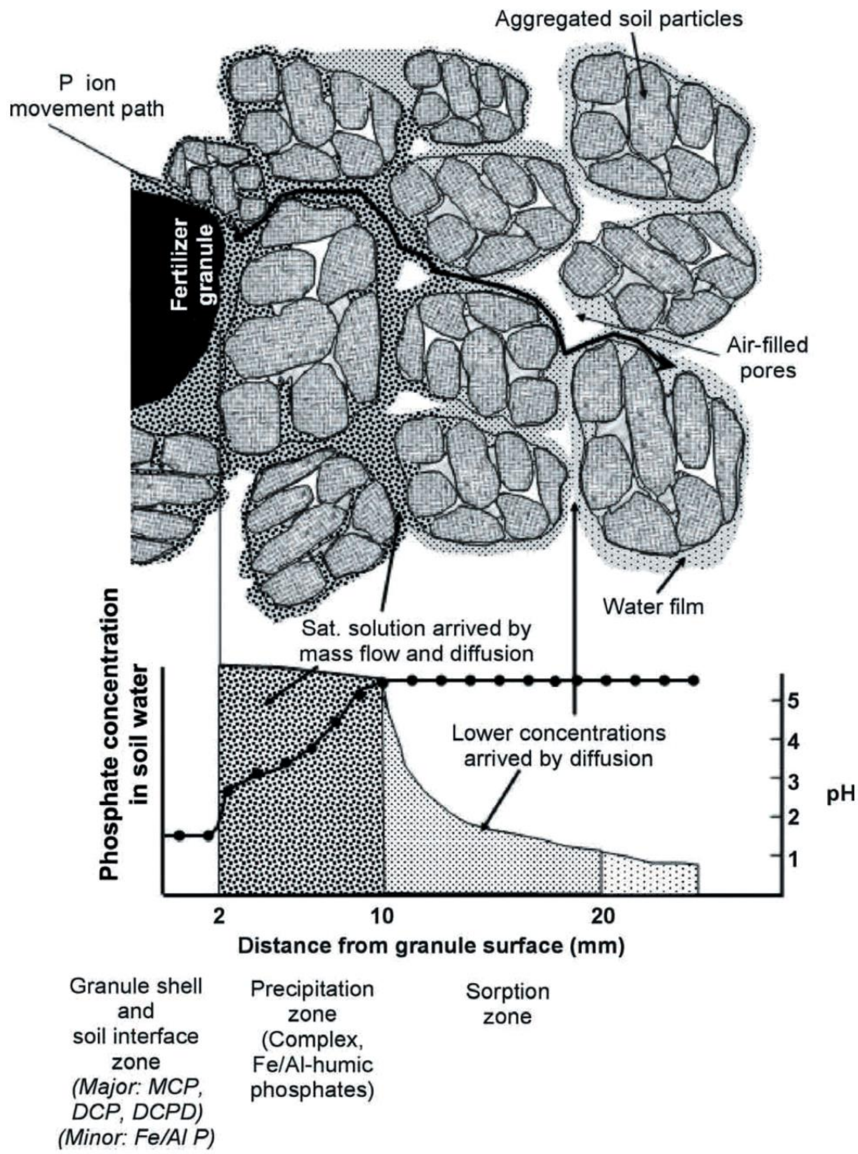

Figure 5. Diagrammatic representation of the movement of phosphate by mass flow and diffusion from a granule of triple superphosphate (or single superphosphate) through water-filled and water-lined large micropores in a well-aggregated soil. Note that the penetration of phosphorus (P) into aggregates is incomplete due to the slow rate of P diffusion in smaller intra-aggregate micropores and discontinuous micropores. (Not to scale.) Lower graph shows relative P concentration and pH (–•–•–) in soil water (Hedley and McLaughlin 2005).

As the distance from the application site increases, the concentration of P in solution decreases due to dilution, precipitation and adsorption until the P concentration in solution approaches background soil levels (Kar et al. 2012). The distance from the fertilizer granule where the P concentration is elevated is normally very small, in the range of a few millimeters. The volume of the reaction zone around the granule where P concentration is increased will be important in affecting plant uptake because a larger volume provides a greater opportunity for roots to grow and access the P. The volume of the reaction zone will be influenced by the P retention characteristics of the soil and factors affecting P retention. The greater the retention capacity of the soil, the lower the P concentration will be in the solution where diffusion is occurring, the slower diffusion will be and the smaller will be the volume of soil where the P concentration is increased to enhance crop P uptake. Soils with a larger adsorbing surface area will have a greater adsorption capacity; clay soils, for example will tend to have greater adsorption than sandy soils.

Adsorption capacity will be large on acid soils with high concentrations of Fe and Al oxides. The Fe and Al oxides will adsorb more P at low than neutral pH. However, if acid soils are limed to increase the pH, Al^{3+} will precipitate as $Al(OH)_3$, creating more reactive surfaces and hence increasing adsorption. On high pH soils, adsorption will increase with increasing levels of $CaCO_3$ or $MgCO_3$.

Adsorption will also be influenced by other ions that compete for P adsorption sites, such as OH^- or HCO_3^-. Organic ions may also compete for adsorbing surfaces, reducing adsorption (Sample et al. 1980). Adsorption capacity will be greater if the adsorption complex is not highly saturated, so for example, there can be greater P adsorption during the early years of P fertilization rather than on soils with a long history of fertilization.

The initial reactions of P fertilizers with the soil described above are relatively rapid, taking place in hours to weeks (Sample et al. 1980). Rapid initial surface adsorption of P can be followed by diffusive penetration of P into soil aggregates where it is adsorbed on internal surfaces (Syers et al. 2008). Similarly, the metastable compounds that are precipitated from the saturated solutions soon after fertilizer application will continue to react to form increasingly more stable and less soluble products. In acid soils, the initial amorphous Fe and Al phosphate and Ca phosphate reaction products are thought to change ultimately to variscite-like and strengite-like crystalline compounds (Sample et al. 1980). On alkaline and calcareous soils, DCPD can change to OCP and other less soluble Ca and Mg phosphate forms over a period of months, with the ultimate reaction products thought to be hydroxy- and fluorapatites (Racz and Soper 1967). Although P transformation that occur when P fertilizer is added to the soil reduce plant availability over time, analysis of P recovery from long-term cropping studies indicates the retention of P in soils is largely reversible and that a large proportion can be recovered in following years (Johnston et al. 2014; Selles et al. 2011; Selles et al. 2007; Syers et al. 2008).

3.3 Residual value of fertilizer P

It is often said that the phosphorus use efficiency (PUE) of applied P fertilizer is low, with the amount of P being taken up by the crop in the year of application rarely being greater than 25% (Syers et al. 2008). However, the P that is not utilized by the crop in the year of application is primarily retained in the soil by the reactions described in the previous section, particularly on dryland soils where leaching and run-off losses are relatively small. Studies around the world have shown that long-term applications of P fertilizers can influence the amount and form of P present in the soil. In general, the majority of the increase in soil P from addition of P fertilizer occurs as inorganic P, adsorbed or precipitated to Al, Ca and Fe although organic forms of P increase somewhat (McLaughlin et al. 2011). Long-term application of P at rates in excess of crop removal or the addition of large one-time applications of P fertilizer can increase the soil residual P. In the past, it was often suggested that retention or “fixation” rendered the P unavailable to crops. However, the residual P present in the soil can remain or become available for crop uptake and serves as a slowly available source of P for growing crops (Spratt and Read 1980; Syers et al. 2008).

Residual benefits of large single-time applications of fertilizer P have been observed in several field trials across the Northern Great Plains. In the 1960s and 70s, at four sites on Chernozemic soils in Manitoba and Saskatchewan, a single large application of phosphate fertilizer at rates from 0 to 800 lb P_2O_5/acre (0 to 400 kg P/ha) was broadcast and incorporated at the initiation of the study (Read et al. 1973). The Manitoba sites were cropped with a wheat-flax rotation and the Saskatchewan sites in a wheat-fallow rotation. Yields were increased from the residual effect of the fertilizer application for the initial 8 years of the study, with higher yields and higher soil P concentrations occurring with the 400 and 800 lb P_2O_5/acre rates. Over the 8 years of cropping, 200 lb P_2O_5/acre was the most efficient treatment in increasing yield. By the final year of the study, the Olsen soil test extractable phosphorus level of the 200 lb P_2O_5/acre treatment was reduced to about 4 ppm which was comparable to the control and would be too low to support optimum crop yield. However, soils treated with 400 and 800 lb P_2O_5/acre still contained between 10 and 27 ppm of Olsen soil test extractable P and little response in yield to additional P fertilization would be expected (Bailey et al. 1977; Read et al. 1977).

Soil was collected from the field sites in the fall after three crops had been grown on the Manitoba sites and after one crop had been grown on the Saskatchewan site. These soils were used in greenhouse studies where 19 crops were grown to evaluate the persistence of the residual effect of the P applied (Read et al. 1973). The Olsen soil test extractable P concentration in the soil decreased to the level of the control after three to five crops on the 200 lb P_2O_5/acre treatment and after 11 to 13 crops on the 400 lb P_2O_5/acre treatment but was still higher than that of the control in the 800 lb P_2O_5/acre treatment, even after 19 consecutive crops. The recovery of applied P was calculated as the difference between P uptake from the fertilized treatments and from the check. The P uptake data from the soil in the field prior to bringing the soil into the greenhouse were combined with the uptake data for the greenhouse study to determine the total P recovery. A total of 87, 81 and 70% of the P applied was recovered in the harvested plant material from the 200, 400 and 800 lb P_2O_5/acre applications, respectively, indicating that the broadcast applications were used efficiently over time. Air-dried samples from the trials were evaluated in 1980 using the Hedley sequential extraction technique (Hedley et al. 1982; Wagar et al. 1986b). The proportion of P present as resin-extractable (consisting of the more soluble calcium phosphates such as DCPD and OCP and surface adsorbed P) declined from approximately 60% of the total P extracted in the samples taken in the first year of the study to approximately 30% in the samples taken in the 5th year of the study, then remained fairly constant until year 8. Sodium bicarbonate-extractable P in the Hedley fractionation test (slightly different from soil test Olsen P) declined from about 12-16% of the P that could be recovered through the extraction procedures in the first year of the study to about 10-11% by year 8. By the end of the study, about 40-50% of the P applied remained in plant-available forms. Approximately 29% was in acid-extractable forms, possibly fractions that were metastable and slowly plant-available. There was also an indication that sodium-bicarbonate extractable P moved downward through the soil profile over time, possibly due to bio-cycling by plant roots, with higher concentrations in the fertilized as compared to unfertilized plots noted at the l5-30, 30-60, 60-90 and 90 to 120 cm depths (Read and Campbell 1981).

A six-year field study in Saskatchewan on a Dark Brown Chernozemic clay soil used single broadcast P applications at 5 rates from 0 to 320 lb P_2O_5/acre and annual seed-placed P applications at 5 rates from 0 to 40 lb P_2O_5/acre under continuous cropping (Wagar et al. 1986a). Broadcast P applications of 40, 80, 160 and 320 lb P_2O_5/acre increased the average yield by 9, 24, 33 and 35%, respectively. Yearly seed-placed P treatments of 5, 10, 20 and 40 lb P_2O_5/acre applied over the first 5 years of the study increased the average yield by 10, 15, 24 and 29% respectively. The broadcast application of 80 lb P_2O_5/acre increased yields over 5 years and had an average yield and P uptake comparable to that of the annual seed-placed applications of 20 and 40 lb P_2O_5/acre. Broadcasting 160 and 320 lb P_2O_5/acre increased yields over 6 years and soil levels of extractable $NaHCO_3$-P in the Hedley fractionation test were still high enough after 6 years to indicate that crop yields would be increased due to the residual benefit. The two higher rates of initial broadcast P applications increased both resin and sodium bicarbonate inorganic P, with about half of the recoverable inorganic P remaining in these forms by the end of the 5-year study (Wagar et al. 1986b). Significant amounts of the applied P were converted into organic P forms which persisted to the end of the study. Phosphorus was also found to have moved below the 15 cm depth at the higher rates of P application, possibly due to bio-cycling in plant residues or possibly leaching of organic P forms, as most of the subsurface P was in the organic form.

In a similar long-term field study conducted in Montana, superphosphate was applied once, at study initiation, at rates of 0, 45, 90, 180, and 360 lb P_2O_5/acre and crops were grown for the following 17 years without additional fertilizer P application (Halvorson and Black 1985a; Halvorson and Black 1985b). A wheat-fallow system was used for the first six wheat crops (*Triticum aestivum*) and then an annual cropping system including wheat, barley *(Hordeum vulgare*), and safflower (*Carthamus tinctorius* L.), was used for remainder of the study. Fertilizer P recovery in the grain for the 45, 90, 180, and 360 lb P_2O_5/acre treatments averaged 32, 25, 23, and 13%, respectively, without N fertilization and 45, 38, 37, and 24% with 40 lb N/acre applied annually. Even after 17 years, the P recoveries at the higher P rates (> 90 lb P_2O_5/acre) were less than 50% of that applied and recovery of fertilizer P was still increasing at the higher P rates through harvest of the last crop in 1983. The researchers concluded that a one-time broadcast application of P fertilizer at rates as high as 180 lb P_2O_5/acre was an efficient way to manage P fertilizer (Halvorson and Black 1985b). However, in studies in Alberta, the residual benefit from application of a single application of 400 lb P_2O_5/acre as triple superphosphate had dissipated after 12 years of barley production (Karamanos and Kruger 2009).

While P content of the soil may be increased rapidly by large, single applications of P fertilizer, it may also be affected by repeated smaller applications. If the balance between P applied and P removed by the crop is positive, P will accumulate over time. A gradual increase in soil P due to long-term annual P applications has been demonstrated in many trials in the Northern Great Plains over the years. Field trials at seven sites across western Canada showed that application of MAP fertilizer at rates of 0, 40, 80 and 160 lb P_2O_5/acre each year from 2002 through 2009 increased both the labile (H_2O-P and $NaHCO_3$-P in the Hedley fractionation analysis) and non-labile (NaOH-P, HCl-P and Residual-P) fractions in surface soils (0-7.5 cm depth) (Grant et al. 2014; Obikoya 2016). When P application was stopped and crops grown for a three-year depletion phase, the labile P forms decreased but the non-labile fractions (HCl- and Residual-P) continued to increase.

In a study at Indian Head, SK, MAP was applied at 7 rates from 0 to 230 lb P_2O_5 per acre, banded with the seed of the summer fallow wheat crop in a wheat-wheat-summer fallow rotation for 20 years with the second wheat crop left unfertilized to evaluate the residual fertilizer effects (Spratt and McCurdy 1966). The sodium bicarbonate-extractable P increased with increasing rate of long-term P fertilizer application. When sub-plot P treatments of 20 lb P_2O_5 per acre tagged with ^{32}P were superimposed on the plots that had received long-term annual P rates, the increase in crop yield and the recovery of the tagged fertilizer P decreased as the past rate of P application increased, indicating that the crop was less reliant on annual applications of P fertilizer as the residual P in the soil increased. On an acid Dark Brown Chernozem at Scott, SK, MAP was applied to one side of split plots during the wheat phase of a wheat-fallow rotation from 1930 to 1987, for a total of 19 fertilizer application, at a rate of 15 lb P_2O_5 per acre until 1978 and at 25 lb P_2O_5 per acre from 1978 to 1987 (Ukrainetz 1990). The repeated application of relatively small amounts of P fertilizer led to an increase in resin-P of 59% and sodium bicarb-P by about 49% in the surface 15 cm as compared to the side that had not received P fertilizer. Resin P and Olsen P also increased to some extent to at least the 45 cm depth. The organic P forms were not substantially affected by fertilization. Over the 57 years of this study, a high proportion of the fertilizer P applied remained in labile forms in this acid soil.

If P removal is greater than P addition, P will move from stable to labile pools to compensate for the decrease in concentration, while P application in excess of removal will shift P towards accumulation of more stable forms (Liu et al. 2015; McKenzie et al. 1992a; McKenzie et al. 1992b; Syers et al. 2008). Effects of long-term management on phosphorus fractions were evaluated in a Chernozemic and a Luvisolic soil in Alberta that had been cultivated for 74 and 57 years, respectively (McKenzie et al. 1992a; McKenzie et al. 1992b). A comparison of the cultivated soils to adjacent uncultivated soils showed that cultivated crop production without application of P fertilizer led to a decline in sodium bicarbonate-extractable organic P (bicarb-P_o) and sodium hydroxide-extractable organic P (NaOH-P_o) as compared to the uncultivated soil. Hydrochloric acid-extractable inorganic P (HCl-P_i) also declined in all unfertilized systems on the Chernozemic soil and declined with unfertilized continuous cropping on the Luvisolic soil. Organic P fractions decreased more when fallow was included in the rotation than with continuous cropping, likely because the higher C return to the soil with continuous cropping slowed the decline of organic P. Cropping without P fertilizer led to movement of P from the stable to the labile forms, depleting soil P to support crop uptake. Adding P fertilizer reduced the drawdown of soil P, and when P additions were increased to exceed P removal rates, increases in most inorganic soil P pools began to emerge (McKenzie et al. 1992a). With P addition, total P and all P_i fractions were higher than when P was not added, with the greatest difference being in more labile inorganic P forms (resin-, sodium bicarbonate- and NaOH-extractable P). On the Chernozemic soils, concentrations of these labile forms of inorganic P were higher on P-fertilized soils than on uncultivated soils, because recent P applications exceeded removal rates (McKenzie et al. 1992a). In contrast, on the Luvisolic soil, sodium bicarbonate-extractable inorganic P and sodium hydroxide-extractable inorganic P forms were lower on the fertilized than uncultivated soils, likely because the fertilizer P rates applied were low (McKenzie et al. 1992b). Fertilizer P alone had no effect on labile organic P forms but adding N fertilizer encouraged greater production of organic matter, increasing the proportion of labile organic to labile inorganic P forms. On the Luvisolic soils, concentrations of HCl-extractable inorganic P in the fertilized treatments were similar to or greater than in the uncultivated soil, indicating that the fertilizer P had been moving into the HCl-extractable inorganic P fraction. Continuous cropping with application of N and P produced the highest total-P levels of all treatments at both locations indicating that continuous cropping with balanced P applications had the most positive effects on P dynamics on both sites.

Changes in soil P over time will be a function of the P balance, calculated by the difference between P addition and P loss, with the main path of P loss being P removal in the crop. Where P input exceeds P removal, soil P fractions can increase and where removal is greater than input, P reserves will decline. In a 12-year field trial on an Orthic Brown Chernozemic soil near Swift Current, SK, changes in soil P were closely related to the difference between fertilizer P additions and P removal in the grain, which was mainly related to the grain yield (Selles et al. 1999). During a 7-yr period of low yields caused by dry conditions, Olsen-P increased, reflecting the positive P balance, while in the following four years when grain yield and crop removal of P were greater due to improved moisture conditions, Olsen-P concentration remained nearly unchanged.

In another long-term study at Swift Current, continuous wheat and a summer fallow-wheat-wheat rotation were grown with each receiving either P only or N plus P fertilizer from 1967 to 2005. In 1993, plots were split, and P withheld on half of the plot for the next 12 years of the study. The balance of fertilizer P minus P removed in the grain accounted for about 60% of the variability in Olsen-P accumulation over the experiment (Selles et al. 2011). Olsen-P in the 0 to 1 cm depth increased by 0.07 ppm for each kg per hectare of P applied in excess of removal on the continuous wheat and by 0.10 ppm in the fallow-wheat-wheat rotation during 39 years of P application. The higher value in the fallow rotation may reflect mineralization of P during the fallow year. Cumulative crop P removal over the entire 39-year cropping period where P was withheld during the last 12 years was equal to between 90 and 105% of the total P applied during the initial fertilization portion of the study, with greater removal where both N and P had been added compared to where only P had been applied. In other words, the residual P accumulated during the early years remained in an available form that was used by the crop when further P application was withheld.

Later studies on this site helped to determine the fate of the residual P. In 2010, after another five years of treatment application, the soil P was characterized in surface and subsurface layers using sequential fractionation, P K-edge X-ray absorption near-edge structure (XANES) and solution ^{31}P nuclear magnetic resonance (P NMR) spectroscopy (Liu et al. 2015). The residual P that had accumulated from 28 years of build-up was enough to support a further 15 years of wheat cultivation, with no difference in yield occurring between the fertilized and unfertilized sides of the plot in 2010. Levels of organic P forms in the soil were not decreased in the unfertilized as compared to fertilized soil. However, the Olsen-P levels in the surface soils in the unfertilized sides of the plots decreased compared with 1995 while the levels in the fertilized sides of the plots were similar to the levels in 1995. So, cropping without fertilization depleted the Olsen-P levels while cropping with fertilizer application maintained the Olsen-P pool. Applied fertilizer P was apparently removed through crop uptake, adsorbed by Fe/Al (hydr)oxides or precipitated as Ca-P minerals. With continuous P fertilization, P accumulated in the surface soil as inorganic Fe-P rather than Al-P. In the unfertilized soils, inorganic Al-P fractions as well as hydroxyapatite and $Ca_3(PO_4)_2$ decreased, indicating possible release for crop uptake or conversion to other P forms. There was an increase of Fe (hydr)oxides-associated P between 1995 and 2010 in both the fertilized and unfertilized soils indicating that this may be an intermediate P reservoir for crop production. When P fertilization stops, it is likely that the plants will access the P left behind in the soil and reduce the labile soil P pools.

Benefits from P fertilizer remaining in the soil can persist for many years. In field studies on low (10 ppm) and high (22 ppm) testing clay loam soils in Minnesota, broadcast P applications of 0, 50, and 100 lb P_2O_5/acre applied annually and 150 lb P_2O_5/acre applied every third year for 12 years in a corn-soybean rotation provided residual benefits for 8 years after fertilizer application ceased (Randall et al. 1997a; Randall et al. 1997b). In studies on a thin Black Chernozem loam soil in Crossfield, Alberta, soil samples were taken in 1997 in smooth bromegrass fields that had been fertilized with P as triple superphosphate broadcast at 0, 32, 66, 110, 132, 220 and 264 lb P_2O_5/acre for 10 years from 1968–1977 (i.e., 20 years prior to sampling) and on soils that had not been fertilized (Malhi et al. 2003). Increases in extractable P (in 0.03 M NH_4F +0.1 N HCl solution) in the soil reflected 10 years of P fertilization relative to no P fertilization, even though applications had been terminated 20 years prior to soil sampling. The magnitude and depth of increase in extractable P (in 0.03 M NH_4F +0.1 N HCl solution) paralleled N and P rates. Most of the increase in extractable P (in 0.03 M NH_4F +0.1 N HCl solution) occurred in the top 10-cm soil layer and almost none was noticed below 30 cm depth. Other studies with established forage grass or alfalfa stands also showed that most surface-applied P remained in the surface 5 cm and did not move below 15 cm (Malhi et al. 1992). The relatively small amounts of the surface applied P that moved downward to deeper soil depths could be due to some leaching of inorganic P, of organic P forms or biocycling in plant roots. Nitrogen fertilization led to soil acidification that increased extractable P and could have increased the leaching of P. Therefore, application of higher than recommended rates of N and P can increase P remaining at the soil surface and shallow depths, increasing availability of P but also potentially increasing the risk of movement of P to water bodies for many years after application is terminated.

While excess applications of P that accumulate in the soil surface can lead to risk of P movement to water bodies, decline of P over time due to P removal greater than application can lead to P depletion and loss of soil productivity. The long-term studies described above show that P will move from the non-labile pools to replenish the labile pools in response to plant uptake (Liu et al. 2015; McKenzie et al. 1992a; McKenzie et al. 1992b; Selles et al. 2011; Selles et al. 1999). However, the soil P pools are not infinite and as they decrease, the ability of the soil to supply P to meet crop demand will decline. The “maintenance”, “balance” or “long-term sustainability” strategy for P fertilizer management suggests targeting a critical desired soil P level by either adding P greater than crop removal if available soil P is low, or less than crop removal if soil P is high. When the target soil test P level is reached, P fertilizer can be applied to match crop removal to maintain the target soil P.

Phosphorus depletion can be of particular concern in organic crop production systems, where options for P application are restricted. Therefore, many organic farms experience declines in soil P status. A survey of 14 organic farms in the eastern part of the Northern Great Plains showed that soil test P levels were frequently low, with available soil P levels that ranged from deficient (2 ppm) to adequate (27 ppm) (Entz et al. 2001). While the range in soil test P was wide, the average P level in the study was 7 ppm. This compares to soil tests for non-organic commercial fields where 76 and 89% of soil samples taken in Manitoba in 1997 and 1998, respectively, tested greater than 10 ppm. In the University of Manitoba’s long term organic rotation at Glenlea, available soil P in the high-yielding organic grain-forage rotations decreased over the first thirteen years of the study, with organically managed soils having lower concentrations of readily available P than conventionally managed soils, while the non-labile forms were similar in the two management systems (Welsh et al. 2009). The lower yielding organic grain-only rotations had lower P removal than the conventional system, resulting in a slightly lower concentration of available-P forms in the soil. The high yielding organic forage-grain rotation decreased available-P forms to below an agronomic response threshold, demonstrating that high-yielding organic rotations that export large amounts of P can lead to P depletion of the soil over time, in the absence of P inputs.

3.4. Assessing P Use Efficiency

As stated previously, phosphorus fertilizer use efficiency (PUE) measured in the year of application will rarely exceed 25% (Johnston et al. 2014; Syers et al. 2008). Traditional methods of measuring nutrient use efficiency that can be applied to PUE are listed in Table 3. However, these methods of evaluation do not normally consider the benefits from residual P.

Use of ^{32}P-labelled P fertilizer can directly show how much of the fertilizer applied moves into the plant and can provide an accurate indication of the short-term use efficiency of fertilizer sources. The half-life of ^{32}P is approximately two weeks, so this technique is limited to studies that are less than about 3 months. While this is a powerful technique for directly studying the fate of applied P, the short half-life, radioactivity hazards and expense of this method limit its application in agronomic field trials.

Table 3. Common methods of calculating nutrient use efficiency (Fixen et al. 2015)

Term	Calculation*	Question addressed	Typical use
Partial factor productivity	$PFP = Y/F$	How productive is this cropping system in comparison to its nutrient input?	As a long-term indicator of trends.
Agronomic efficiency**	$AE = (Y-Y_0)/F$	How much productivity improvement was gained by use of nutrient input?	As a short-term indicator of the impact of applied nutrients on productivity. Also used as input data for nutrient recommendations based on omission plot yields.
Partial nutrient balance	$PNB = U_H/F$	How much nutrient is being taken out of the system in relation to how much is applied?	As a long-term indicator of trends; most useful when combined with soil fertility information.
Apparent recovery efficiency by difference**	$RE = (U-U_0)/F$	How much of the nutrient applied did the plant take up?	As an indicator of the potential for nutrient loss from the cropping system and to access the efficiency of management practices.
Internal utilization efficiency	$IE = Y/U$	What is the ability of the plant to transform nutrients acquired from all sources into economic yield (grain, etc.)?	To evaluate genotypes in breeding programs; values of 30-90 are common for N in cereals and 55-65 considered optimal.
Physiological efficiency**	$PE = (Y-Y_0)/(U-U_0)$	What is the ability of the plant to transform nutrients acquired from the source applied into economic yield?	Research evaluating NUE among cultivars and other cultural practices; values of 40-60 are common.

* Y = yield of harvested portion of crop with nutrient applied; Y_0 = yield with not nutrient applied; F = amount of nutrient applied; U_H = nutrient content of harvested portion of the crop; U = total nutrient uptake in aboveground crop biomass with nutrient applied; U_0 = nutrient uptake in aboveground crop biomass with no nutrient applied; Units are not shown in the table since the expressions are ratios on a mass basis and are therefore unitless in their standard form. P and K can either be expressed on an elemental basis (most common in scientific literature) or on an oxide basis as P_2O_5 or K_2O (most common within industry).

The difference method is commonly used to measure short-term and long-term phosphorus use efficiency in agronomic studies, either using the difference in yield between the fertilized and unfertilized treatments (agronomic efficiency $AE=(Y-Y_o)/F$ in Table 3) or the difference in P uptake between the fertilized and unfertilized treatments (apparent recovery or use efficiency $RE=(U-U_o)/F$). The P supply and yield of the unfertilized control will have a large effect on the efficiency calculated by these difference methods. In a severely P deficient soil, yield and P recovery will be low on the unfertilized soil and both yield, and P uptake will increase to a large extent with P application, other limiting factors being excluded, and the calculated efficiency will be high. In contrast, if the study is conducted on soils that are high in available P, there will be little or no yield response to P and the calculated efficiency will be low. Therefore, the measured P efficiency will be largely dependent on the amount of plant-available P in the unfertilized soil. In addition, the P recovery in the crop is directly proportional to crop yield, which will be affected by a broad range of factors other than P availability. Crop type and genetics, rotation, rainfall, daylength, salinity or other soil constraints, presence of other nutrients, crop disease, weed competition, tillage management, seeding data and other environmental and management practices will influence crop yield and P uptake. Efficiency of P use will be low if crop yield is reduced due to factors unrelated to P availability.

The balance method ($PNB=U_H/F$ in Table 3) has been proposed recently as a method of considering the long-term residual benefit of P fertilizer (Johnston et al. 2014; Syers et al. 2008). In this, the uptake of P by the crop is divided by the amount of P applied and converted to a percentage. Considering PUE in this way relies on the assumption that the fertilizer P not used by the crop will remain in the soil in a form that can remain available to the plant in the short- or long-term. The P that is taken up by the plant in any year is the combination of P from the fertilizer applied that year plus P that is taken up from the soil reserves. A reliable assessment of P fertilizer efficiency using the balance method requires a long-term data set where P inputs and removals are measured annually for many years. The long-term efficiency of P fertilizer measured using the balance method is normally significantly greater than the 25% value often cited as the efficiency in the year of application and can approach 90% (Syers et al. 2008). However, the balance method assumes that all residual P in the soil results from previous fertilizer application, ignoring the naturally occurring P in the soil, which will lead to an over-estimation of PUE, especially if the natural P reserves are substantial (Chien et al. 2011; McLaughlin et al. 2011).

The balance method was used to evaluate the long-term recovery of P fertilizer in the long-term cropping study at Swift Current, SK that was described previously (Selles et al. 1995). Inputs exceeded removal in the treatments where P fertilizer was added. In the P-fertilized treatments, P removal in the grain increased linearly with the P applied. Fertilizer P accumulated in the soil primarily in plant-available forms (Liu et al. 2015; Selles et al. 2011). Changes in Olsen-P in the long-term study were directly proportional to the P balance in the treatment, with a change in P balance of 6 lb P/acre (14 lb P_2O_5/acre) producing a change of 1 lb/acre (0.5 ppm) in Olsen P (Selles et al. 2007). Efficiency calculated using the balance method in the 24 years of fertilization in this study averaged from about 50 to 65%, with the higher values occurring where both N and P were applied. When P fertilizer input was halted and crops were grown for 12 years on the previously fertilized soils without any additional P addition, total P recovery (calculated as 100*(total P removed in the grain/total P applied during the duration of the study)) was 105% of the initial P application on the NP systems and 90% in the P only system. Recovery of residual P was lower on treatments where yields were limited by N deficiency. Therefore, where P fertilizer additions are not lost through erosion or water movement, the P can remain in a plant-available form for many years.

The balance method is also useful in a long-term sustainability management system, where soil P is managed towards a critical P soil test level and then maintained by balancing P inputs with removal. The balance method calculates the P removed in the crop as a percentage of the P applied as fertilizer. If the value is less 100%, P will be building in the soil, apart from any other pathways of permanent P loss. If the P is more than 100%, the P in the soil will be depleted. If the soil reserves are to be maintained or built and not depleted, they must be replenished through inputs from fertilizers or other P sources.

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.

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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 1). 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.

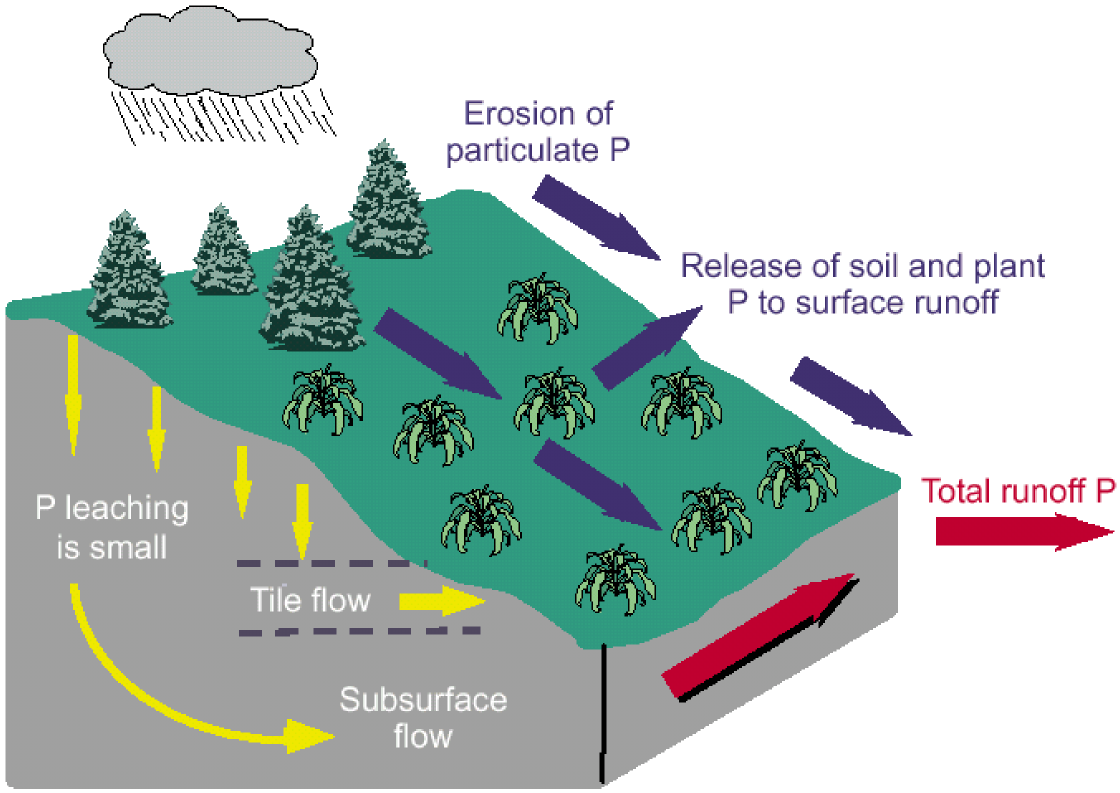


Figure 1. Processes that transport phosphorus to water from agricultural land (Sharpley, A. N., Daniel, T., Sims, T., Lemunyon, J., Stevens, R., and Parry, R. 2003. Agricultural phosphorus and eutrophication. ARS-149, USDA-ARS. https://www.ars.usda.gov/oc/np/phoseutro2/phoseutrointro2ed/

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.

Detailed Information

Phosphorus is an essential nutrient for plant growth and an adequate supply of P is important to ensure optimum crop production. However, P in runoff can lead to eutrophication of surface water. A more long-term issue may be the accumulation of potentially toxic trace elements such as cadmium in the soil from repeated applications of fertilizers containing trace element contaminants. Indirectly, greenhouse gas emission from transport and application of fertilizer is of concern. Soil degradation including organic matter loss and P depletion can occur if inputs of crop residue and P are inadequate to compensate for losses and removal over time. Effective 4R nutrient stewardship practices must be designed to address these types of environmental concerns to ensure long-term sustainability of the land and water resources that support both agriculture and society.

4.1. Phosphorus loss to surface water and eutrophication

The largest environmental issue related to P in the Northern Great Plains region is eutrophication of fresh water caused by nutrient loading (Chambers et al. 2001; Salvano et al. 2009). Eutrophication refers to the enrichment of water with dissolved nutrients that stimulate plant and algal growth. Some stimulation of growth may be beneficial, by increasing the food supply for fish and increasing the productivity of the lake. However, eutrophic lakes can develop dense algal blooms that reduce the water quality for fisheries, recreation, drinking and industrial uses (Lewtas et al. 2015). Excessive plant growth and decomposition can lead to depletion of oxygen from the water, resulting in fish kills.

In freshwater bodies, P is the most commonly limiting nutrient, so increasing the P concentration in the water will increase plant growth and can potentially lead to eutrophication (Chambers et al. 2001; Jeppesen et al. 2007; Schindler et al. 2008b; Wilander and Persson 2001). Lakes are classified according to their nutrient loading status and the risk of algal growth. Oligotrophic lakes are low in nutrients, containing less than 4 to 10 µg P L^{-1} so that algal growth is nutrient-limited and water is usually clear (Table 1). Mesotrophic lakes are moderate in nutrient content, with concentrations of 10 to 20 µg P L^{-1}. As P concentration increases above 20 to 35 µg P L^{-1}, the lakes become eutrophic and are green with algae through most of the ice-free season. Hyper-eutrophic lakes have extremely high nutrient concentration and excessive algal growth. If P concentration is above 100 µg P L^{-1}, algal growth is limited by factors other than P, such as N, micronutrients or light.

Table 1. Total phosphorus trophic thresholds for Canadian lakes and rivers (http://ceqg-rcqe.ccme.ca/download/en/205/?redir=1555081609, accessed April 12, 2019)

Trophic Status	Total phosphorus (ppb, µg/Litre)
Ultra-oligotrophic	< 4
Oligotrophic	4-10
Mesotrophic	10-20
Meso-eutrophic	20-35
Eutrophic	35-100
Hyper-eutrophic	> 100

Lakes and other surface water bodies on the Northern Great Plains are at high risk for eutrophication because they are commonly shallow and fed by large, fertile agricultural watersheds that can supply large amounts of nutrients. Many of the lakes in the region are naturally eutrophic, as this is part of the aging process of lakes located in fertile areas with nutrient-rich soils (Lewtas et al. 2015). However, P and sediment loading from agricultural activity is a major contributor to enhanced eutrophication of lakes in the Northern Great Plains. For example, the increased eutrophication and deterioration of water quality in Lake Winnipeg, the 10^{th} largest freshwater lake in the world, has been attributed in part to nutrient loading from agricultural activity (Schindler et al. 2012).

Phosphorus enters water bodies in local runoff water and regional inlet streams and is lost through outlet streams and by incorporation into the sediments. Some of the soluble P in the lake binds with soil particles and minerals in the water and sediment and becomes less available to bacteria and algae. However, some of the compounds that retain P are sensitive to redox conditions. Therefore, if water at the bottom of the lake becomes oxygen-depleted, the top few cm of sediment, which is usually aerobic, will become anaerobic, releasing soluble P to the water. The plant-available P will move towards the surface water and increase the amount of P that is available for algal growth. In shallow lakes, long-term P accumulation may lead to the release of P from bottom sediments even when the water is oxygenated (Schindler et al. 2008a). Release of P from sediments can lead to continued P problems even after external inputs of P have been remediated.

The amount and rate of turnover of dissolved P has a great effect on the amount of algal growth (Chambers et al. 2001). As P is the primary limiting factor for algal growth in freshwater lakes on the Northern Great Plains, the growth of algae will largely depend on the concentration of P in the lake water, which will be a function of climatic conditions such as rainfall and temperature, the amount, timing and bioavailability of the nutrient load, the rate of input of nutrient-rich water compared to the volume and output of the lake (flushing rate) and the depth of the lake. If a lake is rapidly flushed, its concentration will reflect the concentration in the in-flowing waters, while a slowly flushing lake will have a P concentration that is more controlled by sedimentation. Even if a lake has a low overall P concentration, there may still be problems in specific areas near the shoreline where channels, streams and rivers discharge nutrients and dilution is limited.

Many blue-green algae (Cyanobacteria) species can fix atmospheric N_2, so in waters with low N concentrations they will often out-compete other algae if sufficient amounts of P are available. The higher the P loading and concentration, the more common excessive algal blooms dominated by cyanobacteria become (Table 2) (Lewtas et al. 2015). Cyanobacterial blooms are particularly undesirable because they produce surface scums, noxious tastes and odours and may produce toxins than can be harmful to humans, livestock, wildlife and other aquatic organisms. The toxicity is most harmful to the nervous system or the liver and can lead to derangement, staggering, tremors, abdominal pain and death in almost any mammal, bird or fish (Chambers et al. 2001). Human deaths from drinking water contaminated by blue-green algae are rare because people usually avoid algae-contaminated drinking water, but pet and livestock illness and death can occur. During the summer, sloughs in the prairie pothole region can be prone to this problem because of the prevalence of shallow water bodies, nutrient enrichment and warm conditions.

Excess plant and algal populations can also deplete oxygen concentrations in lake water. While plants are net producers of oxygen because they release oxygen during photosynthesis they will use oxygen during night, depleting the oxygen concentration in the water and stressing fish populations (Chambers et al. 2001). Decomposition of large amounts of organic matter left after algal blooms can also deplete oxygen concentrations, leading to fish kills.

Table 2. Typical characteristics of the trophic state of a lake (Ghosh and Mondal 2012).

Parameter	Oligotrophic	Eutrophic
Occurrence of algal bloom	Rare	Frequent
Frequency of green and blue-green algae	Low	High
Daily migration of algae	Considerable	Limited
Characteristic algal groups	*Bacillariophyceae* *Pinnularia, Cymbella* *Chlorophyceae* *Chrysophyceae* *Synura, Chromulina*	Cyanophyceae *Microcystis, Nostoc*
Characteristic zooplankton groups	Represented by small size species: Cladocerans (*Bosmina*) Copepods	Represented by large size species: *Daphnia* (decreases in hypereutrophic)
Density of plankton	Low	High
Characteristics of fish	Finer variety of fish	Coarse fish
Depth	Deep	Shallow
Summer oxygen in hypolimnion	Present	Absent
Algae	High species diversity with low density and productivity often dominated by Chlorophyceae.	Low species diversity with high density and the productivity often dominated by Cyanophyceae.
Blooms	Rare	Frequent
Plant nutrient flux	Low	High
Animal production	Low	High
Fish	Finer variety of flux (e.g. carps)	Coarse fish (e.g. air breathers)

4.1.1 Reducing P losses from agricultural soils

The amount of P that will move from the field is a function of the P concentration near the soil surface and the degree of transport (McDowell et al. 2001b; Sharpley 1995). 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 is high, and water from the field can easily move offsite to sensitive waters through natural or artificial drainage (Van Bochove et al. 2006). Leaching of P is not normally an issue but may occur on soils with very low P sorption capacity, on soils where there is a large amount of macropore flow, or if soil test P is very high from application of organic wastes to sandy soils or acid organic soils. Labile organic forms of P are more prone to leaching than are inorganic P forms (Campbell and Racz 1975). If conditions conducive to leaching occur in tile-drained land, the risk of subsurface drainage losses of P into surface water may be high (King et al. 2015).

Phosphorus risk indicators have been developed to estimate the risk of P transfer from field to surface waters by numerical ratings that integrate P transport factors such as erosion, runoff class, and distance to water with P source factors such as soil test P and application of fertilizers and manures (Salvano et al. 2009; Sharpley et al. 2012; Van Bochove et al. 2006). Most indicators have been developed to assess the risk of P loss from fields where rainfall-induced erosion carries particulate P from sloping landscapes into water bodies. The erosion-based risk differs from the situation on much of the Northern Great Plains where P losses are largely driven by snowmelt-driven runoff over relatively level landscapes and frozen soils (Salvano et al. 2009). In studies conducted in Saskatchewan, spring snowmelt runoff represented about 80% of annual runoff (Nicholaichuk 1967; Nicholaichuk 1984; Nicholaichuk and Read 1978). In paired watersheds in Manitoba, snowmelt runoff accounted for 80 to 90% of total annual runoff, although snowfall accounted for only 25% of total annual precipitation during the study period (Tiessen et al. 2010).

The dominating effect of snowmelt on runoff in the Northern Great Plains leads to a dominating effect of snowmelt runoff on P transport. In a three-year study in the Red River basin in Manitoba, 62% of the annual P load was delivered during the 12-18 day snowmelt period (Rattan et al. 2017). The method of P movement will differ between snowmelt-driven runoff and rainfall-driven runoff. Snowmelt usually occurs over a few days to weeks, and so is slower than rainfall events than occur over minutes to hours. During snowmelt, the frozen soil is resistant to particle detachments, so snowmelt is not as erosive as rainfall events. As a result, there is normally far less suspended particulate P moving in snowmelt as compared to rainfall runoff, so a higher proportion of P is in the dissolved rather than the particulate form. In paired watershed studies in Manitoba, average concentrations of dissolved nutrients in runoff were higher during snowmelt than rainfall events (Tiessen et al. 2010). The concentration of suspended sediment and particulate P were greater during rainfall events than snowfall runoff events, but losses of dissolved P were much greater (about 5x) than particulate P both in snowmelt and rainfall events (Li et al. 2011). Similarly, in studies in Saskatchewan, the P in snowmelt was primarily in the dissolved rather than the particulate form and the particulate P that was measured in runoff appeared to be associated with organic matter rather than soil mineral matter (Cade-Menun et al. 2013). Because snowmelt in the Northern Great Plains leads to much greater runoff than rainfall events, most P movement occurs during snowmelt as dissolved P (Cade-Menun et al. 2013; Li et al. 2011; Tiessen et al. 2010). Snowfall accumulation and hence the duration and intensity of snowmelt runoff is greater in the black and gray than the brown and dark brown soil zones, likely increasing the relative risk of P movement in runoff. In addition, seasonal variations in precipitation and pattern of snowmelt can influence runoff amount and intensity and hence P movement (Clearwater et al. 2016).

Phosphorus present in snowmelt runoff may originate from residual P from manure or fertilizers that remain at the soil surface, or from P leaching from vegetation (Elliott 2013; Tiessen et al. 2010). Plant material such as cover crops, buffer strips, forages, weeds or winter annuals may release soluble P from cells that are lysed by freezing and thawing, increasing the P concentration in runoff. In field studies in Ontario, water-extractable P was higher in cover crops than in wheat residue and increased with plant decomposition (Lozier et al. 2017). In a comparison of P losses in simulated snowmelt from a range of plant materials, the release of P was strongly related to plant P concentration (Elliott 2013). Juvenile winter wheat had higher P concentration than mature spring wheat straw and about 50 times more P was released from the juvenile winter wheat than from the mature spring wheat residue (Elliott 2013). Most of the P from the winter wheat was released as dissolved P while most from the loss from spring wheat residue was as particulate P. Potential release of P from winter wheat was about 1.3 lb/acre (3.0 lb P_2O_5/acre), more than enough to be of environmental concern. When residue was combined with soil to simulate an active layer, loss was much less than for the soil and plant residues individually, indicating that soil performs an important role in intercepting the P released from vegetative residues during snowmelt.

In the Northern Great Plains, where P loss is dominated by snowmelt runoff events, beneficial management practices (BMPs) for control of P movement should concentrate on reducing the movement of dissolved P during early spring. Movement of dissolved P will be a function of the concentration of P in the runoff water and the volume of runoff that occurs. Many of the BMPs to reduce P movement to waterways have been developed to reduce nutrient loss from erosion (Cade-Menun et al. 2013). Erosion-focused BMPs concentrate on practices such as vegetative buffer strips to trap eroded particles before they enter water bodies, or reduction of bare soil and tillage to reduce erosion. In areas where erosion is a major factor in nutrient transport, practices that use vegetation to prevent erosion or intercept nutrients have effectively reduced nutrient loads. However, in the dry climate and gently sloping landscapes of 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 actually contribute nutrients to snowmelt runoff (Elliott 2013; Sheppard et al. 2006). Long, slow snowmelt leaves the water in contact with the thawing residues and the surface P for a long time, allowing time for meltwater to extract and transport the soluble P.

Similarly, conservation tillage is a recommended practice to reduce erosion losses and hence reduce the risk of P loss when the dominant form of transport is through particulate movement. In areas where rainfall-induced erosion dominates P loss, use of conservation tillage to increase infiltration and reduce runoff can reduce the total quantity of P losses from the field. However, where the dominant path of loss is through movement of dissolved P in snowmelt, conservation tillage practices are not as effective (Tiessen et al. 2010). In a paired watershed study in south-eastern Manitoba, converting to no-till resulted in a small decrease in loss of particulate P but a greater loss of dissolved P. Since dissolved P during snowmelt was by far the dominant form of P loss from the watersheds, total P loss increased with the adoption of conservation tillage (Tiessen et al. 2010). Total P loss was minor from an agronomic viewpoint (1.33 lb P_2O_5/acre/year) but this small amount is environmentally significant and can contribute to eutrophication.

If conservation tillage is combined with broadcast application of P, the risk of P loss is increased (Janssen et al. 2000; Jarvie et al. 2017; Wiens 2017). The lack of soil inversion with conservation tillage can result in accumulation, or stratification, of nutrients at the soil surface, including those in crop residue and those added as fertilizers or manures. This stratification can increase the concentration of dissolved nutrients in runoff. In studies in Minnesota under corn, reduced tillage practices of ridge till or chisel plowing led to higher loss of soluble, particulate and total P than moldboard plowing (Hansen et al. 2000). Most P was lost as soluble P, averaging 75% of the total P loss. Where fall tillage was eliminated, there was more loss of soluble P in snowmelt because of P accumulation at the soil surface in the absence of tillage, P leaching from the crop residue, and more runoff because of the smooth soil surface.

4.1.2 4R nutrient stewardship practices that reduce P movement to water

Fertilizer applications can be a major source of P input into farming systems and a large potential source for P movement into water systems (Yates et al. 2012). However, the amount of P lost from the system will not necessarily relate directly to the amount applied because a large proportion of the P will be retained in the field through adsorption or precipitation or be utilized for crop uptake. Proper 4R fertilizer management practices that increase the amount of P taken up by the crop or retained within the field will be important in ensuring that losses from the field to water bodies are minimized.

Selection of fertilizer application rates that are closely matched to crop demand should be used to minimize the risk of P runoff. In simulated runoff studies on soils collected from a no-till field trial in Saskatchewan, P loss increased with the rate of broadcast P application (Wiens 2017). The largest amounts of total P exported in snowmelt runoff (0.45 lb total P per acre or 1.03 lb P_2O_5/acre) were for the treatment with the high application rate (72 lb P_2O_5/acre) combined with surface broadcast placement, with half or less of this amount for the unfertilized and 18 lb P_2O_5/acre treatments. The high rate and broadcast treatment also had the highest proportion of total P as dissolved reactive P.

Rates of P application matched to crop uptake will help to reduce accumulation of plant-available P in the surface soils. Runoff simulation studies with soils in Alberta and Manitoba have demonstrated that loss of P from the soil is linearly related to the concentration of soluble P present in the surface soil that interacts with moving water (Figure 2) (Sawka 2009; Wright et al. 2006). As the soil test P concentration (STP) increases, the concentration of P in the runoff water increases, as well. Therefore, as in studies conducted elsewhere, increasing the P concentration at the soil surface will increase the risk of P loss (McDowell et al. 2001a; Sharpley et al. 1994). However, contrary to those other studies, P loss relationships with soil test P in the Canadian Prairies have been consistently linear, with no obvious “change point” to indicate substantial increases in runoff losses of P above a specific concentration of soil test P.

In studies on eight field-scale microwatersheds in Alberta that included a range of tillage systems, there was a strong linear relationship between the site mean STP concentration and the P in the runoff water (Little et al. 2007). The relation between runoff P and the soil test measurements in the surface 2.5 cm and the surface 15 cm were similar, indicating that an agronomic sampling depth of 15 cm would be suitable for prediction of runoff risk. The study by Little et al. (2007) included sites that had a long-term history of manure application resulting in very high STP values and sites that had only received agronomic rates of P fertilizer and were low in soil test P. The relationship between runoff P and STP was strongly driven by the very high STP values in the manured plots and the relationship was no longer apparent when only the small range of STP values in the unmanured plots were included. Similar results were measured in watershed studies in Manitoba, where the soil test P concentrations were not related to runoff P, due to a narrow range of soil test P at this single study site, which had received recommended annual rates of P fertilizer rather than large, intermittent applications of P as fertilizer or manure (Liu et al. 2013). In addition, the majority of snowmelt runoff occurred on frozen soil when the soil-runoff interaction was minimal and when the influence of other sources of P, such as thawing vegetation, played a large role.

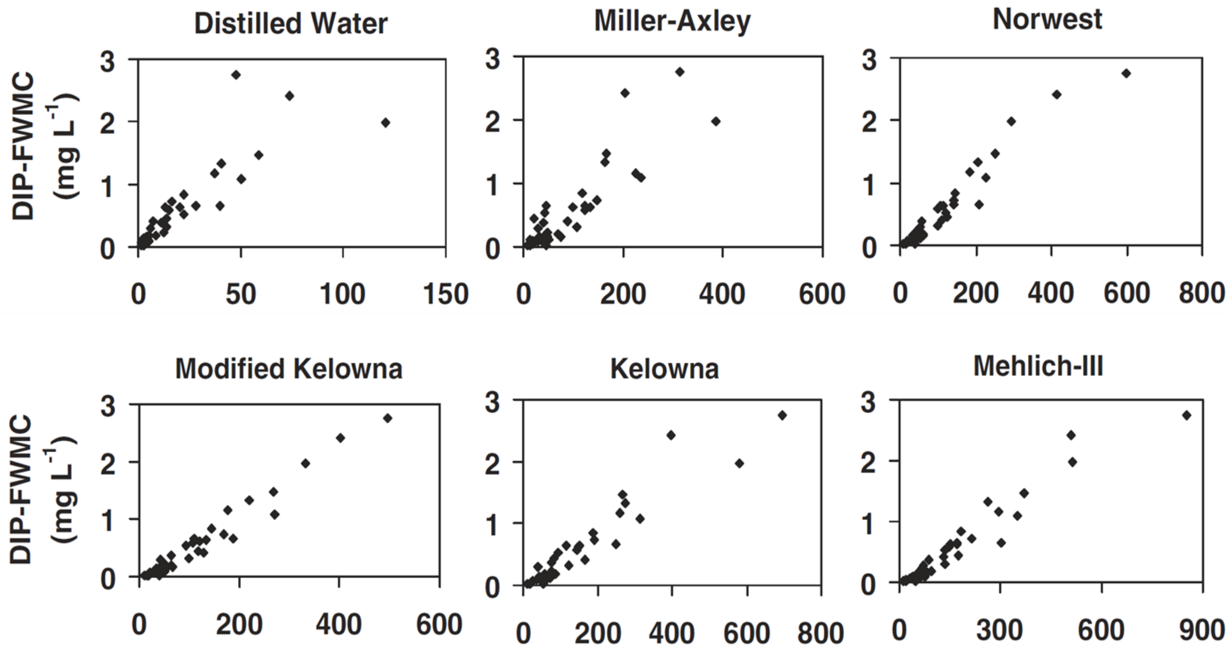


Figure 2. Relationships of soil test P and dissolved inorganic P–flow-weighted mean concentration (DIP–FWMC) for six soil test extraction methods for the first 30 min of simulated runoff in 38 Alberta soils (Wright et al., 2006).

Nevertheless, practices that significantly increase the STP values at the soil surface are likely to increase the risk of P runoff. Managing P concentrations with fertilizer applications closely related to agronomic optimum concentrations based on soil tests can help to avoid excessive concentrations of STP and reduce the risk of P loss. Therefore, once optimum agronomic concentrations of soil test P are achieved, P fertilizer rate should be matched to crop removal to avoid further accumulation of P in the soil over time.

In addition, increasing the rate of P fertilization above agronomic optimum concentrations can lead to luxury consumption of P by the crop, increasing the concentration of P in the crop tissue. Higher P concentration in the vegetative material in contact with runoff water can increase the amount of P leached and the amount of P movement. Again, matching P applications with crop demand can reduce the risk.

While the majority of P losses from agricultural fields are by runoff, P can also be lost by leaching and subsurface flow (King et al. 2015; McDowell et al. 2001b). As discussed previously, P will move more readily in labile organic forms than in inorganic forms. Risk of P leaching can occur with water movement through sandy, light-textured soils, soils with a low P retention capacity, waterlogged soils where reducing conditions mobilize P, organic soils or soils with high manure loading, and soils where there are preferential flow paths, such as root channels, earthworm channels, or cracks in the soil structure. With tile-drained systems on soils that are prone to P leaching, the risk of subsurface drainage losses of P may be high (King et al. 2015). These conditions are relatively rare on the Northern Great Plains, but where they occur, management practices that reduce P concentration in the soil will reduce the risk of P leaching.

To be agronomically effective, most P fertilizer sources are water-soluble, so will be initially available for movement in runoff. In studies on pasture soils in New Zealand, runoff losses of P were smaller with dissolved superphosphate than with granular superphosphate (Sharpley and Syers 1983). The liquid fertilizer may have infiltrated more easily into the soil, reducing the contact between the runoff water and the fertilizer. In addition, moving deeper into the soil may generate more soil-fertilizer contact, increasing the P retention. Use of less soluble fertilizers also can reduce the risk of dissolved P loss (Smith et al. 2016). Broadcast single superphosphate led to less loss of P than the other, more soluble granular fertilizers in studies using runoff boxes. Less soluble forms of P such as bone meal and rock phosphate had soluble P loss that did not differ from the unfertilized control. In rainfall simulation studies in grass and no-till fields in Pennsylvania, P losses were higher for 21 days after application from surface broadcast triple superphosphate fertilizer (TSP) and a low grade single superphosphate than from a rock phosphate source or the unfertilized control (Shigaki et al. 2006). Concentration of P in the runoff was directly related to the water-soluble P in the fertilizer material. The greatest amount of P loss was in the rainfall event that occurred one day after fertilizer application. Contribution of the soluble fertilizers to runoff decreased over time while the less soluble fertilizers continued to gradually release P for 42 days after application. However, as mentioned previously, to be agronomically effective, P fertilizers need to dissolve in soil solution, to become plant-available. Therefore, although use of sparingly soluble fertilizer forms may reduce the risk of environmental fertilizer loss, it will also reduce the agronomic benefit of the fertilizers. Use of higher application rates to compensate for lower fertilizer availability can lead to long-term accumulation of P in the soil and greater long-term risk of P loss. Combining timing and placement selections that reduce the concentration of soluble P at the soil surface during runoff events can allow soluble P sources to be used to optimize agronomic benefits while reducing the risk of P runoff.

Fertilizer placement that increases the concentration of P at the soil surface can increase the risk of P movement in runoff. In agricultural systems, the surface soil will tend to be enriched with P, particularly under no-till and/or with broadcast applications of P (Selles et al. 1999; Weiseth 2015). Because of its immobility, P tends to accumulate at the depth of application, especially under reduced tillage (Grant and Lafond 1994). Broadcast application without incorporation will leave the P fertilizer at the soil surface where it is at high risk of movement in runoff water. As mentioned previously, in a study on soil monoliths collected from a P study on a no-till field in Saskatchewan, broadcast application of 72 lb P_2O_5/acre led to large amounts of P loss in simulated runoff studies (Wiens 2017). Fertilizer P applications that are made by broadcasting without incorporation at rates above that which would normally be utilized by the crop in the year of application, such as the 72 lb P_2O_5/acre broadcast treatment, appeared to increase potential export of P in dissolved reactive forms. Studies with broadcast and in-soil applications of P on soybeans in Saskatchewan showed that broadcast P fertilizer led to higher concentrations of water-soluble P near the soil surface, which increased P export in simulated snowmelt runoff (Weiseth 2015).

Incorporation of broadcast fertilizer will reduce the risk of P movement, by reducing the concentration of P at the soil surface. It should be noted that different tillage equipment will provide different degrees of soil inversion and mixing, with moldboard plough and disc equipment generally providing more vertical mixing than chisel-type equipment (Chen et al. 2004; Mohler et al. 2006). Therefore, some forms of low disturbance tillage practiced on the Northern Great Plains may leave a substantial amount of broadcast P near the soil surface while other forms may be very effective at reducing surface P concentration. In field studies in Indiana, disking in diammonium phosphate fertilizer (DAP) reduced soluble P losses as compared to unincorporated DAP, but sediment loads were higher from disked DAP (Smith et al. 2017). Similarly in Kansas, incorporation of liquid P fertilizer through field cultivation prior to planting reduced P runoff (Janssen et al. 2000). Incorporation of P fertilizer will increase the contact between the fertilizer and the soil, increasing retention through precipitation and adsorption reactions and reducing the proportion of soluble P present that is subject to direct dissolution and movement in runoff water (Hansen et al. 2002). Phosphorus will react with the calcium and magnesium present in high pH soils to form sparingly soluble calcium and magnesium phosphate compounds (Sample et al. 1980). In acid soils, similar reactions occur with iron and aluminum oxides. Soils with a high capacity for P retention will be less at risk for P loss than soils with a low retention capacity. Due to the challenges of losing soluble fertilizer P when broadcast P is not incorporated or losing soil P by erosion when broadcast P is incorporated, P fertilizer should not be broadcast in areas that are prone to runoff.

In-soil banding of P below the surface will reduce the risk of P loss by placing the P in a position where it is protected from runoff. Phosphorus is relatively immobile in the soil and so remains near the site of fertilizer placement unless disrupted by tillage (Grant and Lafond 1994; Selles et al. 1999; Weiseth 2015). Banding will leave the P fertilizer in a zone that is not directly in contact with runoff water, reducing the risk of P movement. In studies that evaluated 30 minutes of runoff using runoff boxes, injecting the fertilizer even 1 cm below the soil surface reduced P losses from monoammonium phosphate fertilizer (MAP) by 98% as compared to broadcasting the fertilizer and leaving it at the soil surface (Smith et al. 2016).

Placing the P in a concentrated band near the seed-row can also increase fertilizer use efficiency and reduce the rate of P required for optimum crop yield. Band placement of P reduces contact with the soil and should result in less P retention than broadcast application, thus increasing fertilizer use efficiency (Tisdale et al. 1993). In P-deficient soils with a high P retention capacity, the optimal method of supplying P for early crop growth is generally by banding the fertilizer near or with the seed, during the seeding operation (i.e., use of “starter P”). The banded fertilizer is available to the crop early in the growing season and the residual P will be located below the surface where it will be protected from movement in runoff.

Timing of P application can also have a large effect on losses. Runoff occurring soon after application of broadcast P fertilizer can lead to large P losses. Studies at Swift Current where P was broadcast in the fall on summer fallow and left unincorporated, a situation that would encourage P runoff, led to losses of about 9.8% of the fertilizer applied (Nicholaichuk and Read 1978). In studies in Ontario, fall broadcast and shallow incorporation of P fertilizer increased the water-extractable P concentration at the surface, increasing the risk of P release to runoff events immediately after P application (Lozier et al. 2017). Large P losses can occur where rainfall or runoff in general follows quickly after surface P application. However, P enrichment of runoff from soluble P fertilizers rapidly declines with time after fertilizer application. Concentration of dissolved reactive P in simulated surface runoff from field runoff plots decreased from 90 mg L^{-1} the day after application TSP to 7.8 mg L^{-1} seven days after application and continued to decline until it was just under 2 mg L^{-1} 42 days after application (Shigaki et al. 2006). Therefore, application of P immediately prior to occurrence of runoff events should be avoided, particularly if P is broadcast. Furthermore, in areas such as the Northern Great Plains, where cold winters and frozen soils restrict the soil's capacity to retain fertilizer P, fertilizer P should not be applied in late fall, or on frozen soil.

When considering the range of BMPs for P fertilization, it is important to identify the major pathways for P movement at a given site, before recommending or adopting specific management practices to address the problem (Salvano et al. 2009; Sims et al. 1998; Flaten et al. 2019). 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 STP 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 immediately prior to rainfall events. It is also important to consider that most of the P loss will generally occur from a small area of the watershed and practices that reduce risk of P movement in those sites are likely to have the greatest benefit on water quality (Sharpley et al. 2011). Within a field, P tends to accumulate in lower-slope and depressional areas where water movement is concentrated (Letkeman et al. 1996; Roberts et al. 1985; Wilson et al. 2016). Reducing or eliminating P application on those sites could reduce the risk of P movement off-field, without impairing crop yield potential.

4.2. Phosphorus Depletion in Soils

Excess accumulation of P in the soil, especially near the soil surface, is undesirable as it 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 and the sustainability of crop production. In studies in Alberta, barley yields on soils with very low soil test P were lower than on higher-testing soils, even when very high rates of P fertilizer were applied (Nyborg et al. 1999). An adequate level of soil P fertility is required to satisfy plant requirements through the growing season for optimum crop yield.

Soil testing laboratories suggest a critical concentration of soil test P, using a soil test suited to the specific region, above which the plant will no longer respond to additional P applications.

Many of the soils in the Northern Great Plains contain soil P concentrations below suggested critical concentrations, indicating that P fertilizer is required to optimize crop yield (Figure 3). Between 2010 and 2015, the percentage of samples taken that were below critical concentrations increased in Manitoba and Alberta but decreased in many of the Northern Great Plains states and provinces (Figure 4). Some caution should be used when interpreting these data since there may be bias if an increasing number of soil samples are being submitted to develop manure management plans, as those samples would be taken on soils that may have been targeted for manure application and may not be representative of the general field situation. In addition, different soil test methods and critical concentrations are used by different testing laboratories, making comparison difficult.

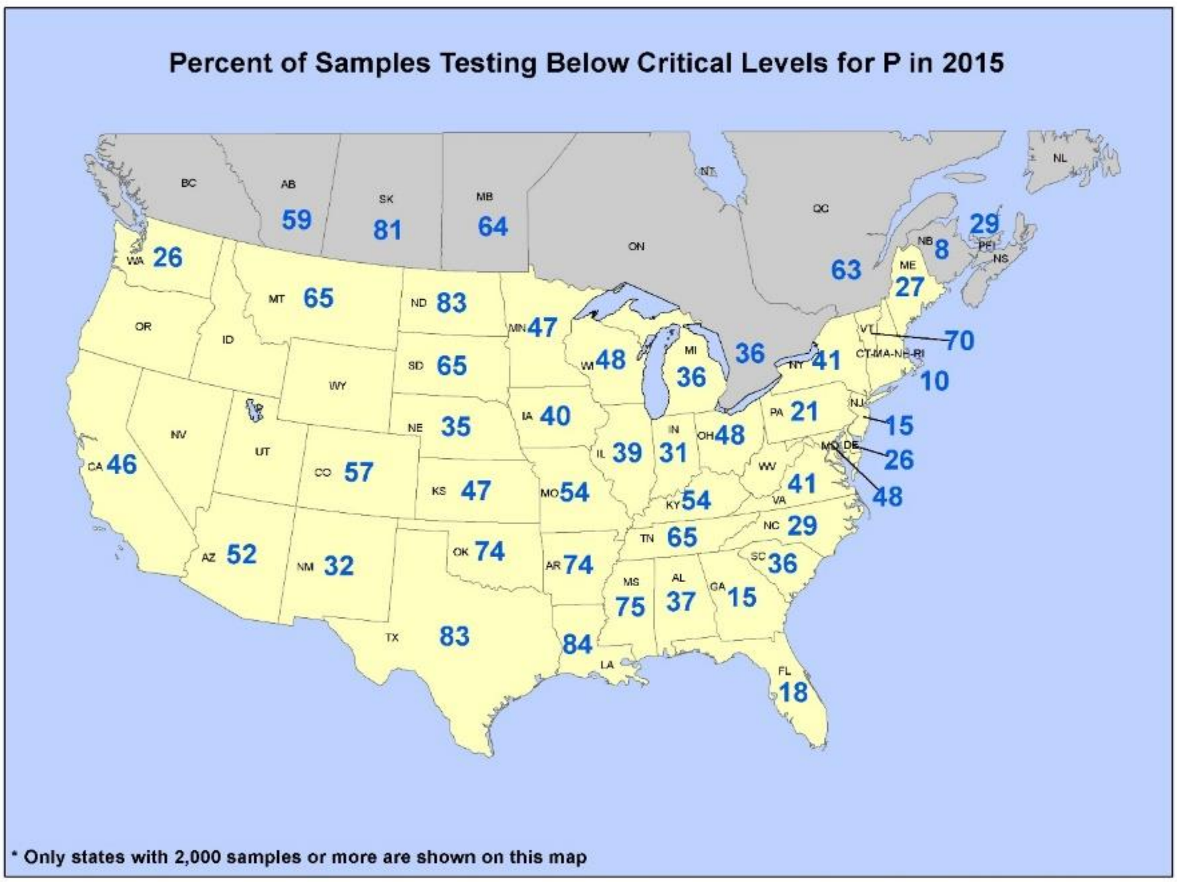


Figure 3. Frequency of soils testing below critical values of P in North America, by state or province (http://soiltest.ipni.net/maps/Percent_Change%20 accessed October 16, 2018)

There is some concern that concentrations of soil test P may be declining in areas that are not being treated with manures, as was seen in the Manitoba sampling. Declining soil P could relate to shifts in cropping patterns, where crops such as wheat that have a high tolerance for seed-placed P are being replaced in the rotation with crops such as canola or soybean that have lower tolerance. Where producers rely on only starter P placed in the seed-row, limiting application to only the safe rate of seed-placed P means that less P is applied than is removed by these oilseed crops. For example, in Manitoba, inputs of phosphate fertilizer and removal of P in the plant were historically relatively well-balanced, because shortfalls in P input during production of canola were compensated by surplus additions of P in the cereal years. However, cropping patterns in Manitoba are changing, with more acres of canola and soybean and fewer acres of cereal crops. Also, crop yields and, therefore, crop removal of P have increased dramatically in recent years. Therefore, the risk of P depletion has increased in many areas of the Northern Great Plains.

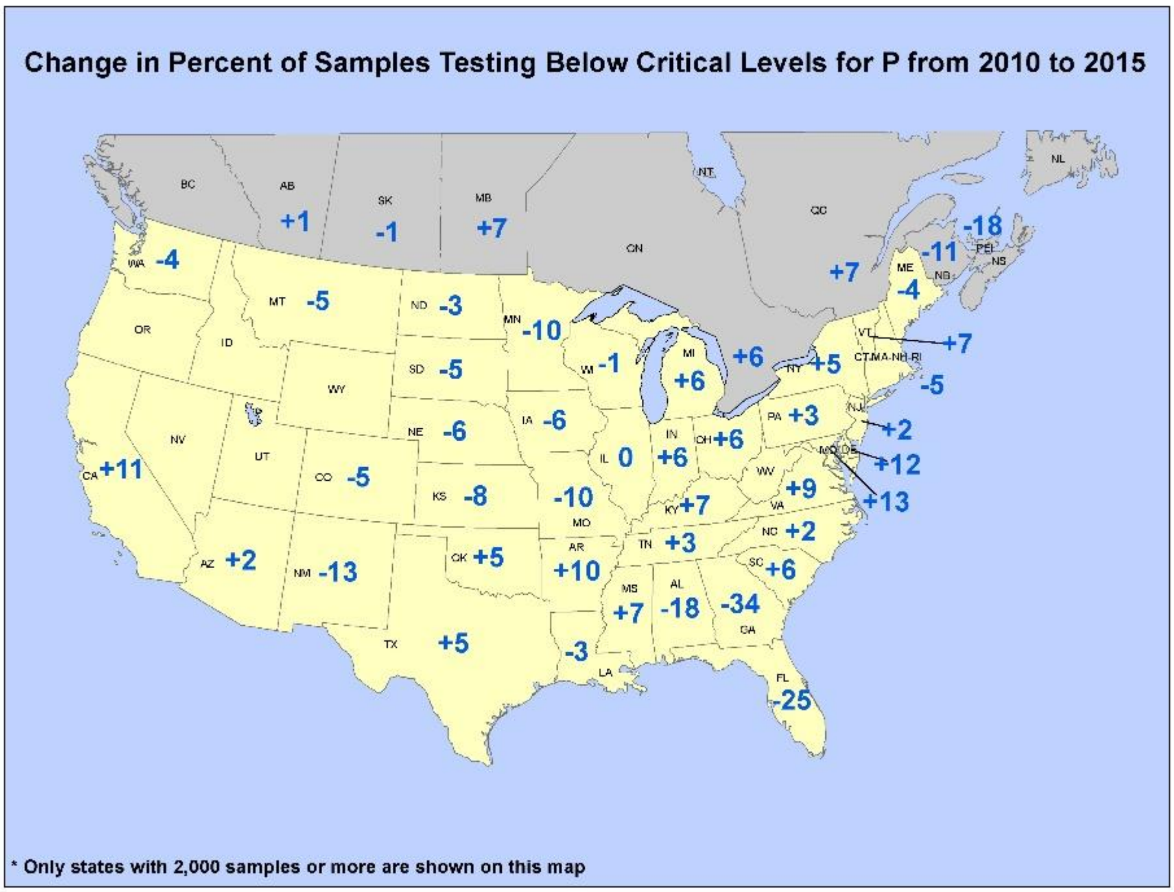
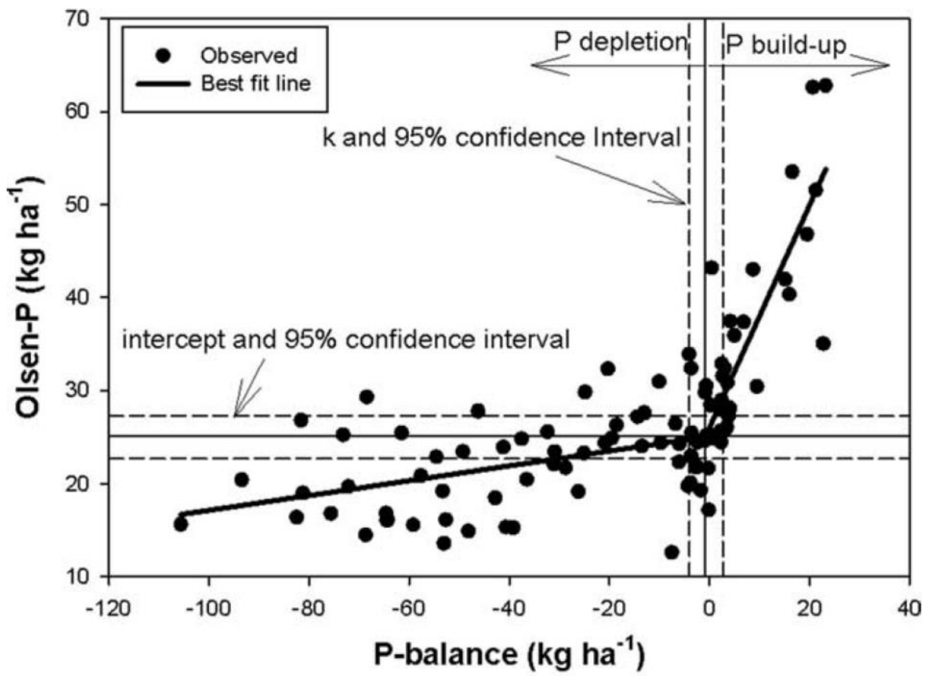


Figure 4. Change in percentage of samples testing below critical concentrations for P from 2010 to 2015 (http://soiltest.ipni.net/maps/Percent_Change%20 accessed October 16, 2018)

Several studies in the Northern Great Plains have illustrated the effect of deficits or surpluses between P applied and P removed on soil test P. Long-term studies conducted at Swift Current, SK showed a good relationship between Olsen-P soil phosphorus concentrations and the balance between P applied and P removed in the crop, with P depletion occurring where P deficits occurred (Figure 5).



$$y = 25 + 0.08 * Pbal$$

$$y = 25 + 0.08 * Pbal + 1.1 * (Pbal - k)$$

Figure 5. Soil test P values in the top six inches of the soil reflect the balance between P input and P removal in the crop in long-term studies at Swift Current, SK (Selles et al. 2011).

Similar results were found in studies across the prairies that evaluated the effect on Olsen P of annual inputs of approximately 0, 40, 80 and 160 lb of P_2O_5 per acre from 2002 to 2010, in a durum wheat-flax cropping sequence (Figure 6). In these studies, withholding P fertilizer led to a large depletion in soil test P while applications of 80 lb P_2O_5 per acre or above led to a large increase. Application of 40 lb P_2O_5 per acre produced minor changes in soil-test P. However, the change in soil test P with P input varied widely with soil type. For example the rate of surplus P (P applied as fertilizer minus P removed by crop harvest) to raise Olsen P by 1 ppm varied from approximately 20 lb P_2O_5/acre on coarse-textured soil near Carman to 37 lbs P_2O_5/acre on clay loam soil near Brandon. In this study, similar rates of P were applied to both crops in the rotation, even though the flax crop tends to remove lower amounts of P. In rotations with canola, that removes greater amounts of P than are normally applied, the depletion would be greater than observed with flax.

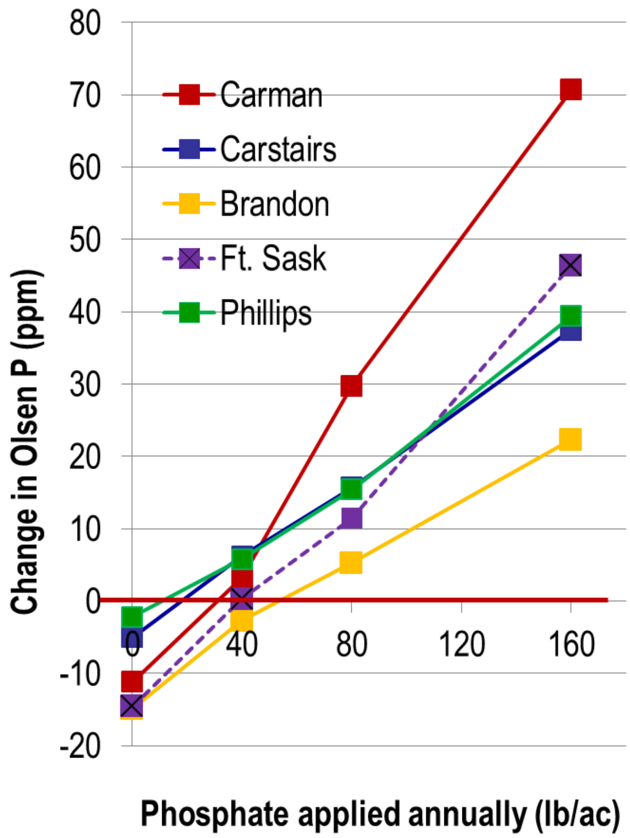


Figure 6. Change in Olsen P values with annual P application after 8 years of cropping following a durum wheat-flax cropping sequence on five soils in Western Canada (Grant 2012).

Depletion of soil P may be a major issue on organic farms due to the restrictions placed on the type of P inputs that may be used (Entz et al. 2001). A survey of organic farms in Manitoba showed soil P concentrations were lower than normally found in conventionally managed fields. The lowest available soil P concentrations were observed on farms with the longest history of organic management. In the University of Manitoba's long-term Glenlea organic rotation studies, soils in the high-yielding organic grain-forage rotations had lower concentrations of readily available P than conventional rotations after 13 years of cropping (Welsh et al. 2009). Regardless of whether a cropping system is organic or conventional, high yielding crop rotations that export significant amounts of P without replenishment will develop P deficiency over time.

Excessive depletion or accumulation of P in soils can cause problems. Excess P accumulation can increase the risk of P movement into water bodies, leading to eutrophication. Conversely, depletion of soil P can reduce the supply of P from the soil to the crop, potentially limiting yield, especially in situations where the P application is reduced to meet safe limits for seed-placement. 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 and optimize soil productivity while avoiding increased risk of P movement to water.

4.3 Cadmium loading to soil

Cadmium (Cd) is a potentially toxic trace element that is naturally present in soils, but is also added from atmospheric deposition, industrial contamination, sewage sludge, irrigation water and agricultural inputs such as manures, fertilizers and soil amendments (Alloway and Steinnes 1999; Sheppard et al. 2009b). Agricultural crops can accumulate Cd from the soil, with the amount of uptake depending on factors including crop genetics, soil Cd concentration and Cd phytoavailability as affected by soil characteristics. Long-term consumption of large amounts of Cd in the human diet, particularly in populations with diets that are deficient in other trace elements, has been linked to chronic toxicity and adverse health effects including kidney tubule dysfunction and reduced bone density (Godt et al. 2006). Soil organisms may also be negatively affected by excess Cd exposure, affecting soil ecology and health (McGrath 1999). Therefore, it is desirable to ensure that concentrations of Cd in soils remain low enough to avoid adverse effects on soil or crop quality.

Phosphorus fertilizers are a major source of Cd input into the soil in agricultural systems (Sheppard et al. 2009a; Sheppard et al. 2009b). Phosphorus fertilizers contain Cd as a contaminant at concentrations varying from trace amounts to as much as 300 mg Cd kg^{-1} of dry product, depending on the concentration of Cd in the phosphate rock used for its manufacture (Table 3) (Syers et al. 1986). Cadmium concentrations in sedimentary rocks are normally higher than in igneous rocks, because Cd will coprecipitate as a substitute for Ca in the phosphate compounds during the geological formation of sedimentary rocks (Traina 1999). The Cd present in raw phosphate rock will be carried through during fertilizer production, so the resulting fertilizer produced will reflect the Cd concentration of the rock source (Chien et al. 2003; Chien et al. 2011; Molina et al. 2009; Syers et al. 1986). While Cd can be removed from P fertilizers during production, the process is costly and is not a priority for the industry (Syers 2001).

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 (Sheppard et al. 2009b). The Cd concentration is most plants is very low, so the amount of Cd removed from the soil in the harvested crop is small. Although both input and removal of Cd tend to be low relative to the total amount of background Cd present in the soil, Cd will accumulate in the soil over time if input is greater than removal (Sheppard et al. 2009b). Total input and net Cd balance will vary widely depending on the fertilizer source, rate of application and the crops grown (Christensen and Huang 1999; Christensen and Tjell 1991; Sheppard et al. 2009b).

Over the long-term, increases in concentrations of Cd occur in agricultural soils that have received high Cd inputs over time, but not on soils where Cd input is low (Schipper et al. 2011). Long-term trials in Sweden (Andersson 1977), Denmark (Christensen and Tjell 1991; Dam Kofoed and Sondergard-Klausen 1983), Norway (Baerug and Singh 1990), Britain (Jones et al. 1987; Nicholson and Jones 1994), Finland (Mäkelä-Kurtto et al. 1991) and the United States (Mulla et al. 1980) have shown increases in soil Cd concentration over time as a result of a surplus Cd balance. In pasture systems in Australia (Williams and David 1976) and New

Zealand (Andrewes et al. 1996; Gray et al. 1999; Loganathan et al. 2003; Loganathan et al. 1997; Loganathan et al. 1995; Roberts et al. 1994) applications of phosphate fertilizers that were estimated to contain in the range of 20 to 50 ppm Cd led to significant increases in the Cd concentration in the surface soils. In a pasture system in Ireland, 31 years of application of 60 lb P_2O_5/acre as triple superphosphate, containing approximately 39 ppm Cd significantly increased Cd concentration of Cd in the surface 10 cm of soil, but the increase was <0.1 ppm (McGrath and Tunney 2010). Trials conducted at seven sites across the Canadian prairie provinces showed that DTPA-extractable Cd in the soil increased with the amount of Cd added over time (François et al. 2009; Grant et al. 2014; Lambert et al. 2007). The change in Cd availability varied from soil to soil but was low with typical agronomic rates of P application.

Table 3. Cadmium concentrations (mg/kg) of sedimentary and igneous phosphate rocks (Van Kauwenberg 2001) as cited by Roberts (2014)

Country	Deposit	Average Cd	Range
Sedimentary Deposits			
China	Kaiyang	<2	—
Israel	Zin	31	20-40
	Undifferentiated	24	20-28
	Arad	14	12-17
	Oron	5	—
Jordan	El-Hasa	5	3-12
	Shidyia	6	—
Morocco	Undifferentiated	26	10-45
	Bou Craa	38	32-43
	Khouribga	15	3-27
	Youssoufia	23	4-51
Senegal	Taiba	87	60-115
Syria	Khneifiss	3	—
Togo		58	48-67
Tunisia		40	30-56
United States	Central Florida	9	3-20
	North Florida	6	3-10
	Idaho	92	40-150
	North Carolina	38	20-51
Other countries		13	<1-100
Overall Sedimentary Averages		21	<1-150
Igneous Deposits			
Brazil	Araxa	2	2-3
	Catalao	<2	—
South Africa	Phalaborwa	1	1-2
Russia	Kola	1	<1-2
Other countries		1	1-5
Overall Igneous Averages		2	<1-4

A number of assessments of Cd balance have shown that the P balance (input - removal) is positive in many agricultural systems, indicating the potential for accumulation of Cd in the soil over time (De Vries and McLaughlin 2013; Keller and Schulin 2003a; Keller and Schulin 2003b; Keller et al. 2001; McDowell et al. 2013; Sheppard et al. 2009b). In studies in European soils, Cd concentration was closely related to phosphate accumulation, indicating that soil Cd was enriched due to applications as a contaminant in P fertilizer (Pan et al. 2010). Mass balance studies in Europe from 1980 to 1995 indicated a positive mass balance for Cd and resulting increase in concentrations of Cd in soil (Six and Smolders 2014). Similarly, correlations between phosphate and Cd in agricultural soils indicate that Cd addition in phosphate fertilizers has been a major driver of increased Cd concentration in soils over time (De Vries and McLaughlin 2013; Jones et al. 1987; Roberts et al. 1994).

In Canada, an indicator of the risk of trace element accumulation in soils was developed that showed that Cd influx was dominated by fertilizer applications in 90% of the soil polygons (Sheppard et al. 2009b). 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 (Sheppard et al. 2009b).

Since the increase in soil Cd is proportional to the total Cd added over time, 4R nutrient stewardship practices to reduce Cd accumulation can include reducing the rate of P application and selecting a fertilizer source that is low in Cd (Sheppard et al. 2009b). Many countries currently have limits on the concentration of Cd that can be present in P fertilizers (Table 4). In 2003, limits on Cd in European fertilizers were proposed to ensure that there would be no long-term accumulation of Cd in agricultural soils, but the limits have not been adopted into EU-wide regulation (Six and Smolders 2014). A new proposed regulation would limit Cd to 60 mg/kg P_2O_5 initially, with discussions continuing about reducing the concentration to as low as 20 mg over time (Ulrich 2019). Low Cd fertilizers can be produced by using low-Cd rock as the phosphate source or by decadmiating the fertilizer during the production process, although strict restrictions on the Cd concentration in fertilizers could increase fertilizer cost or restrict the available supply.

As mentioned previously, increases in soil Cd are often a function of the phosphate application rate (Lambert et al. 2007; Sheppard et al. 2009b). Therefore, accumulation of Cd in the soil can be minimized by avoiding excess applications of P fertilizer. For example, in nine long-term soil fertility experiments in the United States, more than 50 years of application of recommended rates of P fertilizers containing an estimated 5 ppm Cd increased soil Cd concentration by between 0 and 0.5% per year (Mortvedt 1987). In a 15 year study in Sweden, application of 22 lb P_2O_5/acre increased soil Cd in 0 to 20 cm depth by 0.33 to 1.1% per year, a minor effect relative to variation caused by uncontrolled factors (Andersson and Hahlin 1981). In a 29-year barley trial in England, application of agronomic rates of P did not increase soil Cd concentration (Richards et al. 1998), while in a 70-year fertility study in Norway, neither total nor available Cd concentration in the soils was increased significantly by the Cd added in fertilizer (Jeng and Singh 1995).

Table 4. Limits for Cd in P fertilizers in several countries expressed as Cd:P ratio, Cd:P_2O_5 or concentration of Cd in the fertilizer product (Roberts 2014)

Country	Limits	mg Cd/kg P	mg Cd/kg P_2O_5	mg Cd/kg 45% P_2O_5 Product
Limits for Fertilizer-Cd				
USA-Washington	0.0889 kg Cd/ha/yr	2040	889	400
USA-Oregon	7.5 mg Cd/% P_2O_5	774	338	152
USA-California	4 mg Cd/% P_2O_5	412	180	81
Australia	300 mg Cd/kg P	300	131	59
Canada	0.0889 kg Cd/ha/yr	2040	889	400
Japan		340	148	67
Austria	75 mg Cd/kg P_2O_5	275	120	54
Belgium	90 mg Cd/kg P_2O_5	206	90	40.5
Denmark		110	48.0	21.6
Netherlands		40	17.5	7.9
Finland	21.5 mg Cd/kg P_2O_5	49	21.5	9.7
Sweden	43 mg Cd/kg P_2O_5	100	43.7	19.7
EU Proposal (2001)	20 mg Cd/kg P_2O_5	45.8	20	9
	40 mg Cd/kg P_2O_5	91.6	40	18
	60 mg Cd/kg P_2O_5	137	60	27

In Europe, recent estimates of Cd inputs with fertilizers, manure and atmospheric deposition, and outputs of Cd with removal of crop harvest indicate that the mass balance is close to steady state (Nziguheba and Smolders 2008; Smolders 2017). European atmospheric deposition of Cd has decreased because of emission controls and P fertilizer usage has declined by 40%, leading to a prediction that soil Cd in agricultural soils growing cereals and potatoes will decline by 15% over the next 100 years (Six and Smolders 2014). In studies on seven soils across western Canada, allocation of agronomic rates of 40 lb P_2O_5/acre over 9 years led to minimal increases in soil Cd on most sites, regardless of fertilizer source (Grant et al. 2013; Grant et al. 2014). Increasing application rates to higher than normal agronomic levels led to increases in soil Cd concentration proportional to the amount of Cd applied in the fertilizer over time. Rate of P application required to optimize crop growth can be minimized by using P management practices that improve fertilizer use efficiency. On the Northern Great Plains, 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 are BMPs for optimum P use efficiency. These same practices will minimize the risk of excessive accumulation of Cd in soil or crops.

As mentioned earlier, the greatest concern for trace element accumulation due to phosphate fertilizer application is from Cd because of the human health risks associated with Cd accumulation in edible crops. However, a range of other trace elements are also present in phosphate fertilizer and can accumulate in soils over time (Sheppard et al. 2009a; Sheppard et al. 2009b). While some of these trace elements, such as Zn and Cu, have nutritional benefits, others such as As and Pb are not desirable but the concentrations present in fertilizers are not considered a significant risk to human or soil health (Jiao et al. 2012; Sheppard et al. 2009b). Nevertheless, management practices to reduce Cd input and excess application of P fertilizer would also serve to limit the input of other potentially harmful trace elements.

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.

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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. 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.

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. 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.

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. 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.

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.

Detailed Information

5.1 Strategies for Managing Rates of P Fertilization

The nutrients that a crop needs to grow must come from somewhere and in managed agricultural systems, the crop will normally access P from fertilizer additions and from the soil. If more P is removed by the crop than is added, P is mobilized from the soil reserves and they will decline over time. If more P is added than removed, the P in the soil will build over time. Phosphorus may also be lost from the system by erosion or movement in runoff, or to a lesser extent, leaching, and this removal must also be considered in the management program. Also, retention or release of nutrients into or out of less available pools may be considered. 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, strategies for managing rates of P fertilization depend 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, 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 which maximizes the net returns in the year of application. Economic value of the residual 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 (Kastens et al. 2000). Altering the soil test value is not a goal in the sufficiency method and this strategy tends to keep soil test P concentrations in the low to medium range and, in many cases, leads to declines in soil test P concentrations. 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 for annual crops would normally be applied as starter or in band placement to maximize efficiency.

A long-term sustainability strategy (Figure 1) aims to manage the soil test P concentration in the soil towards a specific critical level to ensure that the background level of P in the soil is not limiting to crop production. If the soil test is below a critical level, it would be desirable to **build** the soil P level by more P than is removed by the crop over a specific time frame until the target soil test level is reached. After that, a **balance** or **maintenance** approach is followed, to apply the P that is removed by the crop, plus perhaps some extra P to account for retention and other losses, and maintain a target level of soil P. For example, the objective of fertilization based on removal in Iowa is to maintain a soil test range that results in a 25% probability of a yield response. Therefore, such application rates are designed to maintain soil test values and eliminate nutrient deficiency, but not necessarily to maximize profit from fertilization of a single crop (Mallarino 2012).

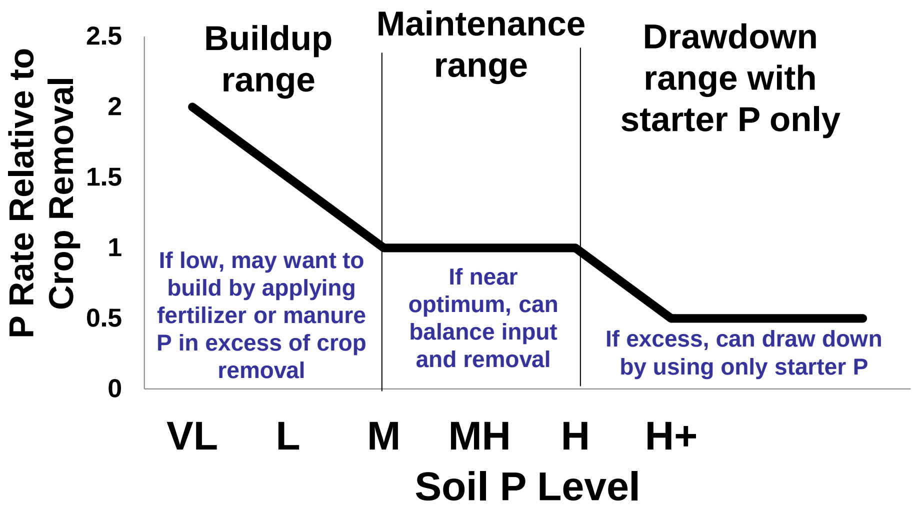


Figure 1. The long-term sustainability strategy for P management relies on building, maintaining or depleting soil P, based on soil test P concentration.

The balance approach to application requires knowledge of the amount of P that is removed in the harvested crop, which is a function of crop yield, the concentration of P in the harvested material and the portion of the crop removed. If the straw from the crop is removed, P removal will be greater than if only the seed is removed. The long-term sustainability strategy operates on the principle that lower net returns in the building years will be balanced by greater net returns in the future, because of higher and more consistent yields.

Targeting levels of soil test P to near or above critical concentrations is important to consider because crops respond both to P fertilizer and to the background P fertility of the soil. For example, in a long term field experiment in Saskatchewan, crop yields did not attain the full yield potential on soils that were very low in P, even with relatively high rates of seed-placed P (Figure 2) (Wagar et al. 1986a). In studies in Alberta, highest barley yields were obtained on soils with moderate to high concentrations of soil P and moderate applications of P fertilizer (Table 1) (Nyborg et al. 1999). On very low testing soils, grain yields were lower than on higher-testing soils, even with very high rates of P fertilization.

The long-term sustainability strategy assumes that P applied to the soil will not be lost from the system in substantial amounts except through crop removal. It is suited to land that has a long tenure arrangement and where sufficient capital is available to carry the operation through the building phases (Kastens et al. 2000). It is also attractive if the present cost of P fertilizer is lower than anticipated future cost or if applying low cost nutrient sources such as manure.

At very high soil test P levels, a **drawdown or depletion** approach may be recommended, to avoid excess expense and to reduce the risk of P movement to water. This may be necessary where soil P has built up due to excessive applications of manure. In this situation, only low rates of starter fertilizer would be applied, if any, to reduce the background level of P in the soil. Starter P may provide a yield response, especially on cold soils, even where background levels of P are relatively high.

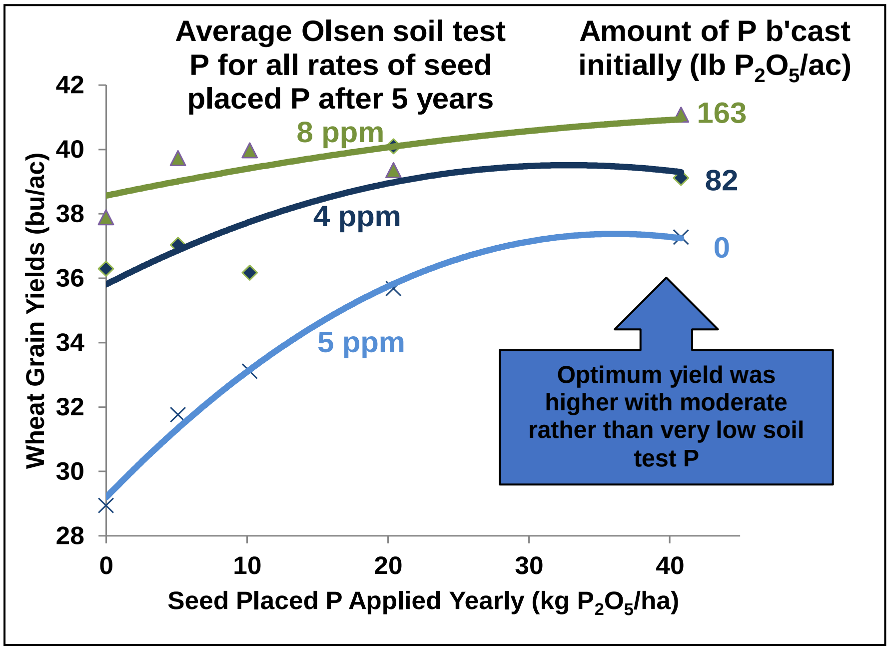


Figure 2. Yield is a function of both background P fertility in soil and annually applied fertilizer P (Wagar et al. 1986a).

Table 1. Grain yield of barley with P fertilizer applied to soils with different concentrations of extractable P at 0-15 cm depth in 60 field experiments in central Alberta (Nyborg et al. 1999).

Extractable P in soil (mg P kg^{-1})	Mean P in soil (mg P kg^{-1})	No. of sites	Yield of barley (kg ha^{-1}) with five rates of fertilizer (kg P_2O_5 ha^{-1})					Marginal yield increases (kg grain kg^{-1} P_2O_5 ha^{-1})			
			0	17	34	51	68	17	34	51	68
0-5.5	3.5	8	2253	2846	3062	3275	3354	34.9	12.7	12.5	4.6
5.6-11.0	8.5	13	2454	3031	3255	3410	3437	33.9	13.2	9.1	1.6
11.1-16.5	14.0	8	2875	3434	3582	3753	3750	32.9	8.7	10.1	-0.2
16.6-22.0	19.0	17	3270	3577	3811	3882	3546	18.1	13.8	4.2	-19.8
>22.0	30.0	14	3283	3320	3389	3530	3571	2.2	4.1	8.3	2.4

5.2 Use of Soil Testing as the Basis for Selecting Rates of P

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. An effective soil test measuring the plant-available P in the soil is essential to determine the need for fertilizer application and estimate the optimum rate of fertilizer application. Different soil testing methods are available using solutions that selectively extract a portion of soil P that provides an index of the plant-available P (Table 2).

Calibration studies are needed to determine the relationship between the concentration of P in the extracting solution, the ability of the soil to supply P to the growing plant, and the probability of a yield response to the crop under locally relevant field conditions. The calibration studies are then used to determine if a response to P fertilizer is likely to occur and to estimate the amount of P that should be applied, based on the P management strategy being used on the farm.

Ion exchange resins may also be used to estimate the P-supplying power of the soil (Qian and Schoenau 2002; Qian et al. 2007; Qian et al. 1992; Schoenau et al. 1993). Two forms of ion-exchange resins are commercially available. One is in the form of a membrane while the other is in the form of resin beads that are enclosed in a nylon bag (Figure 3) (Qian et al. 2007). The resins are organic polymers with a charge that is neutralized by a selected counterion of opposite charge and so behave much like the cation exchange on a soil colloid. The resins act as a sink to attract the nutrient ion that is being measured.

Resins can be used in a batch system in a laboratory, where they are placed in an aqueous suspension with a soil sample and adsorb the ions being released from the soil. Resins can also be placed directly into the soil in the field to measure both the rate of release of the ions from the various soil components and their diffusion through the soil to the resin over a specific time. After the resin has been allowed to adsorb the ions for the selected time period, the resin is treated with HCl as an eluent to desorb the ions and the concentration of nutrient in the eluent is measured. As with chemical extractants, calibration is required to relate the measured values with crop response in the field.

The type of soil test used should be suited to the soil characteristics and calibrated for the specific region (Table 2) (Carter and Gregorich 2008; Howard 2006). The Olsen test is effective across a wide range of soils, including high pH calcareous soils, although it may not be suitable for acid soils, while the Bray test is effective only in neutral to acid pH, non-calcareous soils (McKenzie et al. 1995b). Kelowna and modified Kelowna tests are also considered effective on many of the soils in the Northern Great Plains (Ashworth and Mrazek 1995; McKenzie et al. 1995b; Qian et al. 1994).

Table 2. Summary of soil test phosphorus extraction methods adapted from (Howard 2006).

Analysis method	**Extractant**	**Comments**
Olsen (Sodium Bicarbonate)	0.5 M $NaHCO_3$ @ pH 8.5	- developed in Colorado by Olsen et al. (1954) - best suited for neutral and calcareous soils (Qian et al. 1994) - process of maintaining pH level, driving off CO_2, and filtering extractant through activated charcoal makes the procedure awkward (Qian et al. 1994)
Mehlich-3	0.2 M acetic acid 0.25 M NH_4NO_3 0.015 M NH_4F 0.013 M HNO_3 0.001 M EDTA[a]	- common method for assessing crop-available P in the United States - viewed as reliable on neutral to acid soils - studies in North Dakota indicated a good correlation with Olsen-P concentrations across a range of pH levels (Schmisek et al. 1998) - P values obtained using inductively coupled plasma (ICP) to measure P in the extracts are significantly higher than those obtained using colorimetric methods (Ziadi and Tran 2008)
Bray-1 (Weak Bray)	0.03 N NH4F 0.025 N HCl @ pH 3.5	- designed for neutral – acidic soils - not suited for calcareous soils (Bray and Kurtz 1945)
Bray-2 (Strong Bray)	0.03 N NH_4F 0.1 N HCl @ pH 1.0	(Bray and Kurtz 1945)
Miller-Axley	0.03 N NH_4F 0.03 N H_2SO_4	- not suited for high pH, calcareous soils (Miller and Axley 1956)
Modified Kelowna (Enviro-Test)[b]	0.015 M NH_4F 0.25 M ammonium acetate 0.25 M acetic acid	- good method for a wide range of soil pH levels in the prairie provinces - measures available P and K
Modified Kelowna (Norwest)[c]	0.015 M NH_4F 1.0 M ammonium acetate 0.5 M acetic acid	- good method for a wide range of soil pH levels in the prairie provinces - measures available P and K (Ashworth and Mrazek 1995)
Kelowna	0.015 M NH_4F 0.25 M acetic acid	- suitable for a wide range of soil pH levels
Resin	Adsorption on anion exchange resin followed by elution with 0.5 M HCl	- can be used with soil samples as a laboratory method or buried in the field for in situ measurement of P-supply (Qian et al. 2007)

[a] EDTA is ethylene diamine tetraacetic acid
[b] Formerly used by Enviro-Test Labs
[c] Formerly used by Norwest Labs

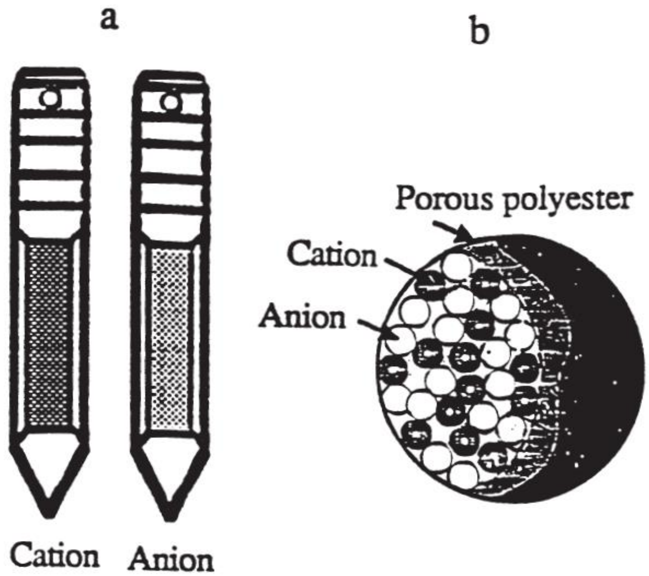


Figure 3. Diagram of PRS™ membrane probes (a) and UNIBEST resin capsules (b) (Qian and Schoenau 2002)

Many of the soil testing methods are highly correlated with one another although the amount of available P measured in the soil test and associated with sufficiency or deficiency will vary with method (IPNI 2015; McKenzie et al. 1995b). In a study using 214 surface soil samples from across Manitoba, 51 of which had received manure applications in the past, the relationships among a wide range of soil P tests were assessed (Kumaragamage et al. 2007). Agronomic methods were Olsen (O-P), Mehlich-3 (M3-P), Kelowna-1 (original; K1-P), Kelowna-2 (modified and formerly used by Enviro-Test; K2-P), Kelowna-3 (modified and formerly used by Norwest; K3-P), Bray-1 (B1-P) and Miller and Axley (MA-P), while environmental STP methods were water extractable (W-P), $CaCl_2$ extractable (Ca-P) and iron oxide impregnated filter paper (FeO-P) methods. The different methods extracted different amounts of P with the mean amount extracted decreasing in the order M3-P ≈ K1-P > K2-P ≈ K3-P > B1-P ≈ FeO-P ≈ MA-P > O-P > W-P ≈ Ca-P. However, the various methods were well-correlated with each other, especially when they contained extractants of similar chemistry, and therefore could be related to one another using a simple linear model. The regressions were stronger among the agronomic soil test methods than between agronomic and environmental methods and among the environmental methods, possibly because the environmental methods extract a smaller amount of the P and are more sensitive to variations in soil conditions.

Studies in Saskatchewan on soils with various loadings of cattle and swine manure also showed that modified Kelowna, Olsen extractable, water extractable, and Plant Root Simulator® probes reflected P additions and were well-correlated with one another (Stumborg and Schoenau 2008). However, the water-extraction is not generally regarded as effective for measuring labile reserves of P that are present in less soluble solid phase organic and inorganic forms.

Similarly, in studies on 145 soils across Alberta, resin P, Olsen P and Kelowna P soil tests were highly correlated, although Olsen extracted less P than resin or Kelowna methods (McKenzie and Bremer 2003). The Miller-Axley method was poorly correlated with resin P, likely because it was less effective in soils with high pH levels.

Even using the same extractants, soil test P concentrations may vary with time of sampling. Soil samples on the Northern Great Plains are commonly taken in the fall. A study using three extractants on samples taken from fall to spring on three sites in Alberta showed that soil test P values varied with the sampling time and extractant (Nyborg et al. 1992). Extractable P increased to a similar degree for all extractants from early to late fall sampling and through the frozen soil period, but the values decreased at the spring sampling after soil had thawed. Another study on 53 sites in Alberta showed extractable P was less in fall- than spring-sampled soil at most sites, with a greater difference and a poorer correlation between fall and spring sampling when the samples were taken in early rather than late fall (Malhi et al. 1991). A 24-year study at Swift Current monitored bicarbonate-extractable P (Olsen P) every autumn and spring in four cropping systems (Campbell and Zentner 1993). Although there were some apparent overwinter increases in Olsen P, there were also some decreases and very few of the overwinter changes were significant, even at the 0.10 probability level. In Minnesota, five sites ranging in size from 3.7 to 4.4 ha were soil sampled for Bray-1 and Olsen P in the same locations in a 18.3 × 18.3-m grid either three or four times over a 2-yr period (Lamb and Rehm 2002). One site showed no pattern and two sites had cyclic patterns where the spring sample values were greater than the fall. Based on the varying results observed in these studies, it appears that although soil test P may differ from fall to spring, the change is not consistent and sampling in late fall should be an acceptable practice.

While soil testing is an important guide to P requirements, it is important to remember that the response of the subsequent crop to fertilizer P addition is often not precisely related to the soil test P concentration of the soil. Soil testing will not predict exactly how much to apply, nor will it assure that a response will be attained every year. Soil test P information is good at estimating the average probability of response to P application and assessing the accumulation or depletion of P from a field over time. It is fair at estimating the average relative yield response to P across similar fields and yields and at estimating the probability of response in a given field and year. However, a soil test is relatively poor at predicting if a specific response will occur in a specific field and a specific year. A wide range of factors that vary from year to year and location to location will modify crop P demand and the availability of P for plant uptake and therefore influence the relationship between soil test P and crop response. Therefore, P tests should be used to broadly define levels of P in the soil where crop response to P is highly likely, probable, or unlikely to occur (Table 3).

Studies across the prairies provinces showed that frequency of statistically significant yield responses to P fertilizer was higher at lower soil test P levels, but even at very low soil test levels, some crops did not respond, while at very high soil test levels, some crops did respond (Figure 4) (Karamanos 2007). In studies conducted in Alberta, resin P, Olsen P and Kelowna P methods were all related to crop P response, indicating that they all measure potentially plant-available P (McKenzie et al. 1995b). For Kelowna and the two modified Kelowna methods (formerly used by Norwest and Enviro-Test) which all use ammonium fluoride and acetic acid in their extraction solutions, approximately 85% of all wheat, barley, and canola sites responded to phosphate fertilizer with a two bushel or greater yield when soil test P was less than 10 ppm. When soil test P concentration was <5 ppm for the Kelowna and modified Kelowna methods, approximately 100% of wheat and >80% of barley sites responded statistically to phosphate fertilizer. The Miller-Axley and Olsen methods did not predict response of wheat and barley as well when compared to the other methods. None of the methods performed well at predicting frequency of P response by canola. At a soil P concentration of <5 ppm, only the modified Kelowna method formerly used by Envirotest had a frequency of canola response of 100% while the Kelowna, modified Kelowna used by Norwest and Miller-Axley methods were at 50%, and the Olsen method at 0%.

Table 3. Approximate soil test phosphorus sufficiency ranges[a] for crop production in Northern Great Plains soils using various soil testing methods.

Soil Test Method	**Very Low to Medium**	**Medium to High**	**High to Excessive**
	---------------- parts per million (ppm) or mg/kg[b] ----------------		
Olsen (Sodium Bicarbonate)	<10	10 to 20	>20
Mehlich-3	<20	20 to 40	>40
Bray-1 (Weak Bray)	<15	15 to 25	>25
Bray-2 (Strong Bray)	<27	27 to 40	>40
Miller-Axley	<13	13 to 22	>22
Modified Kelowna (Enviro-Test)[c]	<15	15 to 25	>25
Modified Kelowna (Norwest)[d]	<15	15 to 27	>27
Kelowna	<15	15 to 30	>30
Water	<3	3 to 5	>5

[a] Ranges were established using Olsen P calibration data as the base (Hedlin 1962; Karamanos et al. 2010; Saskatchewan Ministry of Agriculture 2019), then calculating corresponding values for other soil test methods, based on regression equations from Kumaragamage et al. (2007), McKenzie and Bremer (2003), Ige et al. (2006), Qian et al. (1994), and McKenzie et al. (1995) and from information provided in IPNI (2015). These ranges generally define soil test levels as low to medium, medium to high, and high to excessive, where a crop P response is highly likely, probable or unlikely to occur, respectively. However, other factors such as environmental conditions and crop species will also affect the probability of P response.

[b] To convert soil test P values from ppm or mg/kg to an estimate for lb/acre for a 6 inch layer of soil, multiply the ppm values by 2. However, the soil test value in lb/acre is only an approximation of soil test extractable P for determining whether the soil's P fertility is low, medium or high and is not an estimate of the total quantity of P available to crops.

[c] Formerly used by Enviro-Test Labs

[d] Formerly used by Norwest Labs

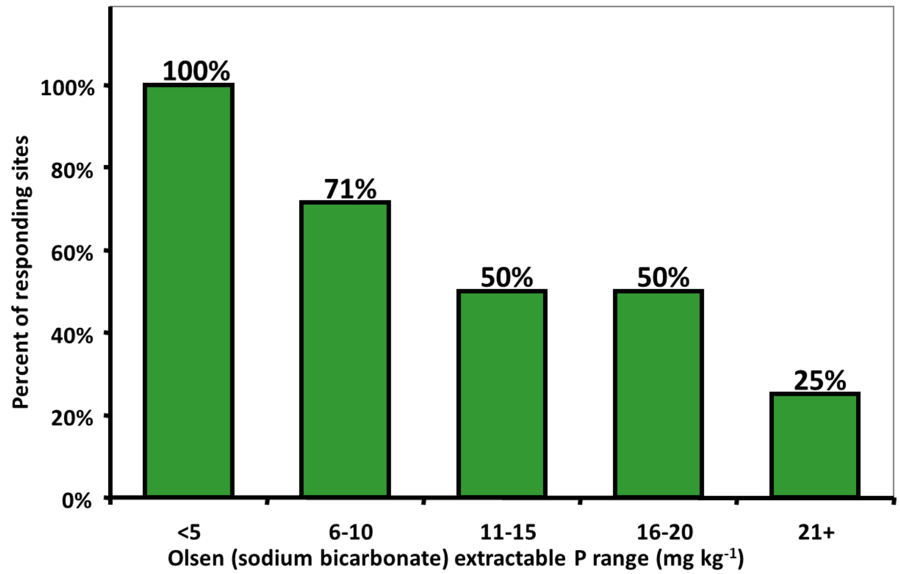


Figure 4. Percentage of sites responding to phosphorus application at various Olsen-P soil test ranges (Karamanos et al. 2010). Of the 47 sites, 5 sites tested less than 5 ppm, 14 sites tested between 6 and 10 ppm, 20 sites tested between 11 and 15 ppm, 4 sites tested between 16 and 20 ppm and 4 sites tested 21 ppm or more.

Availability of soil P for crop uptake and the response of a crop to P fertilization depends on many factors, including the forms and amounts of P present in the soil, temperature and moisture, crop type, crop yield potential and microbial interactions. Therefore, response to P fertilization will vary from year to year even at the same site, depending on environmental conditions. In a long-term study at Swift Current, SK., when spring wheat was seeded on stubble, there was an average increase of about 2 bu/acre to seed placement of 20 lb P_2O_5/acre while on summer fallow, the increase averaged 4 bu/acre (Figure 5) (Campbell et al. 2005; Roberts et al. 1999). However, the response varied substantially from year to year, from a slight negative response to as much as 16 bu/acre for fallow wheat and 9 bu/acre for stubble wheat. Similarly, in southern and south central Alberta, in a study including 427 research sites (145 wheat, 159 barley and 123 canola) yield increases with P application to wheat and barley were more frequent on fallow than on stubble sites (McKenzie et al. 1995b). Yield responses to phosphate tended to be greater on fallow than stubble for wheat and barley, while canola was equally responsive on both fallow and stubble.

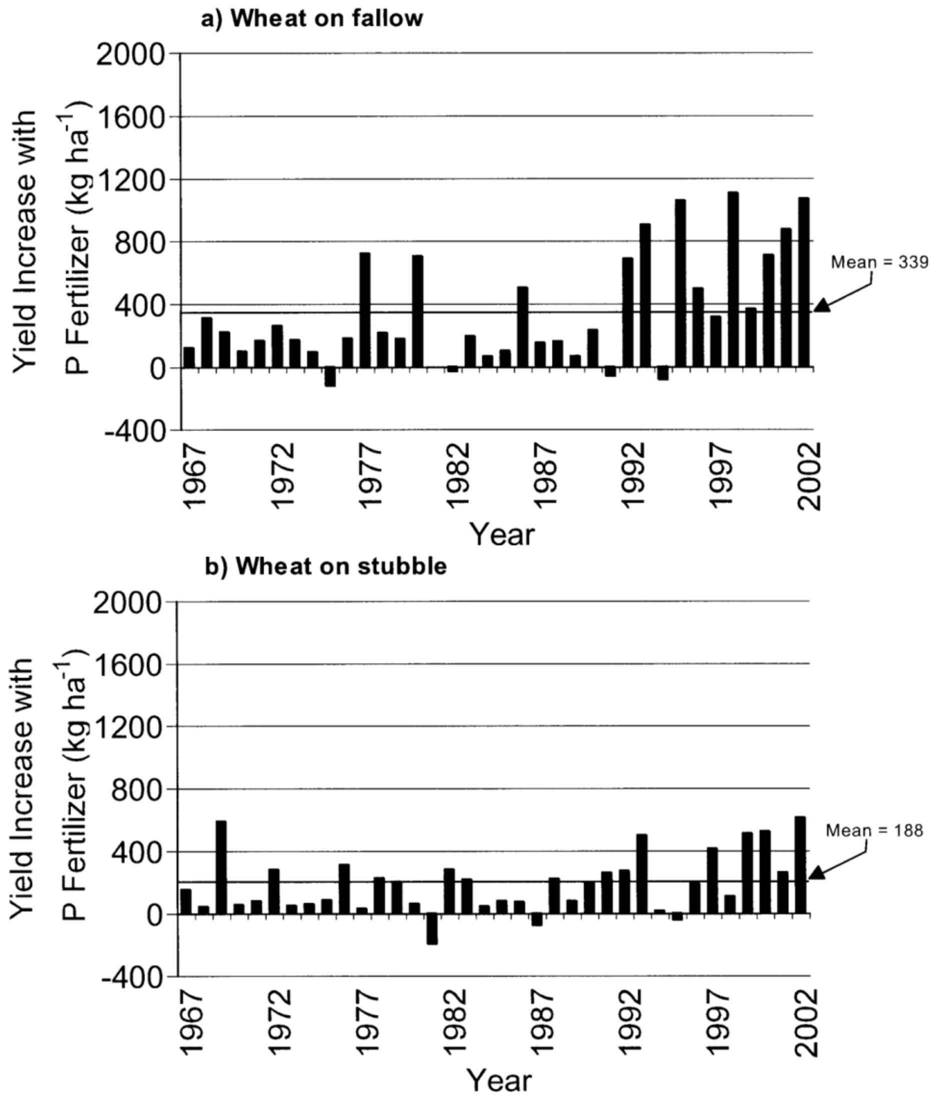


Figure 5. Spring wheat response to annual applications of seed-placed P fertilizer at a rate of 20 lb P_2O_5/acre on stubble and fallow in a fallow-wheat-wheat rotation at Swift Current, SK from 1967 to 1998 (Campbell et al. 2005).

Similarly, in a 72-year study (1930 to 2002) conducted using a fallow-wheat-wheat system in Scott, SK., response to fertilizer P varied considerably, depending on the environmental conditions (Table 4) (Brandt 2007). The 24 driest years (May-July precipitation averaging 4.25 in.), 24 near normal years (May-July precipitation averaged 6.25 in.), and the 24 wettest years (May-July precipitation averaged 8.36 in.) were compared for the response of spring wheat to P fertilizer additions of 30 lb P_2O_5/acre. The absolute yield increase was greatest in the wettest years and lowest in the average years, but on a percentage basis, the response was largest in the driest years. Phosphorus fertilizer helped the crop to use water efficiently during dry years and to take advantage of the higher yield potential during wetter years.

Table 4. Crop yield response to fertilizer P addition to wheat grown on fallow near Scott, SK (Brandt 2007).

Treatment	Check, bu/A	P added, bu/A	Gain, bu/A	Gain, %
24 driest years	18.7	24.1	5.4	29
24 average years	24.1	28.6	4.5	19
24 wettest years	31.2	38.7	7.5	24

5.3 Selecting Rate of P Application in the Long-Term Sustainability Strategy

In a long-term sustainability strategy, the soil test 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. Phosphorus fertilizer applications are used very inefficiently in the year of application when soil test P concentration is much above the critical value (Syers et al. 2008). A long-term sustainability strategy would aim to target a soil P level near the critical threshold, that may range from approximately 15 ppm (Malhi et al. 1993) to over 30 ppm (McKenzie et al. 2003b; McKenzie et al. 2001b) in the Northern Great Plains.

With very low levels in the soil, building of soil test P may be desirable to ensure that crop supply is optimized. The P can be built up slowly over time, with small surplus applications of P fertilizer applied annually or during specific phases of the crop rotation. The approach of slowly building up a low soil P status soil to a satisfactory level will usually be economically viable, since low rates of applied P are generally used efficiently (Syers et al. 2008).

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 amount of P that a crop requires depends on the crop species and the crop yield potential. Different crops have different levels of P uptake and different P removal rates, depending on the concentration of P on the tissue (Table 5). For example, canola has a greater total uptake and total removal of P in the harvested grain per bushel or kg than cereal crops (Heard and Hay 2006; Kalra and Soper 1968; Malhi et al. 2006; Malhi et al. 2007; McKenzie et al. 1995b; Racz et al. 1965). As the yield potential of the crop increases, the total amount of P needed to support crop growth as well as the amount of P removed in the harvested portion will also increase, although the change will not necessarily be linear. The amount of P that must be applied to build soil test concentrations will increase with greater crop removal. Conversely, depletion of excess P will also be more rapid with greater crop removal.

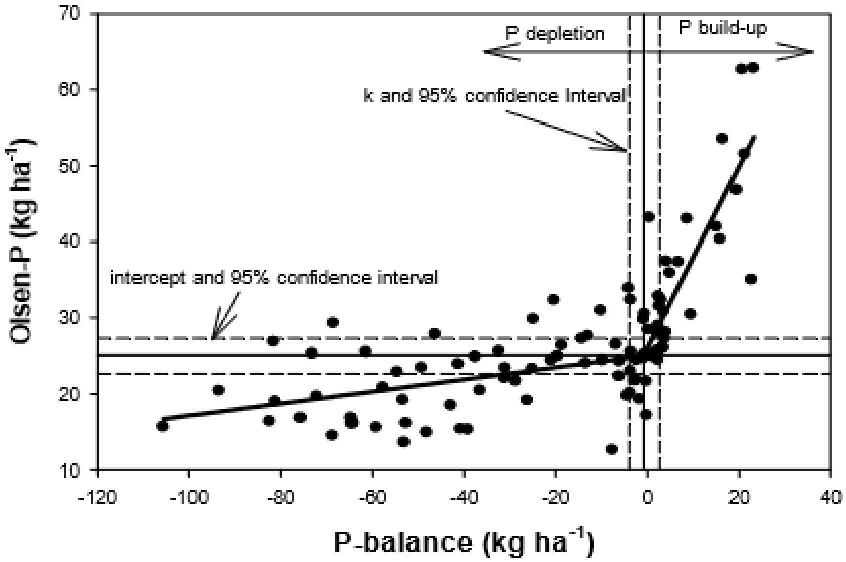
Table 5. Phosphorus uptake and removal (lbs per unit of yield) for a range of crops[a].

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) and values for Canadian Prairie crops are from Heard and Hay (2006). 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.

A 39-yr study at Swift Current evaluating wheat production in a continuous wheat and a fallow-wheat-wheat rotation that received either P only or N plus P showed that changes in Olsen P over time in a long-term cropping study largely reflected the balance between P addition and P removal in the crop (Figure 6) (Selles et al. 2011; Selles et al. 2007). Factors that increased P removal, including moving to continuous cropping, favourable moisture and increased use of N fertilizer, led to a trend towards lower Olsen P in the soil (Selles et al. 1999).

When the removal of P by the crop is large, due to high yields or high P concentrations in the harvested material, higher rates of P application will be required to maintain critical soil P values. Regular soil testing as infrequently as every 4 or 5 years can be used to assess the effectiveness of the program. However, annual testing is the most reliable method to track trends in soil test P.



$$y = 25 + 0.08 * Pbal \quad \text{when Pbal <= k}$$
$$y = 25 + 0.08 * Pbal + 1.1 * (Pbal - k) \quad \text{otherwise}$$

Figure 6. Soil test P values reflect the balance between P input and P removal in the crop in long-term studies at Swift Current, SK (Selles et al. 2011).

Ideally, the P fertilizer in a gradual building program should be managed to optimize efficiency by seed-placing or banding near the seed-row. However, 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 (Table 6). In that case, other options such as banding P away from the seed-row or increasing rate of P application in less sensitive crops should be considered.

Table 6. Phosphorus balance for moderate crop yields of selected crops, using maximum recommended safe rates of seed-placed fertilizer from the Manitoba Soil Fertility Guide (Grant 2012).

Crop	Yield (bu/acre)	P Removal (lb P_2O_5/acre)	Limit for Seed-Placed P (lb P_2O_5/acre)	Balance (lb P_2O_5/acre)
Wheat	40	29	50	+21
Canola	40	40	20	-20
Soybeans	40	32	10	-22
Barley	80	38	50	+12
Flax	32	20	20	0
Peas	50	38	20	- 18
Oats	100	29	50	21

Alternatively, if low cost sources of P are available, it may be desirable to add a larger amount of P, to more quickly increase the soil test P concentration. Studies in Saskatchewan and Manitoba demonstrated that single large applications of P fertilizer could increase the level of plant available soil P for many years (Bailey et al. 1977; Read et al. 1977; Read et al. 1973; Wagar et al. 1986a; Wagar et al. 1986b). Application of livestock manure to satisfy crop N requirements will also lead to a P surplus for the subsequent crop and increase soil test 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. If excess concentrations of P accumulate in the soil it is desirable to deplete the soil reserves, to reduce the environmental risk of P loss to runoff. Once the critical concentration is established, either by building or depleting P reserves, replacing the P removed in the harvested crop will maintain soils near the critical value for the soil type and farming system.

The amount of P fertilizer required to build or maintain soil test P level will vary from soil to soil and may be greater or less than crop removal. For example, unpublished research by Dan Kaiser, at the University of Minnesota shows that in some soils, soil test P can be maintained by applying rates of fertilizer P that are less than crop removal (https://mawrc.org/wp-content/uploads/2017/02/0.2-Kaiser-Fertilizer-Recommendations-Update.pdf). Conversely, in studies in Colorado on irrigated alfalfa stands at a location having low to medium available-P status, 2.2 times the P removed by the alfalfa was required to maintain the Olsen-P concentration while at a location with medium to high available-P status only 1.4 times the removed P was required (Fixen et al. 1983). Greater amounts of P fertilizer must normally be applied on high pH or calcareous soils to build or maintain soil test P levels, because of formation of sparingly soluble calcium phosphates. In studies conducted across the prairies, application of increasing rates of P at 0, 40, 80, or 160 lb P_2O_5/acre/year (0, 20, 40 or 80 kg P/ha/yr) increased Olsen-P concentration to a greater extent on low pH, coarse textured soils than on high pH, fine-textured soils (Figure 7) (Grant et al. 2014; Mohr et al. 2016). For example the rate of surplus P (P applied as fertilizer minus P removed by crop harvest) to raise Olsen P by 1 ppm varied from approximately 20 lb P_2O_5/acre on coarse-textured soil near Carman to 37 lbs P_2O_5/acre on clay loam soil near Brandon. Depletion was also more rapid on the low pH, coarse textured soils when P input was terminated. The rate of change in Olsen-P when P fertilization ceased was also greater when P had been increased to high concentrations with preceding fertilizer applications.

5.4 Selecting Rate of P Application in a Short-Term Sufficiency Strategy

If the short-term sufficiency strategy is selected, a soil test will provide an indication of the likelihood of a response to P application and an estimation of the rate of P required to optimize crop yield in the year of application. The rate of fertilizer application required to optimize crop growth will depend on the ability of the plant to access P from the soil, especially during the early stages of growth, when cold soil restricts soil P release and plant root growth. If the soil supply of P is high enough to provide an adequate supply of P to the plant throughout the growing season, the rate of P application can be reduced or eliminated. If the soil is deficient in P, fertilizer applications can be used to provide supplemental P to the plant as it is required, particularly early in the growing season. The rate of P required to optimize crop yield is usually within a narrow range, from about 10 to 50 lb P_2O_5/acre (5 to 25 kg P/ha) for small grains, oilseed and pulse crops.

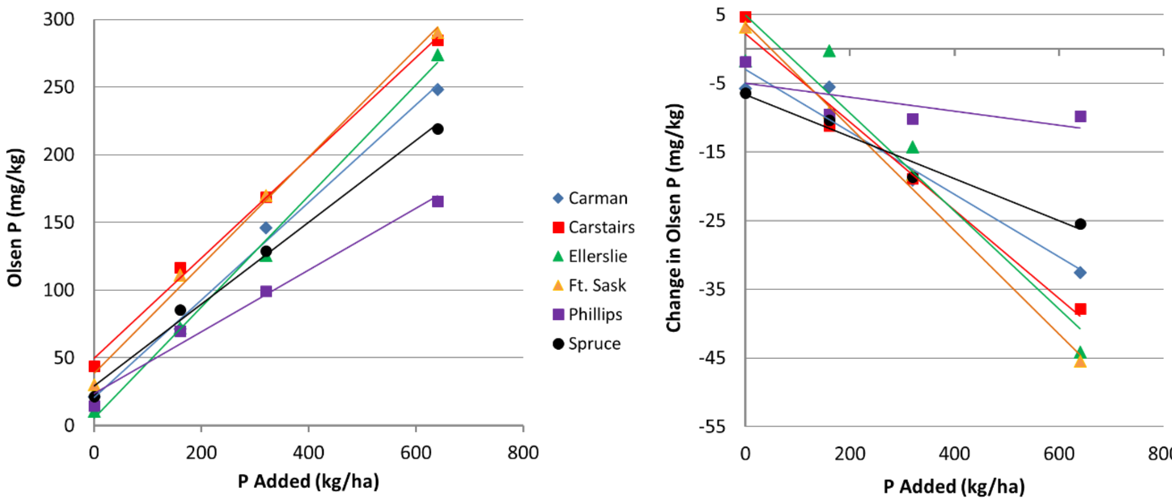


Figure 7. Response of Olsen-P concentration in the surface 6 inches (15 cm) of soil to cumulative rates of fertilizer P applied to a durum-flax rotation at 6 sites over an 8-year period. Left graph shows Olsen P in the surface soil at the end of 8 years of P fertilization, while the right graph shows the change in Olsen P after 3 additional years of cropping with no additional fertilizer added. Study was conducted for a total of 11 years, with fertilizer added for 8 years and not added for the next 3 years (Grant et al. 2014).

The likelihood of a P response to fertilizer application increases as the concentration of plant-available P in the soil decreases. The concentration of soil P below which a yield response to fertilizer P application is likely to occur is often referred to as the critical concentration. As mentioned previously, critical thresholds for P in the Canadian Prairies have been reported from around 15 ppm (Malhi et al. 1993) to over 30 ppm (McKenzie et al. 2003b; McKenzie et al. 2001b). Manitoba data that evaluated the frequency of response of crops to P application at various Olsen P ranges showed that that the probability of a response to P application dropped to just over 50% when the Olsen test P was around 12-18 ppm (Table 7) (Hedlin 1962).

Table 7. Response of cereals and hay to phosphorus as related to Olsen soil test phosphorus in Manitoba (Hedlin 1962).

Available P (ppm Olsen soil test P)	Number of Experiments	% Responding to Fertilizer P
0-5 (Very Low)	15	100
5-12 (Low to Medium)	50	62
12-18 (Medium to High)	16	56
>18 (High to Very High)	14	29
Overall	95	63

Saskatchewan recommendations indicate similar effects of soil test P with the probability of response and recommended rate of P application decreasing as soil test P concentrations increase (Table 8).

Table 8. Banded fertilizer P recommendations and probability of yield response in Saskatchewan, as affected by soil test P level on dryland fields with average moisture conditions (adapted from https://www.saskatchewan.ca/business/agriculture-natural-resources-and-industry/agribusiness-farmers-and-ranchers/crops-and-irrigation/soils-fertility-and-nutrients/phosphorus-fertilization-in-crop-production, accessed May 3, 2019)

Soil Test P (ppm)	Recommended Rate of P fertilizer (lb P_2O_5/acre)	Probability of a Yield Response (%)
0-5	35-40	>75
5-10	25-30	50-75
10-15	20-25	50
15-30	15-20	25-50
>30	5-10	<25

In field experiments conducted at 60 sites in central and north-central Alberta to determine the yield response of barley to P fertilizer on soils with different concentrations of extractable P in the 0-15 cm soil layer, crop yield in the unfertilized plots and the frequency of response to P application were related to the soil test P concentration (Nyborg et al. 1999). The yield of unfertilized plots increased and the yield response and economic return from P fertilization decreased with increasing concentration of extractable P in soil. On soils with extractable P greater than 22 ppm, P application did not provide an economic benefit.

At research trials in 154 locations across southern and south-central Alberta that included studies on wheat, barley and/or canola for a total of 427 site-years of data, soil test P was also a good predictor of probability of a response to P application. Approximately 85% of all wheat, barley, and canola sites responded with a two bushel per acre or greater response to added phosphate fertilizer when soil test P, as measured by the Kelowna, Norwest and Saskatchewan methods, was less than 10 ppm (McKenzie et al. 1995b). At a soil test P concentration of <5 ppm, approximately 100% of wheat and >80% of barley sites responded to fertilizer. Conversely, the frequency of yield response by canola was not well-related to soil test P levels.

Determination of a critical concentration will also depend on the criteria used to determine responsiveness. For example, in studies in Alberta, 60% of wheat sites, 70% of barley sites and 60% of canola sites responded to P fertilizer at soil test P concentrations above 30 ppm based on a two bushel yield increase while 20% of wheat sites, 30% of barley sites and 15% of canola sites responded based on statistical analysis ($p<0.05$) (McKenzie et al. 1995b). Statistically significant reductions in yield at high rates of fertilizer application were observed at 2.5% of all sites, while yield declines of more than 4% were observed at 12% of all sites. This study indicates a high probability of response to P fertilizer even at relatively high soil test P levels based on a two-bushel yield increase and a lower probability of response at high soil test levels based on statistical analysis.

On responsive soils, crop yield will increase with P application until the crop demand for P is satisfied, with no further yield response attained when P applications are increased further. Choice of regression model and whether to use absolute yield increase or relative yield (yield relative to highest yielding treatment) as a criterion for selecting optimal rate of application can make a large difference in the final rate and critical concentration for P application selected (Howard 2006).

Likelihood and magnitude of a response to P will tend to increase with the yield potential of the crop. In field studies conducted in Manitoba over six site-years on soils containing low to moderate levels of soil P, the magnitude of response and the rate required for maximum yield was greatest in the site-year with the greatest yield potential (Grant et al. 2009). In a 42-year field study at Swift Current, evaluating N and P management in a fallow-wheat-wheat and continuous wheat rotation, the response of spring wheat to P fertilizer varied considerably from year to year and was highly dependent on available water (Zentner et al. 2010). Spring wheat responded to P application about 80% of the time in the fallow rotation and about 60% of the time in the continuous cropping system, reflecting the higher available moisture and yield potential when wheat was preceded by summer fallow. Greater mycorrhizal colonization under the continuous cropping system as compared to the fallow system may also have increased plant access to soil P and reduced the likelihood of response to P applications (Grant et al. 2005; Hamel and Strullu 2006). Benefits from P fertilizer may increase with balanced N fertilization, if the N fertilizer increases the yield potential of the crop. In a study including 20 sites, significant barley yield increases with P application occurred in five sites (McKenzie et al. 2004b). At two of the five responsive sites, yield response to P was higher where N fertilizer was applied than in its absence. Similarly, in studies with winter wheat in Manitoba, yield response to P fertilizer increased with increasing rates of N fertilizer (Grant et al. 1985).

Placement of P can have a large effect on optimum rate of P application, with broadcast application requiring several-fold higher rates than seed-placed or banded P applications to achieve similar yields, particularly on low-testing soils (Bailey and Grant 1990; Kaiser et al. 2005; Malhi et al. 2001a; Malhi et al. 2001b; Peterson et al. 1981; Read et al. 1977; Read et al. 1973; Richards et al. 1985; Sheppard and Bates 1980; Sheppard and Racz 1985; Soon 1997; Wagar et al. 1986a). A small amount of P placed near the seed-row may be able to satisfy the crop requirements for early season P until the roots have grown to access adequate P from the bulk soil (Grant et al. 2001). These starter effects from small amounts of P placed close to the seed can occur even on soils with relatively high soil test P concentrations (McKenzie et al. 2003a; Morden 1986; Wagar et al. 1986a). A minimum rate of P application will be required to ensure that individual plants have access to a fertilizer granule or droplet 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 seeding root contacting the fertilizer. However, with sensitive crops such as canola or flax, placement of high rates of monoammonium phosphate or ammonium polyphosphate (MAP or APP) in or too close to the seed-row can reduce stand and limit yield response (Nyborg and Hennig 1969; Qian et al. 2005; Sadler 1980; Schoenau et al. 2005; Urton et al. 2012; Urton et al. 2013). Placement will not always make a large difference in response, particularly on soils with moderate to high levels of available P. For example, in studies in Colorado, on a medium-testing P-responsive soil, increases in no-till winter wheat were similar whether the fertilizer was broadcast, broadcast and incorporated, placed near the seed-row or deep-banded (Halvorson and Havlin 1992).

5.5 Differences in P Response among Crops

If a short-term sufficiency strategy is used for selecting P application rates, differences among various 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. As discussed in Chapter 2, plants may increase root development and root proliferation, exude organic acids or phosphatases, or form associations with mycorrhizal fungi to improve access to P. The ability of the crop to use the various strategies for P access will influence its ability to utilize the P it needs, both from the soil or from the fertilizer application. Therefore, P fertilization requirement and yield response to P fertilizer of a crop will 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.

5.5.1 Small Grain Cereal Crops

Cereal crops such as wheat, oats and barley tend to have a slightly lower uptake and removal of P on a per bushel or tonne basis than do oilseed crops, soybean, and some pulse crops (Table 5). The cereal crops will form mycorrhizal associations, but do not tend to be highly dependent upon mycorrhizae for P access in agricultural systems (Dai et al. 2014; Smith et al. 2015). They are able to proliferate their roots (intensify root growth) to a moderate degree when they contact a concentrated area of P, increasing their ability to extract P from the fertilizer band (Kalra and Soper 1968; Strong and Soper 1973; Strong and Soper 1974a; Strong and Soper 1974b). Small grain cereal crops are able to use both fertilizer P and soil P effectively, with fertilizer P usage dominating during early growth and uptake from the soil reserves dominating later as the root system expands (Kalra and Soper 1968; Mitchell 1957; Mitchell et al. 1953; Mitchell et al. 1952). In early studies on wheat, barley and oats on low-P soils in Saskatchewan, grain yield, P accumulation and the proportion of P derived from fertilizers all increased as the rate of P application increased, with oats and barley being more responsive to phosphate than wheat (Mitchell 1957; Mitchell et al. 1953; Mitchell et al. 1952).

In field studies conducted in the 1960s in Manitoba, accumulation of P and response to fertilizer P was moderate for wheat, being less than for rapeseed and greater than for flax (Racz et al. 1965). Field studies in Alberta in the 1960s also showed increases in barley yield with increasing rates of P fertilizer to 40 lb P_2O_5/acre (20 kg P/ha) with only minor increases when P rate was increased to 160 lb P_2O_5/acre (78 kg P/ha), regardless of fertilizer placement (Nyborg and Hennig 1969). Studies with barley on 60 sites in Alberta showed that barley yield increased with increasing rate of P fertilizer to about 60 lb P_2O_5/acre (30 kg P/ha) on very low-testing soils (Nyborg et al. 1999). As the soil test P values increased, the magnitude of response and the amount of P required to maximize yield decreased, with small and infrequent response at soil test concentrations above 22 ppm. In studies in Alberta, frequency of response to fertilizer P was greater in wheat and barley than canola (McKenzie et al. 2003a). The greatest probability of a yield increase occurred for the first 13 lb P_2O_5/acre (6.5 kg P/ha) increment of fertilizer, especially at low soil test P levels. Wheat was more likely than barley or canola to respond to a second increment of P on the low-testing soils, while none of the crops were likely to respond to a third 13 lb P_2O_5/acre (6.5 kg P/ha) increment, regardless of soil test level. In later studies with barley, maximum response to P addition increased with decreasing soils test P, but a small response could still occur even at high soil test P values (McKenzie et al. 2004b). Studies in Alberta conducted on soils with extractable soil P from 7 to 31 ppm showed there was no statistically significant response for a range of malting barley cultivars to P fertilizer addition, although there was a trend for an economic response ($p<0.2$) at 29% of sites to the lowest rate of application (McKenzie et al. 2005). Responses were not correlated with extractable soil P.

In Manitoba, oat yield increased with P application in two of six site-years (Mohr et al. 2007a). Response was not directly related to soil test P, but was most likely to occur on the seasons with a cool, dry spring. Yield increased with 26 lb P_2O_5/acre (13 kg P/ha) at one location and increased further with 52 lb P_2O_5/acre (26 kg P/ha) at the second location. Studies with oats in Saskatchewan also showed a small yield response of oats to 13 lb P_2O_5/acre (6.5 kg P/ha) on low-P soils, but no further increase when rate was raised to 26 lb P_2O_5/acre (13 kg P/ha) (May and Lafond 2007).

In field studies in Manitoba on soil ranging from 16 to 23 ppm Olsen-P, durum wheat yield increased with banded applications of 22 lb P_2O_5/acre (11 kg P/ha) (Grant and Bailey 1998). When fertilizer was broadcast, grain yields were generally lower than with banded applications of P. Increasing the rate of broadcast P from 22 to 44 lb P_2O_5/acre (11 to 22 kg P/ha) increased yield numerically in most site-years, although the effect was rarely significant. As broadcast applications are used less efficiently than banded applications, higher rates of P application may be needed to optimize yield when fertilizer is broadcast rather than placed near the seed-row. Field studies with durum wheat in Saskatchewan showed an increase in durum wheat yield to 17 lb P_2O_5/acre (8.5 kg P/ha) with no further increase when rate was increased to 34 lb P_2O_5/acre (17 kg P/ha) under drier than normal conditions and a similar trend when rainfall was high (May et al. 2008). In a three-year field study in Manitoba on a soil with Olsen-P of 26 ppm, application of 26 lb P_2O_5/acre (13 kg P/ha) had no effect on durum wheat yield grown under either no-till or conventional tillage management (Gao et al. 2010).

Grain yield of two winter wheat cultivars grown under no-till in Manitoba increased with increasing rate of P fertilizer from 0 to 22 to 44 lb P_2O_5/acre (0 to 11 to 22 kg P/ha) applied in the fall with the seed (Grant et al. 1985). In Saskatchewan, no-till winter wheat yield increased with P applications if soil test P concentrations were lower than 15 ppm (Lafond et al. 2001). Other field studies in SK showed that yield of winter wheat grown on chemical fallow increased with P application where available moisture was favourable and soil test P was low to moderate (Campbell et al. 1996). In Colorado, yield of no-till winter wheat at sites with moderate soil test P levels increased with increasing P rate up to 200 lb P_2O_5/acre (101 kg P ha^{-1}), with similar effects if the fertilizer was broadcast and left on the surface, broadcast and disk-incorporated, banded near the seed-row or deep-banded (Halvorson and Havlin 1992) .

On irrigated soft white spring wheat fields in southern Alberta, soil test P concentrations are commonly medium to high, often between 25-35 ppm (Modified Kelowna) but economic yield increases are still observed at 50 to 75% of sites (McKenzie et al. 2008). In studies on sites with extractable soil P concentrations ranging from 25-60 ppm, only two of nine sites had a significant response to P fertilizer (average yield gain of 9%), but economic yield gains occurred at six of the nine sites. The site with very high extractable soil P had no yield gain from P fertilizer addition. Average grain yield was 5% higher for the three highest P rates, compared to the two lowest rates, so the optimum P fertilizer rate for irrigated soft white spring wheat in southern Alberta was about 25 lb P_2O_5/acre (13 kg P/ha) unless extractable soil P was very high.

The uptake and removal of P by corn on a per bushel or tonne basis is similar to that of the small grain cereal crops (Table 5), but because the biomass yield and grain yield tend to be higher, the total uptake and removal of P per acre will also be greater. Corn tends to be very dependent upon mycorrhizal associations for optimum P nutrition, particularly in soils that are low in available P (Bittman et al. 2006; Grant et al. 2005; Miller 2000; Rogalsky 2017a). Effective colonization by AMF can increase the ability of corn to access P (Miller 2000). Practices that decrease AMF, such as fallow or intensive tillage or a non-mycorrhizal preceding crop can reduce mycorrhizal colonization in corn and increase the requirement for P application (Bittman et al. 2006; Gavito and Miller 1998; Grant et al. 2005; Hamel and Strullu 2006; Lu and Miller 1989; McGonigle et al. 1999; Miller 2000). In studies conducted near Agassiz, BC, corn showed early-season P deficiency when the level of AMF colonization was low due to previous summer fallow (Bittman et al. 2006). The early-season P deficiency symptoms in poorly colonized corn were reduced by application of starter P fertilizer. Effects of colonization and starter P on biomass yield were additive, both being required for maximum yield, even on soils with high soil test P.

Corn that is grown after either canola may also require additional starter P applications to ensure optimal yield. Canola is a non-mycorrhizal crop widely grown in western Canada. As a non-mycorrhizal crop, canola will tend to reduce mycorrhizal colonization of crops that follow it in the rotation (McGonigle et al. 2011; McGonigle et al. 1999; Miller 2000; Monreal et al. 2011). Studies in Manitoba evaluated the response of corn to P applications after a mycorrhizal (soybean) and a non-mycorrhizal (canola) crop (Rogalsky 2017b). Although preceding crop did not have a significant effect on AMF colonization measured at V6, early-season biomass and tissue P concentration response of corn to starter P was greater in corn after canola than in corn after soybean, indicating that there may have been early-season differences in AMF colonization that dissipated by V6 or that the activity of the AMF was greater after soybean than after canola. Starter P advanced maturity, as indicated by earlier silking dates for corn after both crops and reduced grain moisture at harvest for corn after canola. The high rate of monoammonium phosphate (MAP) increased grain yield by 15.4 bu per acre (770 kg/ha) compared to the unfertilized control. Similarly, in field studies in Quebec, if AMF was inhibited by fungicide, corn yield was more responsive to starter P application than where AMF was not inhibited (Landry et al. 2008).

5.5.2 Canola (Rapeseed)

Canola is a heavy user of P with a larger uptake and removal on a per bushel or tonne basis than cereal crops such as wheat or barley (Table 5). With the high yields obtained by modern canola cultivars, crop removal on a per acre basis can be substantial. However, canola is also very effective at extracting P from the soil and at utilizing fertilizer P.

Unlike most crops in the Northern Great Plains, canola (rapeseed) does not form mycorrhizal associations (McGonigle et al. 2011; Miller 2000; Monreal et al. 2011). However, canola has other strategies to increase its ability to access P from the soil. Canola has fine roots with many root hairs and will respond to P deficiency by decreasing the root diameter and increasing the number of root hairs and root hair length to increase the ability to take up P from the soil solution (Brewster et al. 1976a; Brewster et al. 1976b; Foehse and Jungk 1983). Canola can also acidify its rhizosphere under phosphorus deficiency through the exudation of organic acids, increasing P availability (Hoffland 1992; Hoffland et al. 1989a; Hoffland et al. 1989b). In studies at two locations in Alberta, canola roots lowered rhizosphere pH by as much as 0.8 units and had a greater ability to extract P from the soil than did wheat (McKenzie et al. 1995a). Canola is also very effective at utilizing fertilizer P. Canola will proliferate its roots in areas of high P concentration, increasing its ability to extract the P from a fertilizer reaction zone (Strong and Soper 1974a). As a result, canola can use a higher proportion of fertilizer P than crops such as oats, flax or soybean, particularly during early stages of growth (Kalra and Soper 1968).

Due to its large demand for P and its ability to use fertilizer P effectively, canola (rapeseed) will respond well to fertilizer applications on P-deficient soils. In field studies conducted in the 1960s in Manitoba, rapeseed accumulated more P and showed a greater yield response to P fertilization than did wheat (Racz et al. 1965). However, in studies in Alberta, frequency of response to fertilizer P was greater in wheat and barley than in canola, possibly because canola was very effective at accessing soil P (McKenzie et al. 2003a). In the Alberta studies, all three crops responded well to the first 13 lb P_2O_5/acre (6.5 kg P/ha) increment of fertilizer, especially at low soil test P levels. The likelihood of response to the next increment of fertilizer was lower for canola than for wheat, while response to the third 13 lb P_2O_5/acre (6.5 kg P/ha) increment was low for all crops and soil test levels.

Canola can effectively use soil P if soil test P values are adequate, so response to fertilizer P will decline as soil test P concentrations increase. In early soil test studies in Manitoba, canola (rapeseed) responded to P fertilizer if the Olsen soil test concentration was less than 10 ppm (Soper 1971). In later studies conducted in Manitoba and Saskatchewan over three years, canola responded to P fertilizer applications in 6 of 9 site-years, including at all sites where Olsen P was less than 10 ppm and at 1 of 4 sites between 10 and 14 ppm (Mohr et al. 2013). In other field studies in Manitoba, seed yield of canola increased with P application at four site-years where the soil test levels were low and not at the two site-years with the highest soil test values (Grant et al. 2009). Yield was optimized with 22 lb P_2O_5/acre (11 kg P/ha) where soil test levels were moderate and only increased with the next increment of P fertilizer where available soil P was very low. Other studies in Manitoba and Quebec showed that P fertilization increased early season growth in 3 of 5 sites that tested low in P, but increased seed yield at only 1 site (Bélanger et al. 2015).

Modern hybrid canola cultivars have significantly higher yield potential than older open pollinated cultivars. They tend to require higher levels of fertilizer N, but similar levels of fertilizer P and S to optimize yield, as compared to the conventional cultivars, indicating that they are more effective at using soil and fertilizer P than the lower-yielding open pollinated cultivars (Karamanos et al. 2005). The superior ability of the hybrid canola cultivars to "scavenge" P from the soil may affect P availability for following crops in the rotation.

Canola is sensitive to seed-placed fertilizers and high rates of monoammonium phosphate (MAP) or ammonium polyphosphate (APP) placed in the seed-row can lead to seedling damage and yield reduction (Bailey and Grant 1990; Grant 2013; Grenkow et al. 2013; Nyborg and Hennig 1969; Qian et al. 2005; Qian et al. 2006; Schoenau et al. 2005). If high rates of P are needed to optimize crop yield, moving the fertilizer away from the seed-row by side-banding, mid-row banding or deep-banding should be considered.

5.5.3 Flax

Phosphorus fertilization of flax can be problematic, as flax responses to P fertilizer are usually small or non-existent (Racz et al. 1965). In addition, flax tends to be highly sensitive to seed-placed fertilizer and applications of moderate amounts of P with the seed can lead to severe stand reduction (Bailey and Grant 1989; Nyborg and Hennig 1969). Application of P fertilizer is often not used effectively by flax unless it is placed within 1 to 2 inches (2.5 to 5.0 cm) of the seed-row (Bailey and Grant 1989; Sadler 1980). Even if fertilizer P is placed near the seed-row, fertilizer responses of flax are often small (Grant et al. 1999; Grant et al. 2009; Lafond et al. 2003a; Lafond et al. 1998; Lafond et al. 2003b; Malhi et al. 2008; McAndrew 1999).

The poor ability of flax to respond to fertilizer P may relate to the limited ability of flax to proliferate roots in regions of high P concentration, which restricts the ability of flax to extract P from a fertilizer reaction zone (Strong and Soper 1973; Strong and Soper 1974a). In greenhouse experiments, mixing phosphorus fertilizer with a portion of the soil to increase the area of the soil fertilized increased the ability of flax to use the fertilizer, as compared to application of the fertilizer in a pellet, presumably by increasing the volume of fertilized soil that could be contacted by the flax roots (Soper and Kalra 1969). Because of its limited ability to proliferate roots in regions of high soil P concentration, flax tends to be more reliant on P uptake from the bulk soil than from fertilizer applications (Kalra and Soper 1968; Strong and Soper 1974a). In greenhouse radiotracer studies, P uptake from both fertilizer applications and the bulk soils by flax was lowest among 12 crops studied while the ratio of soil to fertilizer P absorption was greater than in any crop, except for soybean (Kalra 1971). However, in these pot studies, the uptake of P by flax from the bulk soil may have been inhibited by the lack of mycorrhizal associations in the highly disturbed soil.

The ability of flax to extract P from the bulk soil may be enhanced by mycorrhizal associations. Flax is highly dependent upon mycorrhizal associations and its growth can be negatively affected when following a non-mycorrhizal crop such as canola (Grant et al. 2009; Khakbazan et al.

2009; McGonigle et al. 2011; Monreal et al. 2011). In field studies in Manitoba, flax following canola had less early season growth, mycorrhizal colonization and P accumulation than flax following wheat (Grant et al. 2009; McGonigle et al. 2011). Increasing the rate of P fertilizer either in the preceding crop or in the flax did not increase seed yield of flax grown on canola, compared to that of flax grown after wheat, indicating that the depressive effect of canola could not be corrected by extra P fertilization (Grant et al. 2009).

As a result of these challenges, the probability of an economic response to P application in flax is low, except on very low P soils. Nevertheless, Manitoba recommends application of 30 to 40 lb P_2O_5 ac^{-1} if the fertilizer can be side-banded or placed below the seed-row (https://www.gov.mb.ca/agriculture/crops/production/flax-and-solin/print,index.html, accessed November 3, 2018). However, some regions do not recommend P fertilization of flax and, instead, suggest a long term sustainability strategy for managing P fertility for flax fields, by increasing rates of P fertilization for other crops in the rotation (https://www.ag.ndsu.edu/publications/crops/fertilizing-flax#section-2, https://flaxcouncil.ca/tips_article/fertility-requirements-for-flax/, accessed September 7, 2018).

5.5.4 Pulse Crops and Soybeans

Many pulse crops, including field pea, lentils, faba bean, various dry beans and chickpea, are grown in the Northern Great Plains. As a group, pulse crops tend to form mycorrhizal associations to assist in accessing soil P (Baird et al. 2010; Fraser et al. 2006) and they have a moderate to high uptake and removal of P per tonne (Table 5).

Another legume seed crop, soybean, has become a major crop grown on the Northern Great Plains and its acreage has recently increased substantially on the Canadian prairies, for example. (https://www150.statcan.gc.ca/t1/tbl1/en/cv.action?pid=3210035901, accessed September 10, 2018). Soybean has a moderate rate of P uptake and removal, compared to other commonly grown crops (Table 5). Soybean will form mycorrhizal associations to enhance the ability to extract P from the soil (Wang et al. 2011). Soybean is very effective at extracting P from the soil but is somewhat less effective at using fertilizer P as compared to canola (Kalra 1971; Kalra and Soper 1968). Ontario studies show that soybean responds positively to increasing levels of soil P (Lauzon and Miller 1997). In contrast, studies in Manitoba that evaluated the response of soybean to soil test P levels accumulated from historical P applications found that soybean yield was not affected by a wide range of P concentrations in the soil (Bardella 2016).

Yield response of soybean to applied P is frequently small or non-existent at even relatively low levels of soil test P. In one study in Iowa, P application increased soybean yield when soil test P was less than 9 ppm (Borges and Mallarino 2000), while other Iowa studies reported economic returns to annual P applications in soybean if soil test P levels were less than 16 to 20 ppm (Webb et al. 1992). Growth chamber studies in Manitoba in the 1980s showed that soybean responded well to banded P on low-P soils under growth chamber conditions, particularly if the P was banded directly below the seed (Bullen et al. 1983). Complementary field studies by the same research group showed that soybean also responded well under low-P conditions if the fertilizer was banded below or below and to the side of the seed-row, but not if the P was broadcast or seed-placed. Studies in Saskatchewan on a P-deficient soil found that soybean responded to 18 lb P_2O_5/acre (20 kg P_2O_5/ha) if it was deep-banded or seed-placed, but did not respond to broadcast applications even when the rate was increased to 72 lb P_2O_5/acre (80 kg P_2O_5/ha) (Weiseth 2015). In contrast, no increase in soybean yield from P application was found in other Manitoba field studies over five site-years, regardless of rate and placement (Gervais 2009). In 28 field studies conducted in Manitoba from 2013 through 2015, evaluating treatments of 20, 40 and 80 lb P_2O_5/acre (22.5, 45, and 90 kg P_2O_5/ha) applied as seed-placed, side-banded or broadcast monoammonium phosphate (MAP), P fertilizer application increased seed yield for soybean in only 1 of 28 site-years, regardless of fertilizer P rate, P placement or soil test P (Bardella 2016). Conversely, in similar studies conducted at four different locations in Saskatchewan over three years for a total of 12 site-years, P application increased yield at 3 site-years when residual P value was very low (4, 5 and 12 ppm Olsen-P) and yield potential was high (Holzapfel et al. 2017). However, there were also situations where response to P fertilization was not significant, even when soil test P levels were low and yield potential reasonably high, indicating the variability of P fertilizer response.

Soybean yield response to P application is not consistent or large, unless soil test P levels are very low. Soybean appears to be very effective at accessing soil P (Kalra 1971), meaning that it is able to access sufficient P from the soil unless soil P supplies are very depleted. Soybean is also sensitive to seed-placed fertilizer, so applications in the seed-row can lead to yield depression (Bardella 2016; Holzapfel et al. 2017). Therefore, it may be less important to optimize P applications for soybean in the year of application and more practical to ensure that P levels are optimized through the rotation using a long-term sustainability strategy (Mohr et al. 2016). Soybean can access enough P to optimize crop yield under a range of soil test P levels and P fertilizer management strategies. While soybean yield responses to P fertilizer application and soil P content are infrequent, it is important that P management strategies consider P removal by soybean to avoid potential depletion of soil P. For this reason, a strategy for applying "extra" P fertilizer to other crops in the rotation has been recommended to soybean growers, to ensure a long term balance between P additions and removal (http://www.manitobapulse.ca/production-resources/phosphorus-fertilization-strategies (Mohr et al. 2016).

Field peas are also widely grown across the Northern Great Plains. In a three-year study at Melfort, Outlook and Saskatoon, seed yield of field pea increased with sideband but not seed-placed application of phosphate at all locations (Henry et al. 1995). The response over six rates of monoammonium phosphate (MAP) applied at rates of 0 to 90 lb P_2O_5/acre (0 to 44 kg P ha^{-1}) was quadratic. Pea emergence was highly sensitive to seed placement, with plant counts and seed yield being reduced by seed-placed P at all locations. In later field experiments in Saskatchewan, P application as monoammonium phosphate (not adjusted for N added) or triple superphosphate (TSP) increased seed yield at 3 of 6 sites (Knight 2012). Seed or side band placement of the recommended rate of 15 lb P_2O_5/acre (16.8 kg P_2O_5 /ha) as MAP was the most consistently effective, although in many cases a smaller application of 7.5 or 10 lb P_2O_5/acre MAP was equally effective, with the higher rate of 23 lb P_2O_5/acre (25.2 kg P_2O_5/ha) occasionally being beneficial. Seedling damage was occasionally observed with seed-placed P, but none of the treatments led to root damage.

In 52 field trials with field pea in Alberta, phosphate applied as triple super phosphate (TSP) increased seed yield by an average of 7% at 19 of the sites (McKenzie et al. 2001b). On the 31 sites with available P less than 15 ppm, 52% responded to P applications, with application of 25 lb P_2O_5/acre (13.1 kg P ha^{-1}) generally enough to maximize yield. The average yield benefit was similar in the Thin Black, Black and Gray soil zones, but was negligible in the Dark Brown soil zone and in irrigated trials. There was no difference in response to seed-placement as compared to side-banding, likely because TSP rather than monoammonium phosphate (MAP) was used. Yield response of pea was modest and less than would be expected for cereal crops. Only one of 17 trials with soil test P concentrations of more than 15 ppm showed a seed yield response to P application. In other field studies in Alberta, P application as MAP or TSP increased dry matter and seed yields of field pea at all 12 sites with less than 10 ppm Olsen P but only on one of the 9 sites that contained more than 10 ppm Olsen P (Karamanos et al. 2003). Maximum yield was obtained with P application rates of 13, 26, 40 and 52 lb P_2O_5/acre (6.5, 13, 19.5 and 26 kg P ha^{-1}) in two, six, four and one trials, respectively. Phosphorus placement affected field pea yield in only three site-years, but where it did, side-banding was superior to seed-row placement.

Field studies in Manitoba on a soil moderate to high in P showed that stand density of field pea decreased with increasing rates of triple superphosphate (TSP) placed below or below and to the side of the seed-row (Gubbels 1992). Yield increased with P applications up to 45 lb P_2O_5/acre but decreased when rate was increased above 90 lb P_2O_5/acre, reflecting seedling damage. Yield responses were small because the soil was relatively high in available P. Later field studies in Manitoba showed that field pea responded to P application in only one of four site-years, even though Olsen P was low in three of the four sites (McAndrew 1999). Field pea did not respond effectively even when fertilizer was side-banded to reduce the risk of seedling damage.

Field studies in Saskatchewan evaluated P fertilization of chickpea (Gan et al. 2003). Starter P at a rate of 14 lb P_2O_5/acre (15 kg/ha) had a marginal effect on plant growth and seed yield, but a higher rate of P (30 lb P_2O_5/acre) increased Kabuli chickpea seed yield. Other field studies in Saskatchewan evaluated the effect of P application on desi and Kabuli chickpea (Walley et al. 2005). Desi chickpea seed yield increased with P application, with little difference in seed yield occurring between the rates of 18 and 36 lb P_2O_5/acre. Application of P fertilizer had no effect on either seed yield or harvest index of Kabuli chickpea (Walley et al. 2005). On soils with low levels of available P, fertilizer placed with or away from the seed at rates of approximately 18 lb P_2O_5/acre was suitable for chickpea production on the Canadian prairies (Walley et al. 2005). In southern Alberta studies on Brown or Dark Brown Chernozemic soils, P application as triple superphosphate (TSP) at rates of 0, 13 and 25 lb P_2O_5/acre (0, 6.5 and 13 kg P/ha) rarely led to a significant increase in seed yield of desi chickpea (McKenzie et al. 2006a). Response of chickpea was similar to that of field pea in that no response to P fertilizer if soil test P was >15 ppm using the modified Kelowna method. The yield response to fertilizer was not correlated with soil test P but net return from the 13 lb P_2O_5/acre application rate was positive if the soil test was less than 15 ppm and negative if it was greater.

Dry bean (Phaseolus vulgaris L.) response to fertilizer application was evaluated at irrigated sites across southern Alberta (McKenzie et al. 2001a). Most sites tested moderate to high in available P (20 to 40 ppm Modified Kelowna). Only one site showed a significant response to P fertilizer with seed yield increasing by 14% with addition of 25 or 40 lb P_2O_5/acre (13 or 20 kg P ha^{-1}) with a soil test P concentration of 20 ppm using the modified Kelowna extractant. Manitoba studies showed no significant positive response to P application, although there was a tendency for higher yields with P application in two of the five site-years when fertilizer was side-banded (McAndrew 1999). Seed-placed fertilizer decreased bean yield at one of the five site-years. Recommendations from North Dakota for dry beans indicate that yield increases have occurred with application of fertilizer P if soil test P was medium or lower (Franzen 2017). Dry beans are sensitive to salts and fertilizers should not be placed with the seed, with placement 2 inches (5.0 cm) to the side and 2 inches (5.0 cm) below the seed-row being recommended. North Dakota recommends up to 45 lb P_2O_5 per acre on very low testing soils, 10 lb P_2O_5 per acre on high testing soils and 0 on very high soils, if the fertilizer is broadcast, with rates reduced by about 1/3 from these rates if it is banded.

In trials with lentil in southwest Saskatchewan, starter P at a rate of 15 lb P_2O_5/acre (7.4 kg P/ha) increased lentil seed yield in 4 of 6 site-years, with an average yield increase of 4% compared to the non-P check; however, the effect was not statistically significant (p=0.21) (Gan et al. 2004; Gan et al. 2005; Gan et al. 2003). In other studies at three locations in Saskatchewan over three years, lentil yield showed a quadratic response to P rates from 0 to 90 lb P_2O_5/acre (0 to 44 kg P/ha) increasing at rates up to 45 lb P_2O_5/acre (22 kg P/ha) if seed-placed and up to 90 lb P_2O_5/acre (44 kg P/ha) if side-banded, with a higher maximum seed yield with side-banded than with seed-placed MAP (Henry et al. 1995). Lentil was less sensitive to seed-placed P than field pea, but yield was still higher when side-banded than seed-placed. Faba bean yield increased with P application, but was not affected by placement, as the faba bean stand did not decrease with seed-placed MAP (Henry et al. 1995).

5.5.5 Small area crops

In studies in northern Saskatchewan on sites that tested moderate in soil P, hemp seed yield response to P was variable from site to site, but the average yield for plots receiving P fertilizer at rates of 18, 36, 54 and 72 lb P_2O_5/acre (20, 40, 60 and 80 kg P_2O_5/ha) was 30% greater than plots receiving no P fertilizer (Vera et al. 2010). The cultivar Finola was more responsive to P (2.14 kg/ha seed yield gain for every additional kg/ha of fertilizer P) than Crag (0.94 kg/ha seed yield gain for every additional kg/ha of fertilizer P). No interactions between N and P fertilizer rates were detected.

Response of mustard to P application was evaluated at sites in southern Alberta for 20 site-years (McKenzie et al. 2006b). Phosphorus fertilizer significantly increased seed yield of yellow mustard at 2 of 20 sites, but at 14 of 20 sites P treatments produced seed yield more than 3% higher than the unfertilized control, with a median increase in seed yield at all sites of 5%. Modified Kelowna soil test P at the sites ranged from 5 to 90 ppm but was not correlated with yield response. The small yield benefit of P fertilizer for yellow mustard was consistent with previous studies. Mustard showed a smaller yield response than was measured for canola in previous studies on similar sites (McKenzie et al. 2003b), likely because of the dry soil moisture conditions at many of the sites in this study.

In field studies in North Dakota, buckwheat was less responsive than wheat to P drill-applied as triple superphosphate in the seed-row (Goos 1998). The fertilizer P was accessed by the buckwheat, which showed more luxury consumption and greater PUE than wheat, but seed yield did not increase in response to the P application. Buckwheat left most of the P it accumulated in the straw, while wheat translocated most of its accumulated P to the grain. Buckwheat uptake efficiency for P was much greater than for wheat, supporting the idea that buckwheat is an efficient P feeder (Goos et al. 1998; Goos 1998; Strong and Soper 1973). Buckwheat may solubilize P from the soil, increasing its ability to access soil P (Teboh and Franzen 2011). This solubilisation, combined with the retention of the P in the straw, may allow buckwheat to increase the P available for following crops, a benefit in an organic production system.

In field studies conducted in Manitoba, monoammonium phosphate (MAP) applications increased buckwheat seed yield at a site with soil test concentrations of 6.5 ppm Olsen P but not at a site with 8.5 ppm Olsen P (Mohr et al. 2007b). The following year, the study was conducted at four locations and P fertilizer application significantly increased buckwheat yield at sites having Olsen soil test P concentrations $\leq$ 10 ppm. In the third year of the study, P fertilizer application had small effects on the growth, yield and quality of buckwheat, even though two of the three sites contained low to moderate soil test P concentration. Overall, response of buckwheat to P appeared more likely where soil test P concentrations were low and with cool early-season growing conditions (Mohr 2006).

Field studies in North Dakota showed that sunflower responded to P application on only two of 12 site-years where soil test P levels were medium or less and that response was poorly related to soil test P (Zubriski and Zimmerman 1974). In 2014 and 2015, twenty-two P rate experiments were conducted in North Dakota (Schultz et al. 2018). The first year of the study evaluated P rates of 0, 25, 50 and 80 lb P_2O_5/acre (0, 13, 26, and 39 kg P/ha) at various N rates while the second year of the study evaluated 0 and 50 lb P_2O_5/acre (0 and 26 kg P/ha). Phosphorus fertilizer did not increase sunflower yield or oil content economically at any location. Based on the infrequent response, it appears that P applications would not normally be required for optimum yield of sunflowers in North Dakota.

5.5.5 Forage crops

With forage crops, large amounts of vegetative biomass are removed from the systems, with harvests often being taken more than once per season. Therefore, forages can remove large amounts of P from the soil reserves. Many forage crops are perennial, so effects of P on winter survival and stand longevity are important. In addition, forage crops can be grown in mixed stands, so impact of nutrient management on stand composition should be considered.

Alfalfa is the major forage legume grown in the Northern Great Plains. It can be grown in pure or mixed stands. As alfalfa is a perennial crop that will normally be grown and harvested for several years, P fertilizer can be applied prior to or during crop establishment, annually in the growing crop, or a combination of the two. Alfalfa is an N-fixing crop, so P is often the primary limiting nutrient for production. In a study evaluating a range of macro and micronutrient applications in a strip trial in Saskatchewan, irrigated alfalfa was more responsive to P than to any of the other fertilizer treatments (Kruger and Oldhaver 2014).

Optimal rates of P for alfalfa will depend on whether the fertilizer is being applied once, at the time of seeding, or annually in the established crop. In field experiments at two sites in Alberta, P fertilizer was applied as triple superphosphate (TSP) either broadcast and incorporated at the time of stand establishment at 122, 244 or 366 lb P_2O_5/acre (60, 120, and 180 kg P/ha) or spread on the soil surface annually at 0, 20, 40, 60, 80 and 120 lb P_2O_5/acre (0, 10, 20, 30, 40, and 60 kg P/ha) (Malhi et al. 1992a). The study continued for three years at the Lacombe site and for five years at the Botha site. Hay yield increased with annual P application, but the magnitude of response was lower at Botha than at Lacombe, presumably because the initial soil test P concentration was 18 ppm at Lacombe and 27 ppm at Botha and the Botha site was drier, with a lower yield potential (Table 9). At Lacombe, there was little increase in yield past the 40 lb P_2O_5/acre annual rate while at Botha, the highest yield was at the 80 lb P_2O_5/acre rate. With the large initial application, the yield averaged over the duration of the study increased with increasing rate to 244 lb P_2O_5/acre then levelled off at both sites. The residual effect of large single P applications on hay yield lasted at least for five years.

Table 9. Yield response of alfalfa hay (t/ha) to five annual P applications (Malhi et al. 1992a).

		Levels of applied P (kg P ha^{-1})						
Location	Year	0	10	20	30	40	60	SE§
Lacombe	1975	5.96	6.55	6.49	6.83	6.79	7.03	0.32
	1976	4.20	5.78	7.14	7.08	7.82	7.52	0.48
	1977	3.44	6.44	8.88	8.49	8.31	8.40	0.61
Botha	1975	10.46	8.61	9.19	10.00	10.22	11.07	1.16
	1976	3.25	3.69	3.94	4.84	6.02	4.71	0.55
	1977	2.74	2.94	3.39	3.55	4.09	3.33	0.26
	1978	6.17	6.32	6.82	6.67	7.04	6.87	0.58
	1979	4.10	4.33	4.75	4.86	5.04	4.65	0.31

§Standard error of the mean.

In-crop applications of P can be broadcast and left on the surface or can be banded into the soil with a knife, coulter or point injection implement. Studies in Manitoba showed that established alfalfa responded similarly to broadcast and banded applications on a P-deficient clay loam soil, with average yield over a four-year period increasing to 35 lb P_2O_5/acre (17 kg P/ha), then remaining constant when rate was increased to 70 lb P_2O_5/acre (35 kg P/ha)(Simons et al. 1995). In three mature pure alfalfa stands in Saskatchewan, 35 lb P_2O_5/acre (40 kg P_2O_5/ha) as triple superphosphate (TSP) banded at a 4 cm depth increased alfalfa yield as compared to the unfertilized control (Farden and Knight 2005).

A four year field experiment on a highly P-deficient Black Chernozem soil near Ponoka, Alberta compared the yield response of an established alfalfa stand to surface broadcasting and subsurface banding annual applications of 20, 40, 60 and 80 lb P_2O_5/acre (10, 20, 30 and 40 kg P/ha) or one-time initial applications of 100, 200, 300 and 400 lb P_2O_5/acre (50, 100, 150 and 200 kg P/ha as TSP) (Malhi and Heier 1998). Phosphorus increased yield in all four years with the highest yield occurring with banding rather than surface broadcasting, whether the fertilizer was applied annually or only at the start of the study. With annual applications, the greatest increase in yield occurred with the first 40 lb P_2O_5/acre although yield continued to increase to the 80 lb P_2O_5/acre rate if the fertilizer was banded but only to 60 lb P_2O_5/acre if it was broadcast. With the single application there was only a minor increase in yield between 300 and 400 lb P_2O_5/acre if the fertilizer was banded, but yield increased substantially between these two rates if the fertilizer was broadcast. Banded application was used more efficiently than broadcast application and lower rates were required to produce a similar yield with banded as compared to broadcast application.

Differences in P response may occur between pure and mixed stands of alfalfa. In a field experiment near Swift Current SK on a soil initially testing 5.4 ppm in Olsen P, P applied as triple superphosphate (TSP) either prior to seeding at rates of 18, 36 or 72 lb P_2O_5/acre (20, 40 or 80 kg P_2O_5/ha) or as annual mid-row band applications of 9, 18 and 38 lb P_2O_5/acre (10, 20 or 40 kg P_2O_5/ha) had no effect on yield of a pure stand of alfalfa but increased the yield of alternate and mixed row alfalfa-Russian wildrye mixtures up to 21 and 34% respectively (Selles and Jefferson 2004). Highest yield of the mixed stands was obtained by annual applications of 35 lb P_2O_5/acre (40 kg P_2O_5/ha) rate, followed by application of 35 or 70 lb P_2O_5/ac (40 or 80 kg P_2O_5/ha) once at the time of seeding and then by annual applications of 18 lb P_2O_5/acre (20 kg P_2O_5/ha). The pure and mixed stands may respond differently because greater mycorrhizal development under monoculture alfalfa may improve use of soil P.

Response of a bromegrass-red clover mixture to broadcast or banded applications of 0, 90 and 180 lb P_2O_5/acre (0, 45, 90 kg P ha^{-1}) applied before planting or cumulatively applied through annual applications of 30 or 60 lb P_2O_5/acre (15 or 30 kg P/ha) each year for three years was assessed on a P-deficient Dark Grey Solod in northern Alberta (Soon 1997). The preplant broadcast application was incorporated by rototilling, and subsequent broadcast applications were topdressings. Dry matter yields were measured for four years following the establishment year in 1991. When P was applied preplant only, yield was greatest with 90 lb P_2O_5/acre, with no further increase occurring when the rate was increased to 180 lb P_2O_5/acre. However, when P fertilizer was applied annually, herbage yields increased linearly with application rates and annual applications of 60 lb P_2O_5/acre gave the highest cumulative herbage yield. The availability of the large initial applications of P fertilizer decreased over time, resulting in lower yield and lower herbage P concentration with the high initial rate than where the rate was split into three annual applications of 60 lb P_2O_5/acre. Application of a preplant broadcast-incorporated application of 60 to 90 lb P_2O_5/acre followed by at least one subsequent surface application of 60 lb P_2O_5/acre would likely produce the optimum herbage production for a legume-grass mixture.

Pure grass stands will also respond to P fertilizer on P-deficient sites. In studies on a Black Chernozemic silt loam soil in central Alberta, smooth bromegrass (Bromus inermis Leyss.) yield increased with triple superphosphate (TSP) applied either once initially at 20, 240 and 360 lb P_2O_5/acre (60, 120, and 180 kg P/ha) or annually for 5 years at 0, 20, 40, 60, 120 lb P_2O_5/acre (0, 10, 20, 30, 40, and 60 kg P/ha) (Malhi et al. 1992b). The P fertilizer was incorporated into the soil before seeding bromegrass for the initial applications, and the subsequent annual applications were spread on the soil surface. The total dry matter yield increased with P rate, but the greatest increase was with the first 20 lb P_2O_5/acre (10 kg P/ha) applied annually, with minor increases occurring at higher rates of annual application. With the initial P applications, the greatest yield occurred with 120 lb P_2O_5/acre (60 kg P/ha), with no further benefit from the higher rates of application, even five years after application. The residual effect of P from the initial application lasted throughout the five years of the study.

Response of irrigated timothy to P fertilizer was evaluated at two locations in southern Alberta (McKenzie et al. 2009). The P was applied as MAP, with applications made at the time of seeding at 0 or 175 lb P_2O_5/acre (0 or 86 kg P/ha) banded at a depth of 100 mm or annually in mid-April at 0, 25, or 50 lb P_2O_5/acre (0, 13 or 26 kg P/ha yr^{-1}) either broadcast or banded at a depth of 10 mm. Phosphorus application did not affect timothy yield at Bow Island in any year, presumably because the Kelowna soil test P concentration was initially very high, at 41 ppm. At Lethbridge, where the initial soil P concentration was only 10 ppm, P fertilization increased timothy yield in all but the first of the four years of harvest. Yield was maximized with the 175 lb P_2O_5/acre initial application or with the 25 lb P_2O_5/acre annual application. There was no advantage to additional annual P application where 175 lb P_2O_5/acre had been applied initially. The annual applications were used more efficiently when broadcast rather than banded. In similar studies in the Parkland region of Saskatchewan, triple super phosphate was broadcast on the surface applied at 0, 35, 70, 105, 140 and 175 lb P_2O/acre at Buchanan and Saltcoats, and at 0, 22, 44, 66 and 88 lb P_2O_5/acre at Carrot River. Although soil test P values were similar at all sites, timothy yields were increased only at the Carrot River site, where yield was maximized at 88 lb P_2O_5/acre. Subsequent studies showed consistent but nonsignificant increases in timothy yield when P was applied with N or with N and S, even on soil that was low to marginal in P (Malhi et al. 2009). Generally, response of timothy to fertilizer P was not predicted well by soil test values, but where responses occurred, yield was optimized at relatively low rates of P application.

Silage barley is an annual crop used for animal feed. Phosphate fertilizer applied at a rate of 25 lb P_2O_5/acre increased silage barley yield at 25 of 32 site year locations in studies conducted in Alberta (McKenzie et al. 2004a; McKenzie et al. 1998). Where soil test P was below 10 ppm, P increased yields at all sites but one. More than 70% of the sites responded to P when the soil test was between 10 and 20 ppm. If P test was above 20 ppm, fewer than 40% of the sites responded The P response was greatest at central Alberta sites and least at southern Alberta irrigated sites.

Forage seed production is also an industry in some parts of the Northern Great Plains. A study established on a three-year old alfalfa stand containing 8 ppm soil P that continued for 8 years in northern Saskatchewan showed that response to 80 lb P_2O_5/acre occurred more frequently when the alfalfa was harvested for hay production than when it was used for seed production (Malhi 2011). In experiments conducted in Saskatchewan, monoammonium phosphate and triple superphosphate (MAP and TSP) were applied at 0, 18 or 36 lb P_2O_5/acre (0, 9 or 18 kg P/ha) to smooth bromegrass, crested wheatgrass, intermediate wheatgrass, and timothy and at 0, 18, 36, 52 or 106 lb P_2O_5/acre (0, 9, 18, 26, or 53 kg P/ha) to alfalfa (Loeppky et al. 1999). Seed yield of all grasses except for the intermediate wheatgrass responded linearly to P application, while alfalfa seed yield responded linearly to P fertilization at one of three sites. Magnitude of response to fertilizer was highly related to soil test P with no response occurring on a soil that tested high in P.

5.6 Site Specific Management

Well-designed 4R management is site specific by definition, with rate being selected based on an effective soil test and managed based on the yield potential of the crop being grown in each field. However, uniform fertilizer application based on an average soil test P value for the field ignores the relatively large variability that may occur in available P concentration, crop yield response and risk of P loss in runoff due to differences in soil type, topography or previous field management. Use of a single P rate across the field may result in over- and under-fertilization in different sections of the field, reducing fertilizer use efficiency. As well, runoff P losses 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 be beneficial to reduce P inputs, increase fertilizer use efficiency and reduce the potential environmental impact of P applications.

In-field variability in the soil's plant available P supply can be large and must be identified to allow variable-rate applications (Bermudez and Mallarino 2007; Franzen and Peck 1995; Wilson et al. 2016). Site specific management can be based on a soil testing map created by intensive soil sampling (Franzen and Peck 1995). The density of sampling required to produce an effective application map will depend on the variability within the field. Highly variable fields would need greater sampling density to accurately define management zones. In studies using 82.5, 165, 220 and 330 ft grid sampling in North Dakota over a three-year period, fertilization based on the 220 ft grid correctly fertilized most areas that were low in P while a 330 ft grid would have resulted in under-application on a large part of the field (Franzen and Peck 1995). In studies in Wisconsin, sampling accuracy decreased when the grid size increased from 106 to 318 ft (Wollenhaupt et al. 1994). A coarse grid could be used for variable rate prediction on soils that are normally high-testing in P, but in fields that have a high proportion of low to moderate P levels, grids should be no larger than 200 ft. As an alternative to grid sampling, the sampling procedure can be based on topography to identify areas within the field that can be treated as management zones. The relatively stable nature of soil test P levels in the soil over a few years in the absence of large applications of fertilizers or manure means that detailed grid or topographic sampling are not required on an annual basis.

Although variations in available P can be identified, varying P fertilizer applications based on soil test P levels may not always provide a yield advantage, but may reduce P fertilizer rates and costs. In strip trials using a corn-soybean rotation in Illinois, variable rate fall-broadcast MAP applications based on small-scale grid-point sampling gave yields that were similar to those for uniform applications based on average field soil test P values, but the amount of fertilizer applied was generally lower using variable rate fertilization (Bermudez and Mallarino 2007). At the end of two years of cropping, field variability in soil test P was lower for variable rate than for uniform P application. Although variable rate application did not increase yield as compared to uniform application, it was more efficient in managing the P and reduced P accumulation in high-testing P areas, potentially reducing the risk of off-field movement of P.

Intensive soil sampling may be costly, reducing the economic benefit of variable rate P applications. Sensor technology using near-infrared reflectance spectrometry (NIR) has been explored as a method of on-the go assessment of P availability in the field to guide variable rate application (Maleki et al. 2008). Near-infrared reflectance spectrometry measures the radiation absorbed by various bonds in organic constituents in the soils (Abdi et al. 2012). The measurements are then correlated to measured properties to predict the content of a range of soil constituents. In studies in Quebec, there was a poor correlation between NIR and Mehlich-3 P but NIR was successful in predicting total P, likely because of its relationship with soil organic matter. Studies using NIR to predict various soil pools of P showed that visible near infrared reflectance (VIS-NIR) spectroscopy was moderately useful for predicting Olsen and Mehlich-3 extractable P in soils collected from short- and long-term P management studies in Indian Head, SK (Abdi et al. 2016). In studies in Belgium, on-the-go measurement of P was evaluated using a subsoiler equipped with an optical unit that connected with a VIS-NIR spectrophotometer to estimate soil P, using a model developed from soils in a large area in North France and Belgium (Maleki et al. 2008). The sensor system was linked to a variable rate fertilization system attached to the planter. Variable rate application was compared to a uniform application of 60 lb P_2O_5/acre (30 kg P/ha). The extractable ammonium lactate extractable P values in the field ranged from 90 to 700 mg kg^{-1} across a 1.55 ha field. The variable rate management led to an average application on the fields that was 2.5 lb P_2O_5/acre (1.25 kg P/ha) lower than the uniform rate of 60 lb P_2O_5/acre (30 kg P/ha) and increased corn yield while reducing yield variability, despite the high P status of the soil.

An alternate approach to variable rate annual applications of P is to apply one-time large applications to build the background P level in low-testing areas and make the soil P levels more uniform across the field. Large P applications can increase the residual P level in the field and contribute to P growth for many years after application (Wagar et al. 1986a; Wagar et al. 1986b). For environmental reasons, this type of building for soil P should be restricted to portions of the field that are not subject to significant runoff of surface water.

Upper slope positions and knolls tend to be lower in available P, due to a combination of erosion and pedogenic factors. Studies in Saskatchewan showed that moisture gradients down soil catenas and across the soil zones had a large effect on changes in soil P (Roberts et al. 1985). Increased moisture results in increased biomass production and increased weathering. Weathering releases phosphate from the native apatites and the soluble phosphate ions can leach from the soil profile, be transformed into labile and secondary inorganic P forms and/or be converted to organic P through plant and microbial uptake. As pedogenic weathering increases towards the lower slope positions, the pH declines, Ca-phosphates become less dominant and secondary P fractions occur in greater concentrations. Increased plant growth is supported both by increased moisture and by increased available P. Over time, the weathering and differences in plant growth leads to a higher proportion of non-available Ca phosphates being present in the drier upper slope positions and a higher proportion of organic and more available inorganic P forms being present in the lower slope positions, even in the absence of erosion.

Measurements in Alberta across an 800 m transect showed a strong relationship between elevation and soil P concentration, with more P in depressional areas of the landscape (Figure 8) (Pauly 2010). Soil pH also varied with elevation, being as low as 5.3 in depressional areas and up to 7.8 in upper slope positions, which could affect P reactions and availability. In studies in a number of fields in SK, highest surface accumulation of P was found in depressional profiles, largely in organic forms that were attributed to biocycling, although there may have been some contribution of erosion (Letkeman et al. 1996). A Manitoba study on an undulating landscape also showed that concentrations of extractable P were lowest on the upper soil positions and highest on the lower slope positions (Manning et al. 2001). In Saskatchewan, modified Kelowna extractable-P was higher at higher elevations while soil P supply as measured with exchange resins was not strongly related to elevation (Noorbakhsh et al. 2008).

Similarly, in field studies on small watersheds in the glacial till region in southwestern Manitoba, Olsen P increased from the upper slope to the lower slope positions (Wilson et al. 2016). Fields that had not received fertilizer and no-till fields showed more in-field variability than fields that had received fertilizer or tillage. In no-till and organic sites without manure, landscape position and topography were more related to in-field variability than in fertilized or tilled sites. However, even on fields that had historically been fertilized and tilled, Olsen P still varied with landform and topography.

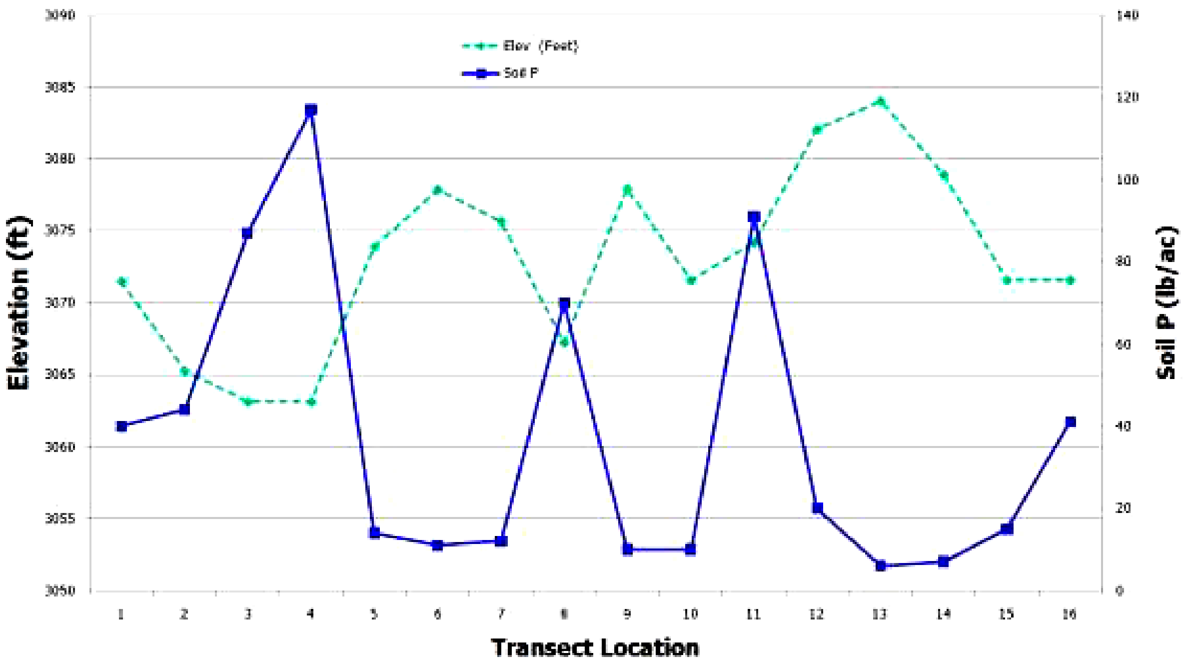


Figure 8. Changes in soil test phosphorus concentration in the 0-15 cm depth and elevation along an 800 m transect in Alberta (Pauly 2010).

Increased applications of P fertilizer or manures could be targeted to upper slope areas of the field where available P concentration is low, such as on eroded knolls. Studies at six sites in Alberta examined the effect of fertilizer application on yield when topsoil was artificially removed to simulate erosion (Larney et al. 1995). Erosion substantially decreased wheat yields on all sites and fertilizer applications were able to mitigate some, but not all, of the yield loss. The response depended on the soil type, with fertilizer response in the order: moderately eroded > severely eroded > non-eroded areas on the Dark Brown and Brown soils. On the Black soil, however, the extra fertilizer was most beneficial on non-eroded areas and least beneficial on severely eroded areas, indicating that yield response was limited by factors other than fertility on the eroded black soils. In addition, the P level in the eroded Black soils was very low and on the highly calcareous knoll, the magnitude of increase may have been restricted by Ca and Mg precipitation of the P. In these studies, application rates were moderate, with a maximum of 45 lb P_2O_5/acre (50 kg P_2O_5/ha) on the non-irrigated sites. Under the highly deficient calcareous situation, this may not have been enough to restore fertility.

Other similar studies at two sites near Lethbridge over a 16 year period showed that although fertilizer applications according to soil test recommendations were beneficial, manure application had a greater and more persistent beneficial effect on crop yield on eroded soil than did agronomic rates of synthetic N and P fertilizer (Larney et al. 2009). High rates of fertilizer P designed to produce a residual benefit may have been more effective. Other studies in Alberta evaluated the effects of applications of manure or high rates of P fertilizers and residues on a site where surface soil had been removed to artificially mimic erosion (Larney et al. 2011; Larney and Janzen 1996). Manure was able to rapidly restore productivity in the eroded soil. Yield with addition of straw plus 400 lb P_2O_5/acre (200 kg P/ha) was initially lower than the uneroded soil, but productivity gradually increased and was restored by 10 years after application. Once soil P was increased by amendments, the effect was maintained over time.

Recommendations from Alberta for fertilizing eroded knolls suggest to apply a combination of P fertilizer and manures because soil test P levels on eroded knolls will likely be very low (McKenzie and Pauly 2013). Normal rates of P fertilizer plus 75 to 100 lb P_2O_5 ac^{-1} as manure are suggested, with manure application equivalent to 10 to 20 tons per acre.

In a long-term sustainability strategy, where P balances are managed to build, maintain or deplete soil P reserves, 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 been depleted in high-yielding areas. Using variable P application rates based on crop yields would correct the rate for crop removal. This approach would assume that 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.

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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 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.

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.

Detailed Information

Phosphorus fertilizer sources are selected to provide available forms of P to the plant as required to optimize growth. Plant roots absorb orthophosphate ions that are present in the soil solution, so fertilizer materials must dissolve before they become plant-available. The availability of the P in different P fertilizer sources is therefore directly related to the solubility of each P source, with the most plant-available forms including those that are water-soluble and those that will dissolve in an ammonium citrate solution (Chien et al. 2011). However, the interactions between roots, nutrients and soil may alter the solubility of P fertilizers in the rhizosphere in ways that are not easily measured with traditional chemical analyses.

As the fertilizer P dissolves and moves into the soil solution, it initiates a series of reactions. The phosphate in the soil solution will react with calcium and magnesium in neutral to alkaline soils and with iron and aluminum in more acid soils to form increasingly less soluble compounds (Chien et al. 2011; Racz and Soper 1970; Racz and Soper 1967). The reaction of phosphate with soil constituents will influence the volume and nature of the reaction zone around the fertilizer granule, influencing the ability of the plant to access the fertilizer P (Bertrand et al. 2003; Bertrand et al. 2006; Lombi et al. 2004). The effectiveness of various fertilizer sources will therefore be affected both by the initial content of plant-available P and by the type and speed of reactions of the soluble P with soil constituents.

6.1 Traditional Sources of Phosphorus Fertilizer

6.1.1 Phosphate Rock

Phosphate rock is the original source for production of most agricultural fertilizers. Phosphate in rock phosphate is primarily present as apatites that include a range of calcium phosphate minerals ($Ca_5(PO_4)_3X$, where X is an anion such as fluoride). Rock phosphate also contains a range of impurities, including potentially toxic trace metals such as cadmium (Syers et al. 1986). Phosphate rock is relatively insoluble, especially on calcareous soils. However, the solubility of phosphate rock will vary, depending on the composition. The greater the isomorphous substitution of carbonate for phosphate in the structure, the less stable is the crystalline structure and the greater the ease of release of the phosphate into the soil solution for crop uptake (Chien and Menon 1995; Nelson and Janke 2007). Particle size will also influence solubility of rock phosphate, with solubility increasing as particle size decreases. Sedimentary forms of phosphate rock tend to be more soluble than igneous sources, due to both the different chemical composition and particle size (Table 1).

Efficacy of rock phosphate as a fertilizer source is directly related to its solubility, so there can be substantial variation in the fertilizer efficacy of various sources of rock phosphate (Chien and Menon 1995). For example, in studies conducted in Alberta, 17 rock phosphate sources were evaluated under greenhouse conditions for their effectiveness for crop uptake as compared to triple superphosphate (TSP) and monoammonium phosphate (MAP) (Kucey and Bole 1984). The most effective rock phosphate was approximately 88% as effective as TSP in a moderately acidic soil and 68% as effective as TSP in a slightly acidic soil when rock phosphate was added at 10 times the TSP rate, while several rock phosphates had no positive effect on wheat growth or P uptake (Kucey and Bole 1984). Partial acidulation of phosphate rock has been used as a way to increase its solubility and availability (Rajan 1987).

Table 1: Total and citrate-soluble phosphorus (P) concentration in phosphate rock (PR) from various sources (Nelson and Janke 2007).

PR source	PR type	Total P ($g \cdot kg^{-1}$)[z]	Citrate soluble P ($g \cdot kg^{-1}$)[z]	Citrate soluble P (% total P)
Algeria[y]	Sedimentary	131	48	37
Gafsa,Tunisia[x]	Sedimentary	127	23	18
North Carolina[x]	Sedimentary	117	20	17
Florida[y]	Sedimentary	157	13	8
Tennessee[w]	Sedimentary	131	11	9
Montana[y]	Igneous	159	8	5
Araxa, Brazil[w]	Igneous	162	6	4

[z]1 $g \cdot kg^{-1}$ = 1000 ppm.
[y]Zaharah and Bah, 1997.
[x]Centre for Industrial Development, 1967.
[w]Van Kauwenbergh and McClellan, 2004.

Soil characteristics, most notably pH and calcium content, will affect solubility of rock phosphate. Dissolution of apatite follows the following reaction, using fluorapatite as an example:

$$Ca_5(PO_4)_3F + 6H^+ \leftrightharpoons 5Ca^{2+} + 3H_2PO_4^- + F^- \qquad \text{(Lindsay and Moreno 1960)}$$

Since H^+ is an ingredient for the dissolution reaction, increasing the solution concentration of H^+ on the left side of the equation will push the reaction towards dissolution of the rock phosphate, while increasing solution concentration of reactants on the right side of the equation will suppress dissolution. Therefore, a high concentration of H^+ ions, as occurs in acid soils, will increase the solubility of the apatite, so rock phosphate may be beneficial as a P source on acid soils (Choudhary et al. 1996; Choudhary et al. 1994; Ellis et al. 1955; Kucey and Bole 1984). However, high concentrations of calcium (Ca^{2+}), as in calcareous soils, will decrease solubility of rock phosphate, making it much less likely to be an effective P source on high pH, calcareous soils that make up a large portion of the land area on the Northern Great Plains. For example, studies conducted in Saskatchewan showed no increase in barley seed yield when rock phosphate was applied on a P-deficient calcareous soil, while use of triple superphosphate produced a substantial yield increase (Malhi et al. 2014). Calcium ions released from the dissolution of rock phosphate may adsorb to the soil cation exchange, removing them from solution and shifting the equilibrium towards dissolution. Therefore, agronomic effectiveness of rock phosphate may increase with increasing cation exchange capacity (CEC) in soil (Chien and Menon 1995).

Increasing organic matter content may also increase dissolution of rock phosphate, both because of the effects of organic matter on CEC and because the organic matter may form direct complexes with Ca^{2+}, again shifting the equilibrium towards dissolution.

Due to its lack of effectiveness as a phosphorus source, rock phosphate is rarely used as a fertilizer in conventional farming in the Northern Great Plains. Rock phosphate is slightly more commonly used in organic farming systems, because it is considered a permissible organic fertilizer source while other more soluble phosphate fertilizers are prohibited. Organic farming systems may differ somewhat from conventional systems in having more extended rotations, more use of N-fixing legume crops and more use of green manure crops. They also tend to have lower P concentrations in the soil than conventionally farmed fields (Entz et al. 2001). These factors may influence the effectiveness of rock phosphate as a P source.

6.1.1.1 Management to Increase Effectiveness of Rock Phosphate

Effectiveness of rock phosphate as a fertilizer is affected by management practices including tillage, placement, cropping sequence and time between application and crop uptake. Broadcasting and incorporation of rock phosphate will increase the contact between the fertilizer particles and the soil, increasing dissolution. Increasing the time between fertilizer application and crop demand will allow more time for the fertilizer to dissolve and thus increase efficacy. An exception could be on high P-adsorbing soils where the P retention reactions with soil constituents may be more rapid than the dissolution of the P from the rock phosphate (Chien and Menon 1995).

Since the solubility of rock phosphate is highly dependent on pH, factors that influence pH may also influence the solubility and hence the availability of rock phosphate for crop uptake. Lime application will decrease dissolution of rock phosphate by increasing both pH and calcium concentration (Chien and Menon 1995; Nelson and Janke 2007). Conversely, application of acidifying fertilizers such as elemental sulphur with rock phosphate may increase the dissolution and effectiveness of the fertilizer (Stanisławska-Glubiak et al. 2014), although the benefit may be greater on poorly buffered acid soils than on the more highly buffered, higher pH soils common on the Northern Great Plains (Evans et al. 2006).

Rock phosphate may be more effective for long-term supply of P to perennial crops than for use in annual crops, because the slow dissolution of the P over time may be able to supply the needs of the perennial crop over a number of years (Chien and Menon 1995). Also, plant species differ in their ability to access rock phosphate. Buckwheat appears to be particularly effective at accessing rock phosphate, while legumes are intermediate and grasses are relatively ineffective (Fried 1953). Crops that acidify their rhizosphere or that take up large amounts of Ca^{2+} tend to be relatively effective at accessing P from rock phosphate (Bekele et al. 1983; Hinsinger and Gilkes 1995). Studies on an alkaline artificial soil medium showed that lupins secreted H^+ and lowered the pH of the rhizosphere by approximately 2 units compared to the bulk soil, which led to increased solubilization of reactive rock phosphate (Hinsinger and Gilkes 1995).

The use of green manure crops to provide N in organic farming systems may have the additional benefit of mobilizing and releasing P from rock phosphate for the following crops in the rotation. A field study on an organic farm in Ontario examined the effect of residues from a buckwheat (*Fagopyrum esculentum*) green manure (GM) crop grown with an igneous and a sedimentary source of phosphate rock (PR) on soil P supply the following spring (Arcand et al. 2010). Application of a sedimentary phosphate rock application did not increase buckwheat dry matter production but did increase above-ground tissue P concentration. In the following spring, in situ soil P supply and Olsen P were increased in GM residue-applied soils, if the concentration of P in the residue was greater than 2.9 g P kg^{-1}. The quality of the GM residues in terms of P concentration had more influence on P availability than the quantity applied to the soil. However, the change in available P due to the GM application was not large enough to be of agronomic benefit.

Studies on neutral to alkaline soils on organic farms in Montana evaluated the ability of spring pea, buckwheat and yellow mustard grown as green manure crops, compared to summer fallow, to mobilize P from applications of rock phosphate (Rick et al. 2011). Three rates of pelletized rock phosphate were applied in the three green manure crops. The following year, winter wheat was grown. The biomass yields of the green manure crops were not affected by the rock phosphate application, although P uptake was higher with rock phosphate application than in the control. Winter wheat grain yields were not affected by the green manure crops but were approximately 10% higher where P had been applied at the highest rate to the preceding crops. Among the green manure crops, spring pea had about three- to five-fold higher P uptake than mustard or buckwheat, but there was no effect of green manure crop on wheat, indicating that the extra P in the pea biomass was not an advantage, possibly because the pea had higher water use than the other crops. It may also be that the P from the crop residue was immobilized rather than mineralized and therefore might be of long-term rather than short-term benefit. On these neutral to alkaline soils, the phosphate rock was not highly available, nor did the preceding crop improve availability, compared to summer fallow.

The P-solubilizing fungus *Penicillium bilaiae* (also known as *Penicillium bilaii* or *Penicillium bilaji)* may increase the availability of rock phosphate, presumably by effects on soil acidity (Takeda and Knight 2006; Takeda and Knight 2003). In Alberta studies on a neutral pH soil, addition of *Penicillium bilaiae* with rock phosphate and straw increased P uptake and yield of wheat in greenhouse and field studies and of bean in greenhouse studies (Kucey 1987). Mycorrhizal fungi, which are naturally present in soils, were needed to optimize the benefit of the system. Similarly, in growth chamber studies using Saskatchewan soils, *Penicillium bilaiae* was able to enhance the solubility of rock phosphate (Takeda and Knight 2006; Takeda and Knight 2003). In unbuffered medium, the addition of *Penicillium bilaiae* increased the release of P from rock phosphate by about 5-fold, while in buffered medium, the increase was approximately 50-fold. Buffering the media increased the organic acid production. The increase in organic acid production was also related to a decrease in Ca concentration in the media, suggesting that the oxalate and citrate complexed with the Ca, reducing the reaction of P and Ca and hence increasing P solubilization.

6.1.2 Commercial Phosphate Fertilizers

The common commercial phosphorus fertilizers are produced from rock phosphate that is treated to increase its solubility. Normally, impurities such as sand, clay, carbonates, organics and iron oxide are initially removed from the rock phosphate ore through a process of beneficiation. The beneficiated ore is then ground and reacted with acid to form more soluble, plant-available commercial fertilizers. Phosphoric acid (H_3PO_4) is formed by reacting rock phosphate with sulphuric acid (Follett et al. 1981). The impure phosphoric acid contains gypsum that must be filtered out. The phosphoric acid is then heated to drive out water and increase the P concentration. High quality phosphoric acid can be used directly as a liquid fertilizer source (0-55-0), although its corrosive nature can cause problems in handling. It is more commonly used in the production of other fertilizer materials.

6.1.2.1 Dry Granular Phosphate Fertilizers

Single superphosphate (SSP, e.g., 0-20-0-10) is also known as normal superphosphate (NSP) or ordinary superphosphate (OSP) and was the first improved phosphate fertilizer produced, dating back to a patent issued in 1845 (Follett et al. 1981). Single superphosphate is produced by blending ground, beneficiated rock phosphate with sulphuric acid of about 60-72% concentration and allowing the mixture to react for several weeks until the apatite in the rock is converted to monocalcium phosphate ($Ca(H_2PO_4)_2 \cdot H_2O$) and gypsum. The resulting fertilizer is low analysis, ranging from about 18 to 20% P_2O_5, which makes it costly to transport per unit of available P. Single superphosphate is reasonably soluble and serves as a source of available S as well as P, but is not a common fertilizer source in the Northern Great Plains.

Triple superphosphate (TSP, e.g. 0-45-0) has a higher phosphorus concentration than SSP, containing about 40 to 46% P_2O_5. As with SSP, the P in TSP is in the form of monocalcium phosphate, but TSP does not contain gypsum. The TSP is produced by reacting rock phosphate with phosphoric acid. It is highly water soluble and is agronomically similar in availability to SSP.

Monoammonium phosphate (MAP, e.g., 11-52-0) is the most common form of phosphorus fertilizer used on the Northern Great Plains. It is produced by reacting a 1:1 ratio of ammonium and phosphoric acid and solidifying the resulting slurry into granules. Monoammonium phosphate has an analysis of between 48 and 61% phosphate and 11 to 12% nitrogen, with the chemical analysis $NH_4H_2PO_4$ (Follett et al. 1981). The P is present in the form of orthophosphate (Figure 1). MAP is highly water soluble and provides both ammonium and phosphate ions for plant uptake. 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, which increase crop uptake of phosphate, by decreasing pH in the rhizosphere during root uptake and reducing precipitation of phosphate (Miller et al. 1970). Specifically, the uptake of ammonium by plant roots leads to the expulsion of H^+ that lowers pH in the rhizosphere and can reduce the formation of $CaHPO_4.2H_2O$ near the root surface. Ammonium has also been shown to increase root proliferation in the fertilizer reaction zone which would increase the ability of the plant to absorb the applied P (Miller and Ohlrogge 1958).

As a result of these attributes, monoammonium phosphate is well-documented as being superior to triple super phosphate for P fertilization of crops in the Northern Great Plains. For example, in 75 site-years of field trials on summer fallow fields in Saskatchewan from 1939 to 1943, the wheat yield response to monoammonium phosphate was 30% greater than to triple super phosphate (Mitchell 1946). Although these studies were not balanced for the N applied in the MAP, N responses would have been unlikely on summer fallow fields, given the large amounts of N mineralization in these soils at this time.

Diammonium phosphate (DAP, e.g., 18-46-0) is produced in a similar manner to monoammonium phosphate, but a 2:1 ratio of ammonium to phosphoric acid is used, resulting in a product containing 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 (Figure 1) and ammonium is present in the fertilizer which can improve P availability to 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 ammonium content leads to 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 toxicity of DAP is greater than that of MAP at a given P concentration and the effect is accentuated by $CaCO_3$ (Allred and Ohlrogge 1964). The higher pH of DAP as compared to MAP may also make it less plant-available on calcareous soils but may make it more available on acid soils (Bouldin and Sample 1959). In short-term growth chamber studies on a calcareous Saskatchewan soil, uptake of P by oats was greater from MAP than from DAP (Beaton and Read 1963). In studies using ^{32}P-labelling in nine Manitoba soils, the movement of P away from the fertilizer pellet was greater with MAP than DAP (Lewis and Racz 1969). The extent and rate of phosphorus movement was greater in noncalcareous than calcareous soils for both sources of P when added as a pellet. The high pH and large amounts of calcium and magnesium found in the soil solutions of the calcareous soils resulted in a rapid precipitation of the added phosphorus very close to the pellet, restricting P movement.

6.1.2.2 Fluid Fertilizers

Ammonium polyphosphate (APP, e.g., 10-34-0) is the most common fluid phosphate fertilizer on the Northern Great Plains. APP contains both polyphosphate and orthophosphate forms of P (Figure 1). The first stage in the production of ammonium polyphosphate is the dehydration of phosphoric acid to form superphosphoric acid (Follett et al. 1981; IPNI 2010). The superphosphoric acid is then reacted with ammonia and water to form ammonium polyphosphate. Ammonium polyphosphate contains about 70-75% of its P in the form of polyphosphate, with the remainder being orthophosphate. The polyphosphates are polymers of orthophosphate, with most being in the form of pyrophosphate, which contains two linked phosphate molecules. However, longer phosphate chains will also be present. The analysis of ammonium polyphosphate is usually 10-34-0 or 11-37-0. The presence of ammonium in the fertilizer will increase the P availability as discussed in the section on MAP.

Orthophosphate Polyphosphate

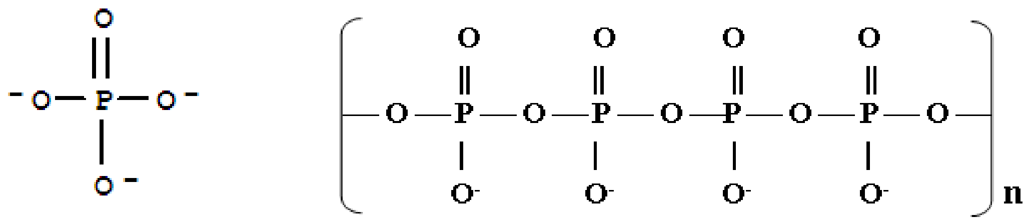

Figure 1: Linear structure of orthophosphate and polyphosphate

Plants take up P only in the orthophosphate form and are unable to take up intact polyphosphates. However, polyphosphates are quickly hydrolyzed to orthophosphate by chemical and biochemical reactions in the soil, with the rate of conversion influenced by factors such as soil pH, temperature and moisture content (Dick and Tabatabai 1986; Racz and Savant 1972). Incubation studies using two Manitoba soils showed that hydrolysis of polyphosphates was very rapid (Chang and Racz 1977). Hydrolysis rate of pyrophosphate and tripolyphosphate increased linearly with increased temperature at temperatures of 5 to 50° C. About 40 to 70% of the added polyphosphate hydrolyzed in 120 h at 5° C, whereas about 80 to 95% hydrolyzed in 120 h at 35° C. Increases in incubation temperature also increased the total amount of added polyphosphate hydrolyzed at the end of the incubation period. Hydrolysis was slowed by retention of the added polyphosphate by soil constituents. Polyphosphate hydrolysis was greater in the noncalcareous Newdale soil than in the calcareous Lakeland soil. Increasing the amount of polyphosphate applied to the soils increased the rate of orthophosphate production. Hydrolysis was rapid both at field capacity and under flooded conditions (Racz and Savant 1972). The rates of polyphosphate hydrolysis and total amounts of polyphosphate hydrolyzed shortly after application would normally be great enough to supply plants with their P requirement and would not constrain the early season crop uptake of P (Chang and Racz 1977; Dick and Tabatabai 1986; Khasawneh et al. 1979; McBeath et al. 2006). Therefore, there does not seem to be evidence that increasing the proportion of orthophosphate in fluid formulations increases the nutritional value of the P fertilizer.

An additional advantage to APP is its suitability for uniform blending with other nutrients. Polyphosphates are able to form metallic-cation multivalence chelate coordination complexes that are more soluble than the salts and oxides of the metals, thus increasing the concentration of micronutrient that can be present in the fertilizer solution (Cichy and Folek 2005; Havlin et al. 2014). Therefore, using ammonium polyphosphate can act as an effective carrier for trace elements such as zinc, by increasing the amount of nutrient that will remain in solution. Increasing the volume of solution that is used for micronutrient application by blending the micronutrient with the macronutrient solution will also increase the uniformity of micronutrient distribution, compared to applying the micronutrient separately.

The efficacy of APP may be influenced in part by the fact that 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 (Bertrand et al. 2003; Bertrand et al. 2006; Holloway et al. 2001; Lombi et al. 2004; Lombi et al. 2005; McBeath et al. 2005; McBeath et al. 2007). Commercial fluid APP or applications of MAP or DAP in dissolved form were more effective than dry granular products in increasing yield on highly calcareous alkaline soils in field and pot studies (Holloway et al. 2001). On the dry, calcareous soils used in these studies, precipitation of P with Ca was rapid when the dry fertilizer forms were used, reducing P availability. More detailed evaluations showed that the P from the fluid forms diffused further from the site of application than did the P from the granular forms (Bertrand et al. 2006; Lombi et al. 2004; Lombi et al. 2005). The proposed reason for the improvement in effectiveness with fluid fertilizer sources was that soil moisture moving along the osmotic gradient towards the dry fertilizer granule carried Ca that rapidly precipitated the P, limiting the size of the fertilizer reaction zone and the ability of the plant to access the P. With fluid sources, the fertilizer was not precipitated as rapidly, and the size of the reaction zone was larger, increasing the fertilizer availability. In laboratory studies that compared the lability, solubility and mobility of three P products applied in a fluid form and three applied in a granular form on two calcareous and one alkaline non-calcareous soils, between 9.5 and 18% of the P initially present in the dry fertilizer granules did not diffuse into the surrounding soil over a five-week period (Lombi et al. 2005). The degree of granule dissolution was independent of the soil type. In contrast, P solubility, lability and diffusion were significantly greater when fluid products were applied to the calcareous soils, but not to the alkaline noncalcareous soil. Benefits in availability were also seen when MAP was applied as a dissolved solution rather than as a granule (Lombi et al. 2004).

In contrast to the studies in Australia, large differences between the behaviour of fluid versus granular sources have not consistently been observed in the Northern Great Plains. Field studies near Brandon, MB showed that MAP increased both dry matter yield and P uptake more than APP early in the growing season, but that APP had a greater benefit on final grain yield (Spratt 1973). Dry matter production and the uptake of P continued after the dough stage with APP but not with MAP. The author suggested that the hydrolysis of polyphosphate by roots later in the season may encourage later-season responses. However, later field studies in Manitoba and Alberta showed no difference between the response of spring wheat yield to APP or MAP (Figure 2) (Grant et al. 2007). In other field studies in Manitoba, durum wheat (Grant et al. 2008) and canola (Grant and Relf-Eckstein 2009) showed similar responses to APP and MAP, while soybean did not respond significantly to either P source (Grant et al. 2008). The effect of two liquid ammonium orthophosphates (6–24–6 and 9–18–9), APP and MAP on plant-available phosphate was assessed over time in laboratory studies conducted using soils collected from Manitoba (Goh et al. 2013). The water-soluble and bicarbonate-extractable phosphate was increased in the first few days after application by all four sources as compared to the control. The liquid products produced greater water-soluble and sodium bicarbonate-extractable P concentrations than MAP until the second day of incubation, while the 9-18-9 ammonium orthophosphate produced higher concentrations than MAP until day 4. However, the differences among the products disappeared quickly and the available P was similar among the products after 4 days of incubation. These brief, transient differences in availability among the different fertilizer forms would be unlikely to have a major effect on crop growth and final yield. The difference between the results of studies with fluid P in Manitoba as compared to Australia may be because the Australian soils were much more highly calcareous than are commonly found on the Northern Great Plains and the growing conditions in that region of Australia tend to be drier.

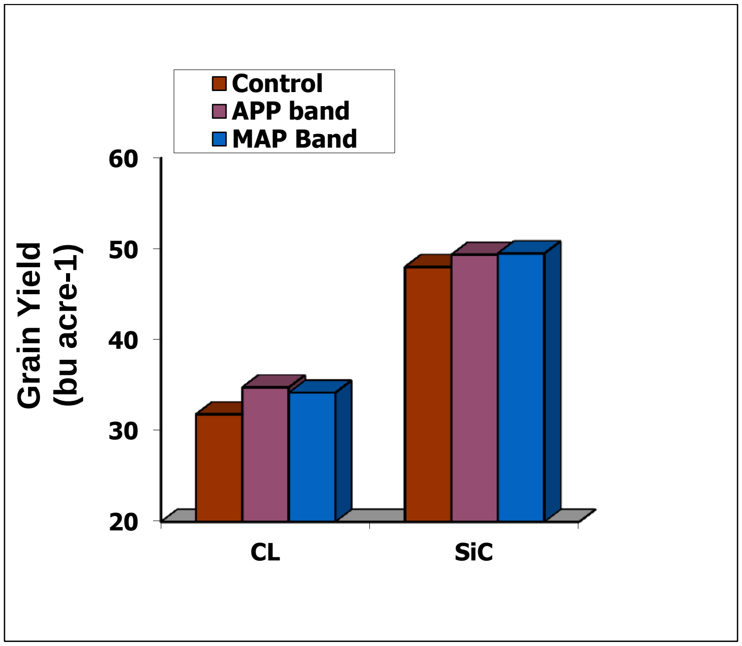

Figure 2. Effect of banded ammonium polyphosphate (APP) as compared to monoammonium phosphate (MAP) on grain yield of wheat on two Manitoba soils (Grant et al. 2007). Phosphorus response at the CL site was significant (p<0.0382) while differences between APP and MAP were never significant.

6.2 Fertilizer Special Formulations, Additives and Coatings

Crop uptake of phosphate from a fertilizer reaction zone is related to the concentration of phosphorus in the soil solution and the amount of roots present to access the fertilizer (Claassen and Barber 1976). Therefore, uptake can be increased by increasing the solubility of the fertilizer, the size of the reaction zone or proliferation of roots in the zone of high P concentration around the fertilizer granule. Phosphate ions in the soil solution will diffuse away from the area of high concentration around the fertilizer granule and interact with the cations in the solution. The distance that the phosphate ions move, and therefore the size of the reaction zone, will be affected by the type and concentration of ions that react with the diffusing phosphate ions. Adding products with the phosphate fertilizer to alter the solution chemistry and slow the soil reactions with the phosphate ion could therefore improve the availability of the fertilizer by increasing solution P concentration and/or increasing the volume of the reaction zone. In addition, as mentioned previously, some ions such as ammonium may increase root proliferation and/or lead to H^+ exudation and acidification of the rhizosphere, further increasing the ability of the plant to access fertilizer P.

Elemental S - Studies in the early 1950s looked at the effect of adding elemental S to MAP and dicalcium phosphate-nitrate to acidify the area around the fertilizer and potentially slow soil reactions with P (Mitchell et al. 1952). While growth chamber studies on a soil with pH of 7.4 showed a benefit in P availability from both P sources due to the addition of elemental S, field study results on soils with pH values of 8.4 and 7.2 did not. The authors speculated that oxidation of the elemental S was too slow under the cool soil conditions in the field to have an effect or that there were not enough S-oxidizing bacteria available to convert the elemental S rapidly. In a subsequent study, they added S-oxidizing bacteria to dicalcium phosphate-nitrate, which increased S oxidation and also the availability of the P (Mitchell et al. 1952). The action of S-oxidizing bacteria on elemental S in the fertilizer doubled the availability of dicalcium phosphate-nitrate, but even this more effective mixture of S and dicalcium phosphate nitrate was only about 30 per cent as effective as monoammonium phosphate (11-48-0) in supplying phosphorus to cereals under the conditions of the experiment. The MAP was much more effective than any of the calcium-based phosphate sources.

Non-Phosphate Salts - Many subsequent studies evaluated the effect of various non-phosphate salts on the solubility and movement of fertilizer P. In laboratory studies, movement of phosphate in columns containing a Ca^{2+}-saturated resin-sand mixture was reduced when KH_2PO_4 was applied with KCl (Akinremi and Cho 1993). The mobility and solubility of the applied P was reduced by Ca^{2+} ions displaced from soil exchange sites by the K^+ (Akinremi and Cho 1991a; Akinremi and Cho 1991b; Akinremi and Cho 1993). The decrease in mobility of P with KCl addition on high pH soils fits with models in other studies (Barber and Ernani 1991; Ernani and Barber 1991). Laboratory column studies also showed that the addition of $(NH_4)_2SO_4$ and $MgSO_4$ with MCP significantly increased P diffusion whereas $(NH_2)_2CO$ (urea) had little or no effect (Kumaragamage et al. 2004). Application of urea initially increased soil solution pH, favoring precipitation of calcium phosphate. In contrast, the sulphate ions competed with P for Ca, reducing the formation of Ca phosphates and increasing P solubility and mobility. Other column studies using cation exchange resin-sand mixtures containing $CaCO_3$ to simulate calcareous soils showed that adding ammonium sulphate (AS) or potassium sulphate (KS) salt to MAP or monopotassium phosphate reduced the pH of the system at a greater distance from the site of application than for the phosphate fertilizers applied alone (Olatuyi et al. 2009a; Olatuyi et al. 2009b). Adding AS or KS to the MAP increased the concentration of water-soluble P in the reaction zone by 43% and 21% respectively, while with monopotassium phosphate, the corresponding increases were 48% and 41%. The AS was likely better than the KS at enhancing P solubility because the NH_4^+ ion would replace less exchangeable Ca^{2+} than would the K^+, leaving less Ca^{2+} in the soil solution to react with the phosphate ions. In addition, combining sulphate sources with MAP could increase the solubility and mobility of phosphate in calcareous soils by pH reduction and competition between sulphate and phosphate ions for precipitation with soil Ca. In growth chamber studies, seed-placement of various forms of soluble S fertilizer sometimes slightly increased P availability as measured with PRS probes or by canola uptake, but the effect was small and not always significant (Ahmed et al. 2017).

Homogeneous Blends - A homogenous blend of monoammonium phosphate, ammonium sulphate and elemental sulphur formulated in a single granule is available on the Northern Great Plains. The product contains 13% N, 33 % plant-available phosphate, plus 7.5% S as sulphate and 7.5% S as elemental S, forms of S which may improve P availability on calcareous soils for reasons discussed previously. In addition, the presence of ammonium may also enhance phosphate availability through both chemical and biological mechanisms, as discussed previously (Miller et al. 1970; Miller and Ohlrogge 1958). However, there appears to be little benefit under field conditions for the novel product in terms of enhanced P availability, compared to conventional MAP. Field studies on five sites in Manitoba comparing the homogenous product to MAP determined that the midseason uptake of phosphate by wheat and canola showed a tendency to be slightly higher, numerically, with the novel product, but the differences were not statistically significant (Kroeker 2005). In growth chamber studies, P uptake was increased by either blending MAP and AS or by the use of the homogenous product, with the effect presumably being due to a crop response to the added sulphate-S in otherwise S-deficient soil (Kroeker 2005). Over a two-crop sequence in the growth chamber, total P uptake for both crops tended to be slightly higher, numerically, for the homogenous product than for MAP + AS, but the effects were not statistically significant. However, P uptake was higher with both the homogenous product and MAP +AS than with MAP alone, likely due in large part to an S response of the crops that led to greater yield and nutrient uptake. In studies conducted in Quebec, Ontario, Manitoba and Alberta, canola yield on P-deficient sites was similar with the homogenous product and MAP + AS, indicating that both P fertilizers were good sources of phosphate for canola (Grant 2013). The homogenous product led to less seedling damage when seed-placed with canola than did a blend of MAP and AS that provided the same ratio of total nutrients applied, without adjusting for the difference in availability between the forms of S in these two treatments (Grant 2013; Grenkow 2013; Grenkow et al. 2013).

Maleic-Itaconic Co-Polymer Additive - A maleic-itaconic co-polymer additive is available that can be applied to either granular or liquid P fertilizer. It is designed to sequester antagonistic metals in the soil around the fertilizer granule to reduce the retention of phosphorus and keep it in a plant-available form throughout the growing season. The suggestion is that the copolymer reduces P-binding by soil exchangeable Ca, Fe, and Al by reacting with these ions to form Ca-, Fe-, or Al-maleic and itaconic acids, thus reducing the formation of less soluble Ca, Fe or Al phosphates. However, calculation of the equilibrium constants for the Ca phosphates as compared to the maleic or itaconic acid complexes indicate that the product would not block formation of the phosphate compounds on either acid or high pH soils (Chien and Rehm 2016). The equilibrium constants of the various reactions of P with maleic acid and itaconic acids as well as with $CaHPO_4 \cdot 2H_2O$ (DCPD), an initial reaction product of soluble P fertilizers in calcareous soils, indicate that precipitation of P to form DCPD would occur before chelation with the copolymer (Chien and Rehm 2016). These theoretical calculations are in line with laboratory assessments of effects of the products on availability and mobility of P fertilizers (Degryse et al. 2013).

Studies using model systems showed that dissolved PO_4 concentrations in aqueous suspensions of ferrihydrite and poorly crystalline aluminium hydroxide (pxl-$Al(OH)_3$) at pH 6.2 increased with increasing additions of PO_4 and the maleic-itaconic co-polymer with greater effects shown for pxl-$Al(OH)_3$ (Doydora et al. 2017). The (hydr)oxides evaluated are models of high-capacity phosphate sorbents in soils. The primary mechanism for enhanced PO_4 solubilization by the co-polymer would be competitive adsorption between the co-polymer carboxyl groups and $H_2PO_4^-$ for either ferrihydrite or pxl-$Al(OH)_3$. A greater enhancement of dissolved PO_4 by the co-polymer in these model systems at higher PO_4 inputs suggests that a co-application of fertilizer and co-polymer that concentrates both materials in a smaller soil volume (e.g., a banded fertilizer application) would enhance plant-availability of P. However, the concentrations of the co-polymer used in these model systems were orders of magnitude higher than the current application rates recommended in the field.

Several studies on corn, winter wheat and potatoes conducted in the United States as well as studies with wheat in Alberta report benefits of using co-polymer with band-applied P (http://www.chooseavail.com/research.aspx, accessed December 20, 2018). Field studies conducted with irrigated corn in Kansas showed increased yield and P ear leaf concentration when the co-polymer was included to a starter fertilizer as compared to the starter treatment alone (Gordon and Tindall 2006). However, other independent field studies show no benefit from treatment with the co-polymer (McGrath and Binford 2012). Studies in Kansas on corn and winter wheat showed no benefits of using the co-polymer, even on sites where a P response occurred (Ward 2010). In two 3-yr trials in Alberta on wheat that included an unfertilized control and three rates of seed-placed P (13, 26 and 40 lb P_2O_5/acre) applied as MAP with or without the co-polymer and arranged in a randomized complete block design with six replications, neither a significant effect of treating MAP with the co-polymer nor a significant interaction between the co-polymer treatment and rate of P on the yield of wheat and P uptake was observed (Karamanos and Puurveen 2011). Studies on two soils in Manitoba showed no advantage of using the co-polymer as compared to untreated MAP or polymer-coated MAP (Grant 2011). A meta-analysis of published and unpublished studies on the co-polymer showed no benefit of the product (Chien et al. 2014). However, a subsequent meta-analysis including studies conducted up to and after those used by Chien et al. (2014) showed a benefit of the co-polymer under conditions of low soil test P, extreme pH and low rate of P application (Hopkins et al. 2018).

Polymer Coatings - Polymer coatings on granular P fertilizer 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 (Grant and Wu 2008). Controlled release MAP, DAP, and APP were simulated under greenhouse conditions by making small, periodic additions of fertilizer P (Nyborg et al. 1998). The plants rapidly depleted the supplied P from the soil solution, minimizing the potential for precipitation. Where the P was gradually supplied to the plant over several weeks, P retention was reduced, and P uptake increased as compared to a single application of P at the start of the growing period. In an evaluation of an experimental polymer coated MAP, release of P from coated MAP was slower in soil than in water, decreased markedly with increasing thickness of polymer coating on MAP, and increased with increasing temperature (Zhang et al. 2000). Coating MAP improved P uptake, fertilizer efficiency and barley dry matter yield, but the performance of DAP was not consistently improved (Pauly et al.

2002). Under field conditions in Manitoba, both coated and uncoated MAP were effective at increasing spring wheat yield but there was no significant benefit of using coated MAP as compared to uncoated MAP (Grant 2002). Growth chamber studies with 10 different crops showed that use of controlled release polymer coated MAP increased the seedling safety so that rates of 70 lb P_2O_5/acre could be safely seed-placed as compared to about half of that for the uncoated product (Schoenau et al. 2007). Under field conditions on two sites in Manitoba, seedling damage occasionally occurred with agronomic rates of seed-placed MAP in canola, but not with a polymer coated MAP (Grant 2011). In greenhouse studies, using two soils collected from Manitoba fields, a polymer coated MAP produced yields similar to that of uncoated MAP, but led to lower seedling toxicity when seed-placed at higher rates of P (Katanda et al. 2016; Katanda et al. 2019).

6.3 Reclaimed and By-Product Sources of Phosphorus

Manures, composts and municipal biosolids are valuable sources of P for crop uptake. However, due to the focus of this review on management of commercial fertilizers, these raw forms of organic byproducts will not be dealt with in this review.

Struvite - Wastewater streams, including municipal wastewater and liquid livestock manure, contain large amounts of P. Struvite is a P-containing mineral that can be manufactured from municipal wastewater and hog manure (Ackerman et al. 2013; Degryse et al. 2017; Katanda et al. 2016; Talboys et al. 2016). The struvite ($MgNH_4PO_4 \cdot 6H_2O$) can then be used to recycle wastewater and manure P as a concentrated granular fertilizer. The higher P concentration in the struvite as compared to the wastewater or manure makes it more economical to transport from areas of P surplus to areas of P deficit. Studies from Rothamstad in southern England comparing the effectiveness of 11 different struvites to that of monocalcium phosphate showed that all supplied similar amounts of P to ryegrass (Johnston and Richards 2003). Some non-significant differences occurred among the different sources and the suggestion was that differences in crystal size might be affecting efficacy.

Pot studies at the University of Manitoba showed that although P uptake was similar for hog manure-derived struvite and commercial fertilizers at P_2O_5 rates of 38 mg/pot or lower, biomass yield per unit of P taken up was smaller for the struvites (Ackerman et al. 2013). The lower yield as compared to commercial fertilizers may be due to lower initial solubility of the struvites in the alkaline (pH 7.7) soil used in this experiment, which gave an early stage growth advantage to canola fertilized with conventional or polymer coated MAP. Alternately, the banding method used in the Ackerman study may have reduced the dissolution of the struvite as compared to mixing the struvite through the soil as was used as the method of application in other studies (Degryse et al. 2017). Reducing the contact between the struvite and the soil through banding would slow dissolution of the fertilizer.

When struvite is used in canola–wheat rotations, there is a potential for greater residual P availability for subsequent canola crops than with MAP or coated MAP. In the greenhouse bioassay conducted by Ackerman et al. (2013), the soil was left to rest for only 14 d, was not subjected to freeze–thaw or wet–dry cycles, and the crops were not grown to maturity. Longer-term field-scale studies would allow a more complete evaluation of the P availability through the growing season and the residual benefits from the product. In addition, the P-release rate from struvite in different soils needs to be evaluated to provide a better understanding of the mechanisms of P transfer from this P source.

Other pot studies from University of Manitoba evaluated coated MAP as compared to struvite and uncoated MAP for seed safety and efficiency in canola and wheat grown in rotation on two Manitoba soils (Katanda et al. 2016; Katanda et al. 2019). The struvite was applied as granules formed by moistening the finely ground struvite powder, air-drying the resulting paste and cutting it into uniform granules that were similar in size to those of MAP. The fertilizers were applied either in the seed row or in a sideband at two rates. Dry matter yield in the first wheat and canola crops were similar for all three fertilizer sources but seedling damage in canola was greater with MAP than with the more slowly available products when seed-placed at the higher P rates. Struvite had more residual benefit than MAP, with dry matter yield being higher than with MAP in the second crop after application and higher than with either MAP or controlled release MAP in the third crop.

Many studies have used a powdered form of struvite, but commercial fertilizer forms would likely be in granular form to facilitate blending and handling. Growth chamber studies conducted in Australia compared granular MAP, a commercial granular struvite and several other synthesized struvites (Degryse et al. 2017). The P in MAP was almost completely soluble in water while the commercial struvite was only 3% soluble. The struvites in this experiment differed in the amount of Mg that they contained. In water, the differences in Mg had little effect on solubility of the struvites, but in the soil, the presence of extra Mg reduced the solubility and movement of the struvite, reducing the volume of the reaction zone. There was much less diffusion with the struvites than with the MAP when the products were applied as granules. However, when the products were ground and mixed through the soil, the solubility of MAP and struvites were similar. The pattern of movement for the struvite and the MAP followed the pattern of dissolution. The greatest movement of MAP occurred in the first few days after application and then decreased as the phosphate reacted with the soil. In contrast, diffusion for the struvite proceeded slowly and gradually as the struvite dissolved. In pot studies, P availability was much lower for the granular struvites than for MAP, especially on the high pH soils where granular struvite provided no increase in yield and P uptake over the untreated control (Degryse et al. 2017). Similarly, in studies conducted in Brazil using soils from Brazil and the United States, mobility of P from three small struvite granules was less than from a MAP granule (do Nascimento et al. 2018). However, as mentioned previously, in other studies, if struvites are ground and mixed through the soil, yield and P uptake can be similar to that of the MAP (Degryse et al. 2017).

Struvite would presumably be similar in effectiveness to soluble fertilizers once it dissolves, but the time to reach near-complete dissolution may range from days to years depending on fertilizer, soil and plant properties (Degryse et al. 2017). Large granule size, high excess base content, and high pH would slow the dissolution (Degryse et al. 2017; Everaert et al. 2017). Plant roots would also affect the dissolution rate though uptake of P and by modifying the chemistry of the rhizosphere. In laboratory assays, the initial rate of dissolution of a commercial granular product and the equilibrium concentration of P in the solution was increased by adding organic acid anions to the buffered solutions (Talboys et al. 2016). In subsequent pot experiments using a P-deficient soil collected in Wales, buckwheat (*Fagopyrum esculentum* L.) a plant that exudes a high amount of organic acids, absorbed similar amounts of P from struvite and DAP. In contrast, wheat, which does not exude many organic acids, had plant P uptake from struvite that was only about 30% as much as from DAP. Early season uptake of struvite was lower than uptake from DAP but blending mixtures of struvite and DAP where struvite was no more than 20% of the blend provided comparable levels of P uptake to the full DAP treatment. Therefore, blending some struvite with more soluble traditional P sources may be able to supply enough P for early crop growth but also provide a slow release source that will release P throughout the growing season.

Layered double hydroxides - Layered double hydroxides (LDH) are inorganic anion exchangers, typically consisting of layered hydroxides of divalent and trivalent cations that hold anionic species in the interlayer galleries and at the outer surface of the crystallites by competitive electrostatic interactions (Everaert et al. 2017). They are highly selective for HPO_4^{2-} anions and have been suggested as a mechanism to remove P from waste streams. The P-exchanged layered double hydroxide that is recovered from the waste stream has potential as a slow release P fertilizer (Everaert et al. 2017; Everaert et al. 2016). In a neutral or alkaline soil, ion-exchange of the interlayer or surface bound HPO_4^{2-} will allow LDH to release P slowly into the soil solution, while in an acid environment, there may also be phosphate release by dissolution of LDH. Phosphorus uptake by barley from an LDH powder treatment on an acidic soil from Kenya was up to 4.5 times greater than from a soluble KH_2PO_4 treatment, likely because of a beneficial liming effect from the LDH. In a calcareous soil from Spain, P uptake by barley from the LDH was less than from KH_2PO_4 at the higher P rates and similar at low P rates (Everaert et al. 2016). In subsequent studies using two Australian soils, when granulated forms of the LDH were evaluated in pot trials with wheat, the granular product produced lower crop yields and P uptake than did granular MAP due to slow dissolution or P release from the SRF granules (Everaert et al. 2017). As in Everaert's previous experiments with LDH and KH_2PO_4, when the LDH was applied as a powder, its agronomic performance was much better than in the granular form, slightly better than MAP on an acid soil, possibly because it had a liming effect, but slightly worse than MAP on an alkaline soil. All of the powdered fertilizers produced less P availability than granular MAP, with the advantage of the granular P likely related to more precise placement of the fertilizer granule close to the seed. The agronomic performance of LDH in soils from the Northern Great Plains is not known.

Humic Acids - Although they are not considered direct sources of P, humic and fulvic acids (HA and FA) have been investigated as substances to increase P availability by supplementing the organic acid content of the soil to slow the precipitation of sparingly soluble calcium phosphates (Delgado et al. 2002). In laboratory incubation studies, a mixture of humic and fulvic acids (HFA, which contained 11% HA and 4% FA) was applied at 0, 1, 2, and 5 g/kg to six calcareous soils with different levels of salinity and Na saturation (these rates of application were equivalent to approximately 0, 2000, 4000, and 10,000 lb of product per acre to a 6 inch depth of topsoil).

The soils were then fertilized with 200 and 2000 mg P/kg soil as MAP (Delgado et al. 2002). The recovery and forms of P were studied after 30, 60 and 150 days, using sequential chemical fractionation and ^{31}P NMR spectroscopy. Application of the HFA increased the amount of applied P recovered as Olsen P in all the soils except the soil with the highest Na saturation. The HFA appeared to inhibit the precipitation of poorly soluble Ca phosphates, with the ^{31}P NMR spectra showing reduced formation of apatites and more formation of amorphous Ca phosphate and dicalcium phosphate dihydrate (DCPD). The increase in the recovery of applied P due to HFA shows that application of organic matter soil amendments may improve the efficiency of P fertilizers and may also explain how manures and other organic amendments that contain P can be more efficient than inorganic P fertilizers in increasing available P in calcareous soils.

While humic acid supplements have shown promise in some laboratory incubation studies, benefits have not been consistent, especially in pot or field studies. Laboratory studies using soils from Brazil and the United States showed that mobility of P from humic-acid coated MAP was lower than from uncoated MAP on soils with a high Fe content, but did not affect mobility in the other soils tested (do Nascimento et al. 2018). A three-year field study conducted on calcareous low organic matter soils at University of Idaho to investigate application of low rates of humic acid to liquid P bands in potatoes showed a tendency for increased petiole P and higher yields of large no. 1 tubers compared to liquid P alone (Hopkins and Ellsworth 2005; Hopkins and Stark 2003). In contrast, lysimeter measurements of soluble P near a simulated fertilizer band was not affected by treatment of MAP fertilizer with one of two humic acid products on either a calcareous silty clay loam or a noncalcareous sandy loam soil collected from Montana fields through most of a 48-day incubation period (Jones et al. 2007). The second product in the Montana study increased the soluble P concentration 1.5 inches (3.8 cm) below the band in the calcareous soil at 16 and 32 days, indicating that the second product may have increased P solubility. The rates of HA used in the Montana study were about 100 to 300-fold lower in the area around the band than those used in the incubation study by Delgado et al. (2002) discussed previously. Pot studies using the same two Montana soils showed that additions of low rates of two humic acid products did not improve use of phosphate fertilizer or increase yield of spring wheat on either a calcareous or non-calcareous soil (Jones et al. 2007). The lack of response at low rates of HA application may indicate that HA may only be effective at high rates of application.

Leonardite, an oxidized form of lignite that overlies the more compact coal in coal mines, is a rich source of humic acid (Akinremi et al. 2000). Rather than being viewed as a P source, it has been suggested that as an organic amendment, it may increase the availability of P and other nutrients, particularly on low organic matter soils. In greenhouse trials at the University of Manitoba, leonardite did not provide a benefit for wheat or green beans, crops that have a lower S requirement than canola. However, the dry matter yield and uptake of N, P, K and S for canola, a crop with a large requirement for S, was increased by the application of leonardite as an indirect result of the influence of S supplied by leonardite. Both the dry matter yield and the nutrient concentrations of canola increased with increasing rates of leonardite, indicating that nutrient uptake by canola was facilitated at high rates of leonardite. However, there was no response to leonardite observed if N and P were not applied as well, or if S was applied, indicating that the response to leanardite was an S response that required an S deficiency and an adequate supply of other nutrients to occur.

Ash - Gasification is used for disposing various types of organic waste, including bone meal, meat and dried distillers grain (Alotaibi et al. 2013). The resulting ash is rich in P and may be suitable for use as a P fertilizer. Growth chamber studies in Saskatchewan evaluated the effect of meat and bone meal ash and dried distillers grain ash as compared to MAP as a P source for canola (Alotaibi et al. 2013). The ash from the distillers' dry grain was an effective P source and produced a yield response similar to equivalent rates of MAP, while the meat and bone meal ash was less effective.

Wood ash, a by-product of the forestry industry, can be used for land application, largely as a liming material due to its very high pH (Arshad et al. 2012). Wood ash varies widely in mineral composition but can contain significant amounts of P (Vance 1996). The solubility and availability of the P in wood ash may be low and contribution of wood ash to crop uptake of P will reflect the concentration in the ash, the solubility of the P present and the impact of pH-induced changes in soil nutrient availability. In studies in northern Alberta, application of wood ash to an acid soil at liming rates increased crop yield more than application of lime (Arshad et al. 2012). Extractable P was higher in the top 2 inches (5 cm) of the wood ash treated soil than in the lime-treated soil, but the two treatments did not differ in crop P uptake. While wood ash may serve as a source of P, the major benefit appears to be in improving crop growth and P availability through alleviation of soil acidity.

Biochars - In many soils around the world, including Chernozemic soils in the Northern Great Plains, carbon residues from natural or human-initiated burning events can make up a substantial proportion of the soil carbon (Atkinson et al. 2010; Schmidt et al. 1999). This carbon contributes to the nutrient and water-holding capacity of the soil. Application of biochars to soils is being investigated as a way of using waste biomass to sequester carbon and improve soil quality.

Biochars are highly condensed carbon products formed from pyrolysis through the incomplete burning of biomass at low levels of oxygen (Atkinson et al. 2010; Solaiman et al. 2019). The C compounds in biochars are highly stable and can remain in the soil for decades to centuries, improving soil physical, chemical and biological quality. Biochars were historically used to improve soil quality on low organic matter soils, providing a great benefit in tropical soils such as the "Terra preta" in the Amazon basin (Atkinson et al. 2010; Cunha et al. 2009; Glaser et al. 2001). Biochars can also contain varying amounts of nutrients, including P (Atkinson et al. 2010; Solaiman et al. 2019). Conversion of biomass to biochar will increase the proportion of P in the material.

Greenhouse studies using a 1% addition of biochars produced from different feedstocks showed that biomass production and P uptake of wheat was positively correlated with the P concentration of the biochar (Solaiman et al. 2019). However, biochars may also influence P availability through effects on pH, microbial activity, anion exchange capacity and the activity of other cations that affect P availability (Atkinson et al. 2010). While the benefits of biochar application have been demonstrated on many low organic matter tropical soils, relatively little research has been conducted on temperate soils that are naturally higher in soil organic matter (Atkinson et al. 2010; Hangs et al. 2016). Greenhouse studies in Saskatchewan evaluated the effect of biochar produced from willow feedstock applied at 2 % w/w; incorporated within a 10-cm depth, on a black and a brown Chernozemic soil (Hangs et al. 2016). Effects on pH were minimal but biochar increased the CEC by ≈13 %, water holding capacity by ≈16 % and porosity by ≈11 % while decreasing bulk density by ≈11 % and water-filled pore space by ≈15 %. These improvements in soil quality could indirectly influence P dynamics.

6.4 Microbial Products

Penicillium bilaiae and mycorrhizal inoculants are the two major types of microbial products that are marketed in the Northern Great Plains to improve P availability.

***Penicillium bilaiae* -** *Penicillium bilaiae* has been sold in the Northern Great Plains as an inoculant to improve the availability of soil P. It is a fungus that occurs naturally in agricultural soils and is said to improve P availability by secreting organic acids that can solubilize P. It is also referred to in the literature as *Penicillium bilaii* or *Penicillium bilaji*.

Laboratory and greenhouse studies have shown enhanced P uptake with the use of P. bilaiae (Kucey 1988; Kucey and Leggett 1989). Other *Penicillium* species have also been shown to have P-solubilizing effects (Wakelin et al. 2007; Wakelin et al. 2004). Studies on field peas in Saskatchewan and Alberta showed that P. bilaiae increased root growth and P concentration in the tissue in one site-year on P-deficient soils, possibly because of the effect of the fungus in stimulating root growth (Vessey and Heisinger 2001). In greenhouse studies with wheat, *P. bilaiae* increased solubilization of inorganic P and increased the amount of P in solution through a decrease in the solution pH (Asea et al. 1988). The improved P supply led to an increase in wheat dry matter yield and P uptake. In nutrient solution studies, neither P nor *P. bilaiae* influenced the root length or mean root diameter of field pea roots, but the proportion of the root with root hairs was higher with inoculation (Gulden and Vessey 2000). The differences in root morphology and the stimulation of P uptake were related.

In studies conducted under field conditions on the Northern Great Plains crop yield responses to use of P. bilaiae have been mixed. Some field studies have shown a benefit from *P. bilaiae.* A total of ten field trials were established throughout the major alfalfa-producing regions of Saskatchewan in 1994 to determine the effects of inoculating alfalfa seed on the early season vegetative growth and P uptake, and forage yield response of alfalfa over a range of soil and climatic conditions (Schlechte et al. 1996). Increased alfalfa dry matter production, P uptake, and forage yield responses occurred following inoculation with *P. bilaiae*, most likely due to increased P availability from the solubilization of otherwise unavailable soil P (Beckie 1997; Beckie et al. 1998). In subsequent alfalfa trials in Saskatchewan, the *P. bilaiae* treatments generally did not increase, and in some cases seemed to decrease, biomass yield, although in one site application of *P. bilaiae* + 20 kg P_2O_5 increased yield (Farden and Knight 2005).

Field studies with annual crops have also shown inconsistent benefits to use of *P. bilaiae*. In nine site-years of a study with wheat in Manitoba and Alberta, there was no significant increase in grain yield due to use of *P. bilaiae* (Grant et al. 2002). In 47 site-years of experiments with hard red spring wheat across western Canada, yield increases with fertilizer P occurred in 33 site-years, while there were five increases in yield and nine decreases in yield with *P. bilaiae* inoculation (Karamanos et al. 2010). These responses could not be attributed to extractable P soil concentration, soil organic matter or texture, or weather conditions and were considered random events. In studies conducted at four sites in North Dakota, fertilization with P consistently enhanced early season growth, main stem development, tillering and P uptake while seed inoculation with *P. bilaiae* had little or no effect on these measurements (Goos et al. 1994). Grain yields were significantly increased by P fertilization and by *P. bilaiae* inoculation at one site. The reason why *P. bilaiae* inoculation increased yield at this location is not evident, as it did not increase plant growth and P uptake earlier in the season. Averaged across all four sites, *P. bilaiae* inoculation increased wheat yields by 1 bu/acre (66 kg/ha) (Goos et al. 1994).

In studies in Manitoba and Saskatchewan, *P. bilaiae* had small and infrequent effects on early-season plant P uptake, seed yield, and seed P concentration and content of canola (Mohr et al. 2013). Inoculation with *P. bilaiae* produced a small increase in early season P concentration in 4 of 9 site-years, but increased canola yield in only one site-year and decreased canola yield in one site-year while P application increased canola yield in 6 of 9 site-years (Mohr et al. 2013). Phosphorus fertilizer application generally resulted in comparatively more consistent and marked increases in early-season P uptake, yield, and seed P concentration and content. Similarly, there was no yield benefit of using *P. bilaiae* on flax in nine site-years of field studies in Manitoba (Grant et al. 2005; Grant et al. 2000). Field trials have demonstrated no consistent effects of *P. bilaiae* on the growth, development and seed yield of lentil in field trials in Saskatchewan (Gan et al. 2005). Studies on corn and winter wheat in Kansas also showed no benefit to the use of *P. bilaiae* when applied with or without P fertilizer (Ward 2010). Therefore, it appears that *P. bilaiae* is unreliable as a method of improving P nutritional status of crops on the Northern Great Plains.

Mycorrhizal Inoculants - Another class of microbial product being marketed on the Northern Great Plains is mycorrhizal inoculants. Mycorrhizal fungi form associations with the roots of many plants (Grant et al. 2005). Mycorrhizae play a key role in the soil microbial community and are of great importance to a wide range of domestic and wild plant species (Dai et al. 2014; Hamel 2004; Hamel et al. 2014; Hamel and Strullu 2006; Miller 2000; Miller et al. 1995). The plant provides photosynthate to the fungus and the fungus provides nutrients and possibly water to the plant. The external hyphae of arbuscular mycorrhizal fungi (AMF) extend from the root surface to the soil beyond the P depletion zone and so access a greater volume of undepleted soil than the root alone (Grant et al. 2005). Some hyphae may extend more than 10 cm from root surfaces (Jakobsen et al. 1992) which is a hundred times further than most root hairs. The length combined with the small diameter of hyphae (20–50 μm) allows the root-mycorrhizal system to access soil pores that cannot be explored by roots alone. Therefore, a root system that has formed a mycorrhizal network will have a greater effective surface area to absorb nutrients and explore a greater volume of soil than nonmycorrhizal roots. Mycorrhizae are naturally present in soils and extremely important in natural ecosystems, but their populations can be reduced by summer fallow, excess tillage, P fertilization and growing a non-mycorrhizal crop such as canola or sugar beet (Gavito and Miller 1998a; Grant et al. 2005; McGonigle et al. 2011; McGonigle et al. 1999; Miller 2000; Miller et al. 1995; Monreal et al. 2011). Some crops such as corn or flax are more dependent on mycorrhizal associations than crops such as wheat or barley and can show a negative response when grown after a non-mycorrhizal crop such as canola (Bittman et al. 2006; Grant et al. 2009a; McGonigle et al. 2011; McGonigle et al. 1999; Miller 2000).

Inoculation with a mycorrhizal fungus may be able to increase mycorrhizal colonization, especially under conditions where the background level of mycorrhizal spores is low. 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 modest, at best.

In studies conducted in Saskatchewan, seed yield of N-fertilized barley increased substantially with application of triple superphosphate (TSP) on a P-deficient soil, but there was only a slight increase in yield from application of an AMF inoculant (Malhi et al. 2014). Similarly, field trials conducted over three years at two locations near Brandon, MB and one near Lacombe, AB, assessed the effects of combinations of AMF inoculant and APP on mycorrhizal colonization, wheat yield and P uptake (Grant et al. 2006). Mycorrhizal colonization of wheat roots was increased by application of a mycorrhizal inoculant but biomass production was reduced and grain yield generally unaffected by inoculation (Grant et al. 2006). Grain yield tended to be greater when P fertilizer was used alone than when mycorrhizal inoculant was used alone. Effect of inoculant when applied with P fertilizer varied, causing increased yield at some sites and decreased yield or no effect at others. Decreased yields from inoculation may have occurred because wheat did not require the mycorrhizal association to access adequate P, so colonization was detrimental to the plant (Dai et al. 2014; Ryan and Angus 2003; Ryan and Graham 2002). If there is no advantage to the plant from the mycorrhizal colonization, the fungus may depress yield potential by using the photosynthate of the crop.

The conditions historically used in plant breeding of wheat may have affected the response of wheat cultivars to AMF. Growth chamber trials were conducted in Saskatchewan to evaluate effect of soil P availability on AMF symbiosis in modern and historic wheat cultivars (Germida et al. 2001). At low P availability, historic cultivars had a higher level of AMF root colonization than modern cultivars, whereas at high P availability the modern cultivars were more extensively colonized. The AMF associated with historic cultivars could benefit the host plant through increased nutrient uptake, but the tissue P concentration and P uptake efficiency of the modern cultivar was higher, indicating that modern wheat cultivars were less dependent on AMF for P nutrition than were historic cultivars.

Crops such as corn, flax, or pulse crops that are dependent on AMF inoculation may be affected when soil levels of inoculum are reduced by tillage, fallow or crop sequence (Dai et al. 2014; Hamel et al. 2014). Growth chamber studies using soil containing native AMF and fertilized with 0, 5, 10, 20 ppm of added P evaluated the growth responses of lentil (*Lens esculenta* L. cv. Laird) and two wheat cultivars (*Triticum aestivum* L. cv. Laura and Neepawa) to *Glomus clarum*

NT4 (Xavier and Germida 1997). Lentil was more dependent on mycorrhizae than wheat and responded to an AMF inoculant for the soil receiving low rates of P fertilizer even in soil containing high concentrations of indigenous AMF. In outdoor container studies using four Saskatchewan soils transported and tested at four different locations, a commercial AMF bio-fertilizer was applied to field pea in the first year of the study and residual benefits were evaluated in a wheat crop the next year and a field pea crop the year after that (Islam et al. 2014). Inoculation increased the amount of mycorrhizal infective propagules present in all soil-climate combinations after the initial pea harvest, but there were no consistent residual benefits in the following two crops. Other growth chamber and field studies in Saskatchewan evaluated AMF colonization of flax roots and the effectiveness of AMF inoculants in improving flax P status (Walley and Germida 2015). Flax is a crop that tends to be reliant on mycorrhizal interactions (McGonigle et al. 2011). Flax typically supported a relatively high level of AMF colonization in both growth chamber and field studies, showing the importance of this association for flax nutrition and growth (Walley and Germida 2015). Application of the AMF inoculant containing a non-indigenous form altered the AMF root community composition, showing that the introduced AMF was able to compete with native AMF communities to colonize flax roots. Some growth parameters such as root growth, midseason biomass, or nutrient uptake improved with AMF inoculation in some instances, but the responses were not frequent or predictable and there were no significant seed yield responses in the growth chamber or field and no economic benefits for AMF inoculation.

Similar results occurred in a field demonstration at Indian Head, SK that failed to show any benefits to mycorrhizal inoculation for field pea, lentil or soybean (Holzapfel 2014). This demonstration was conducted following a spring wheat or barley host crop and in long-term no-till fields, factors that may encourage native AMF and so reduce reliance on and response to mycorrhizal inoculant (Gavito and Miller 1998b; Grant et al. 2005; McGonigle et al. 2011; McGonigle et al. 1999; Miller 2000; Miller et al. 1995; Monreal et al. 2011). Benefits for inoculation would be more likely to occur following non-host crops such as canola or summer fallow or when tillage disrupts mycorrhizal hyphal networks.

Another study in Saskatchewan examined inoculation of wheat, lentil, mustard and flax with commercial formulations of AMF and *P. bilaiae*, applied alone or in combination, for effects on seedling emergence, biomass production, and nutrient uptake on an organically managed soil and a conventionally managed soil (Knight 2011). When the inoculation treatments were applied at seeding, crops grown in the conventionally farmed soil were generally unresponsive to inoculation, except for lentil that showed increased yield and nutrient uptake with AMF inoculation. The lack of response of the other crops on the conventionally farmed soil could be because the nutrient content of the soil was higher than that of the organically farmed soil, so plants growing in the conventional soils were not nutrient limited. In the organic soil, biomass production of wheat and mustard in the year of inoculation increased with at least one of the inoculants and wheat showed higher nutrient uptake. Dual inoculation with the two organisms showed no advantage over single inoculation, and the two organisms were not complementary. Mustard showed a response to AMF inoculation, which was unexpected since mustard does not form mycorrhizal associations. In mustard, nutrient uptake was not affected so it may be that the

AMF had an indirect effect on other soil microorganisms that affected overall growth. Flax grown in the organic soil was unresponsive to inoculation with either organism, showing no difference in productivity or nutrient uptake. Lentil grew poorly in the organic soil and showed low AMF associations with colonization, which was approximately 1/3 of the colonization observed in the conventional soil. The lower colonization in the organic soil was reflected in the overall poor growth and low nutrient uptake. There was some carry-over of the inoculant effect into the second crop grown after inoculation, especially for wheat grown after flax or lentil but not mustard. Mustard also showed higher biomass and nutrient uptake from inoculant carryover when grown after lentil and wheat. Lentil also showed improved growth and nutrient uptake from inoculation of the preceding crop. However, none of the crops showed carryover benefits from inoculation of the preceding crop when grown after mustard, presumably because mustard is not an AMF host crop, which indicates that the carryover effect will occur only if new spores are produced by the crop-fungal association.

While inoculation of crops with AMF spores may have small and infrequent benefits for field crops, the AMF association is important to many crops, including flax, legumes and corn. Therefore, management practices that encourage AMF, such as reduced tillage or rotations with mycorrhizal crops preceding mycorrhizal-dependant crops would likely benefit yield (Grant et al. 2009b; McGonigle et al. 2011; Monreal et al. 2011). Furthermore, although AMF clearly aid in P uptake, and uptake of P from fertilizer may be enhanced by AMF inoculation, the AMF populations provided by currently available inoculants may not be an improvement over a well-established and maintained native AMF 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.

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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. 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.

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.

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. 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.

Detailed Information

Phosphorus placement should be managed to ensure that the nutrient is available to the plant when required to optimize growth. In the northern Great Plains, many of the soils have a high pH, with the exchange saturated by calcium and magnesium. Phosphorus will react with the calcium and magnesium present in these high pH soils to form sparingly soluble calcium and magnesium phosphate compounds. These calcium and magnesium phosphates are less available to the plant than the fertilizer and become increasingly less available over time. On acid soils, similar retention reactions occur, but with iron and aluminum. Due to these reactions, P is relatively immobile in the soil and so remains near the site of fertilizer placement (Kar et al. 2012). Phosphorus does not move readily with water, so will not readily move towards roots via mass flow. It also will generally not leach from surface applications deeper into the soil, especially in dry regions such as the Northern Great Plains. Therefore, fertilizer P should be placed under the soil surface in a zone where the soil is moist and the roots are active. Placing the fertilizer below the soil surface avoids the risk of stranding the fertilizer in dry soil at the surface and reduces the risk of erosion or run-off losses. Phosphorus fertilizer should be placed in a position in or near the seed-row, where it will be accessed by the plant during early growth, when it is required to establish crop yield potential. Band placement can also minimize the contact between the soil and the fertilizer material to minimize the retention of the fertilizer and keep it in an available form to allow greater crop uptake.

While foliar placement of P is possible, in most cases P fertilizer is most efficient and effective if it is soil-applied, where the placement options can be broadly divided into broadcast and banded applications.

7.1 Efficiency of Band versus Broadcast Application

Broadcast application is the simplest form of P fertilization. It is rapid and does not require highly specialized equipment. Broadcast P is spread on the soil surface and may or may not be subsequently incorporated through a tillage operation. Broadcast and incorporation of P fertilizer distributes the P relatively uniformly through the surface soil. It provides a large zone of fertilized soil and maximizes contact between the P fertilizer and the soil. There is little chance of significant P fertilizer injury to the seedling from broadcast, incorporated P fertilizer, but because of the high degree of contact between the fertilizer and the soil, P retention may also be high. 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 for perennial crops such as forages. On low P-testing sites in Minnesota, corn and soybean yields were generally increased more by a 100 lb P_2O_5/acre broadcast P treatment than by 50 lb P_2O_5/acre starter or deep-banded treatments, suggesting that band applications at a half rate are usually not sufficient to meet crop requirements for P in low to very low P-testing soils (Randall and Vetsch 2004). The broadcast application in corn also provided residual benefits to the following soybean crop. Broadcasting higher rates of P provided a greater economic return on the low-testing soil than using only lower starter or deep-banded applications.

However, broadcasting P fertilizer, especially without incorporation, can be environmentally harmful because it leaves soluble P at the soil surface, leading to a high risk of movement of P into water-bodies (Smith et al. 2016).

Band applications place the fertilizer in narrow zones, usually below the soil surface, that provide a concentrated source of P. Reactions of the soluble P from the fertilizer with soil constituents restrict the movement of the P, leading to a high concentration of P near the point of application that decreases with distance from the band (Kar et al. 2012). Band applications may be placed any time before planting, at the time of planting, or after planting. Unless the narrow bands are disturbed by tillage, they remain intact through the growing season. Fluid sources may be dribble-banded on the soil surface. Under no-till systems or with perennial crops, the bands may remain intact over several years, because of low or no disturbance of the soil by tillage. By placing the fertilizer in a concentrated region where the reaction zones of the individual granules or droplets overlap, the contact between the fertilizer and the soil is minimized, reducing the retention of the fertilizer by the soil constituents. Therefore, banding can maintain the fertilizer in a plant-available form for longer than a broadcast incorporated application, particularly on soils with a large capacity for P retention (Fixen 1992). Banding also enables precise placement of P fertilizer in or near the seed-row, in the optimum position for early season uptake by the crop. A meta-analysis of studies on fertilizer placement described conditions where banding of nutrients would be more beneficial than broadcast application (Nkebiwe et al. 2016). That analysis determined that banding was beneficial for nutrients such as P that are required in large amounts by plants and that are relatively immobile in the soil.

The benefit of reducing retention may be counteracted to some degree by the reduction in the volume of the soil that is fertilized, as this decreases the size of the region that may be accessed by roots (Barber 1958; Claassen and Barber 1976). However, many plants can proliferate their roots (i.e., intensify their root growth) when they contact a concentrated source of P such as a fertilizer band, allowing the plant to effectively extract the P from the band (Strong and Soper 1974a). Uptake of P by roots is proportional to both the concentration of the P at the root surface and the area of absorbing root surface that contacts the P, so the combination of root proliferation in a zone of high P concentration increases the ability of the plant to take up P. In a meta-analysis of studies of banding versus broadcast application of nutrients, banding was beneficial with formulations that increased rooting in the band, so including modest amounts of ammonium or ammonium-producing fertilizers within the P band improves the P fertilizer's effectiveness (Nkebiwe et al. 2016).

Placing the fertilizer in a band below the soil surface, in or near the seed-row may give the crop a competitive advantage against weeds for P uptake, because many weeds are shallow-rooted (Blackshaw and Brandt 2009; Blackshaw et al. 2004). Also, as roots cannot take nutrients up from dry soil, placing the band in a position where the soil does not dry out early in the season avoids having the fertilizer "stranded" in the dry soil at the surface, where the roots cannot use it. Therefore, placement of the P deeper in the soil may keep the P fertilizer in moist soil for longer in the growing season than with surface application. In a reduced tillage system, where soil mixing is minimal, stratification of P may occur, where the P accumulates near the soil surface at the depth of placement (Grant and Bailey 1994). This stratification is accentuated by broadcast applications. Residual P in the fertilizer bands may lead to problems in soil testing, since it makes it difficult to get a representative soil sample (Kitchen et al. 1990). But, retention of intact bands may improve the long-term availability of P fertilizer under reduced tillage. Placement of fertilizer in bands below the soil surface also reduces the accumulation of P at the soil surface, lowering the risk of P movement off-field to sensitive water bodies (Li et al. 2011; Smith et al. 2016).

Band applications of P are generally more efficient than broadcast applications of P when soil levels of P are low. In studies in Saskatchewan, broadcast applications of P at 40 or 80 lb P_2O_5/acre (20 or 40 kg P/ha) were ineffective at increasing winter wheat yield, while seed-placed and mid-row banded P at the same rates provide a yield benefit (Campbell et al. 1996). Banding provides the maximum agronomic benefit per unit of fertilizer applied under such conditions. In studies in Alberta, P banded with or near the seed of barley gave higher yield increase than P incorporated into the soil, while with rapeseed, the method of P placement had no effect on yield response (Malhi et al. 1993). In field studies conducted on two durum wheat cultivars over three years at two sites in Manitoba, grain yields on a clay loam soil increased with P application of 45 or 90 lb P_2O_5/acre (22 or 45 kg P ha) in each year, with banded applications being more effective than broadcast application where differences between the two placements occurred (Grant and Bailey 1998).

Field studies in Manitoba with rapeseed showed banding or seed-placement of MAP with rapeseed gave higher seed yield than broadcast application across a range of application rates on both a calcareous and non-calcareous soil (Bailey and Grant 1990). Banding 20 lb P_2O_5/acre (10 kg P/ha) near or with the seed produced seed yield and P uptake equivalent to broadcasting 50 lb P_2O_5/acre (25 kg P/ha). A recent one-year study near Swift Current, SK found that side-banded P at 22 lb P_2O_5/acre (11 kg P/ha) gave higher stand density and yield of canola than broadcast P at 22 or 50 lb P_2O_5/acre (11 or 24 kg P/ha) (Wheatland Conservation Area 2018). In Alberta, seed-placement or side-banding was the most effective method of applying phosphate fertilizer for both fall and spring seeded canola (Karamanos et al. 2002).

The advantage of band-placement over broadcast tends to decrease as soil test P levels increase or as the rate of application increases. In field studies in Minnesota, application of starter P in a band near the seed-row was important for optimum corn yield on low testing soils, with seed-placed P resulting in greater yields than deep-banded or broadcast applications (Randall and Vetsch 2004; Randall and Vetsch 2008). However, corn yield was not affected by P placement on high and very high soil test P soils. In studies in Kansas and Nebraska, band applications of low rates of P (<45 lb P_2O_5/acre or 22 kg P/ha) were more effective than broadcast P for increasing yields of winter wheat in the year of application (Halvorson and Havlin 1992a). However, as the rate of application increased, differences between placement decreased. In a medium testing soil in Colorado or under no-till management, Halvorson and Havlin (1992) found no effect of placement of superphosphate (broadcast incorporated, broadcast, or side-banded at seeding) on winter wheat in a wheat-fallow rotation, although yield increased with increasing P rates from 0 to 270 lb P_2O_5/acre (0 to 134 kg P/ha) (Halvorson and Havlin 1992b).

Conversely, in winter wheat studies on a Brown Chernozem in Southern Saskatchewan using chemical fallow, seed-placed or mid-row banded MAP at 40 lb P_2O_5/acre (20 kg P/ha) produced higher yields than broadcast P under moist conditions in one of three years, but not under dry conditions (Campbell et al. 1996). In later studies in Saskatchewan, in-soil placement of P produced higher soybean yield than did broadcast P on a low-fertility soil (Weiseth 2015), but there was no response of canola yield to P placement on a high P fertility soil (Wiens 2017).

A review of placement methods for P also indicated that at high soil test levels, crop yield response differences due to placement methods are rare (Randall and Hoeft 1988). That review determined that, at low soil test levels, corn yields were generally greatest with a band placement that was 2 inches beside and 2 inches below the seed-row (2x2 in. sideband). Surface strip and deep subsurface bands (6 to 8 inches below the surface) were generally superior to broadcast applications, particularly in dry years, for soils testing low in P or when reduced tillage was used. Small grains also tended to respond better to seed-placed and banded applications than to broadcast applications, especially under dry conditions. In contrast, soybean generally responded better to broadcast than banded applications. Studies in Iowa also evaluated the effect of banding as compared to broadcast applications of P fertilizer in soybean and found that placement of P did not affect crop yield or early season growth, although early season uptake of P was greater with band than broadcast application (Borges and Mallarino 2000).

Effects of banding versus broadcasting have also been evaluated in perennial forage crops. Under the dry conditions near Swift Current, banding P fertilizer into established alfalfa stands led to root damage that decreased yield for 2 years after application, indicating that broadcasting was a better choice than banding for established alfalfa stands under these conditions (Leyshon 1982). A four year field experiment on a highly P-deficient Black Chernozem soil near Ponoka, Alberta compared the yield response of an established alfalfa stand to surface broadcasting versus subsurface banding annual applications of 20, 40, 60 and 80 lb P_2O_5/acre (10, 20, 30 and 40 kg P/ha) or one-time initial applications of 100, 200, 300 and 400 lb P_2O_5/acre (50, 100, 150 and 200 kg P/ha as TSP) (Malhi and Heier 1998). Phosphorus increased yield in all four years, with the highest yield occurring with banding rather than surface broadcasting, whether the fertilizer was applied annually or only at the start of the study. With annual applications, the greatest increase in yield occurred with the first 40 lb P_2O_5/acre, although yield continued to increase to the 80 lb P_2O_5/acre rate if the fertilizer was banded, but only to 60 lb P_2O_5/acre if it was broadcast. With the single application, there was only a minor increase in yield between 300 and 400 lb P_2O_5/acre if the fertilizer was banded, but yield increased substantially between these two rates if the fertilizer was broadcast. Banded application was used more efficiently than broadcast application and lower rates were required to produce a similar yield with banded as compared to broadcast application.

Other studies in Alberta evaluated the response of alfalfa to P fertilizer banded or broadcast, either once at the time of establishment or each year (Malhi et al. 2001b). Banding was consistently more effective in increasing forage yield and phosphorus use efficiency than was broadcast application, especially at low rates of application with both the annual and one-time application. The differences between banding and broadcasting were generally greater at lower than at higher P rates. In contrast, in studies on established alfalfa in Manitoba, broadcast P performed as well as or better than banded P on a clay loam and sandy loam soil (Simons et al. 1995). Differences between the Malhi study and the Simons study may relate to moisture conditions or to the fact that the Simons study was in an established stand and the Malhi study began when the alfalfa was seeded, so Malhi's study was in a newly established stand. A study in Alberta with bromegrass *(Bromus inermis* Leyss) also showed that banding P at establishment led to greater increases in yield than broadcasting, but that once the stand was established, annual broadcasting of P led to greater yields than annual banding (Malhi et al. 2001a).

Band placement is most important for small seeded crops in short season growing regions such as the Northern Great Plains, because these crops are sown into cooler soils and because they have less of a chance to recover from early season P deficiencies than in warmer, longer growing season areas (Fixen 1992; Grant et al. 2001). On cold soils, band applications may be beneficial, especially if placed in or near the seed-row, because the low temperatures will reduce the solubility and mobility of P in the soil and the rate of root growth, restricting the ability of the seedling to access the P required for early plant establishment (Grant et al. 2001). At the same time, cold conditions will reduce the speed of reaction of the fertilizer P in the soil, keeping the fertilizer P in an available form for longer than under warm conditions (Sheppard and Racz 1984a). Several studies from both the United States and Canada looked at the combined effects of banding starter P with the seed superimposed over residual effects of large broadcast applications of P fertilizer over multiple years after broadcast fertilizer application (Alessi and Power 1980; Bailey et al. 1977; Read et al. 1977; Read et al. 1973; Wagar et al. 1986). The studies generally showed that long-term benefits from residual P applied in previous years persisted for at least 6 to 8 years. However, an additional effect of starter fertilizers superimposed over the residual P was often observed, indicating potential benefits of starter P on the cold soils of the Northern Great Plains (Alessi and Power 1980). On very low-P soils, broadcast-incorporation of high rates of P to build the background P levels combined with low rates of starter P placed in or near the seed-row may provide the greatest yield benefit, particularly on the cold soils of the Northern Great Plains (Figure 1). Cold soils may be more common under reduced tillage, where the soil is slightly slower to warm in the spring and where bulk densities in the soil surface may be greater than in soils that were recently tilled in the fall or spring (Grant and Lafond 1993).

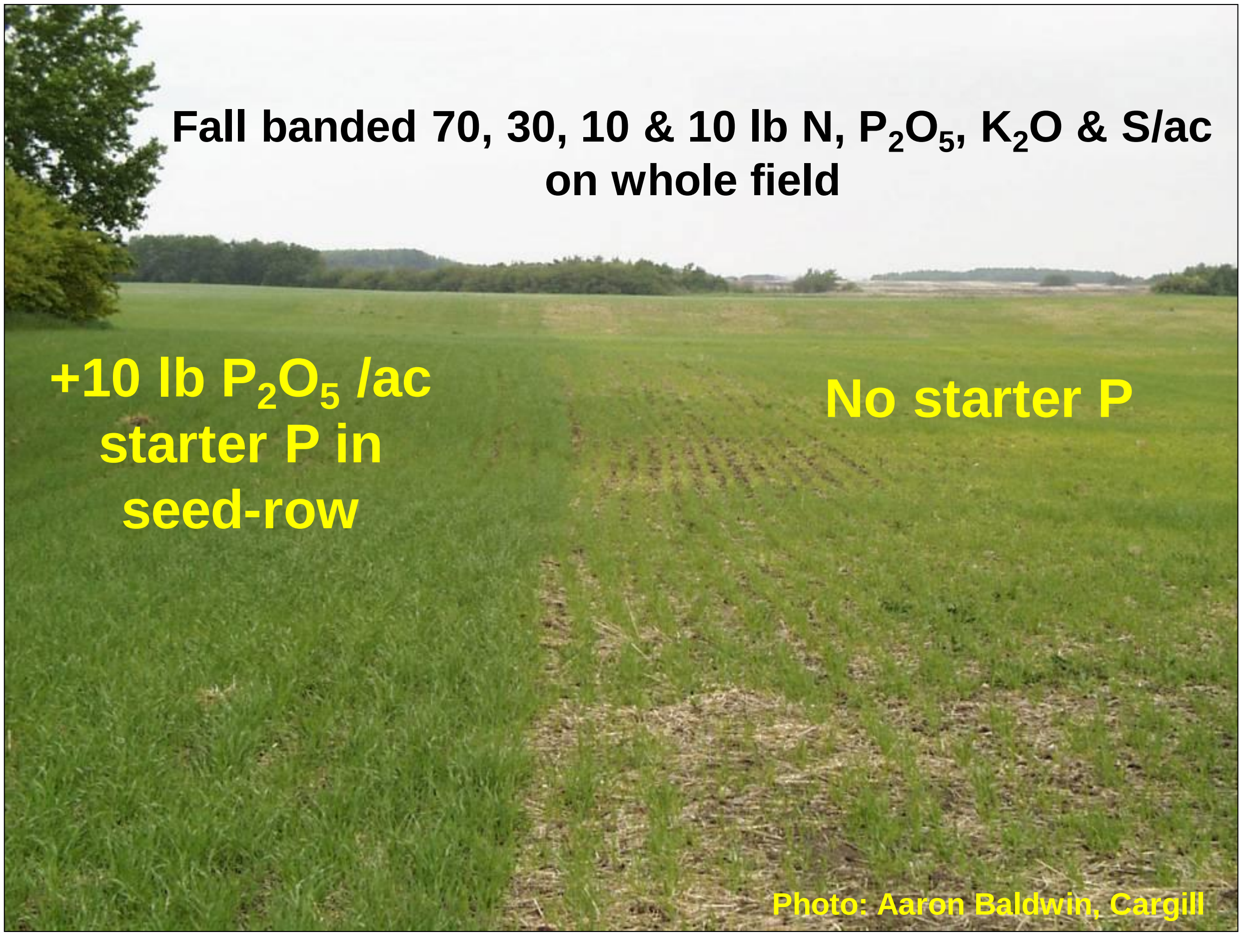

Figure 1. Placement of P in or near the seed-row can improve early growth on cold soils, as shown in this picture of starter P response in Saskatchewan. On the left, a low rate of starter P was applied in the seed-row during spring seeding; both areas of the field received a fall banded application of 30 lbs P_2O_5/acre.

7.2 Effect of Band Position

In a one-pass seeding and fertilizing operation, phosphorus fertilizer can be band applied precisely 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. 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.

If the concentration of plant-available P in the soil is low, the seedling may not be able to access enough P from the soil to satisfy its early season demand, and the plant will need to access the P from the fertilizer band early in the growing season to ensure optimum growth (Grant et al. 2001). Under these conditions, the fertilizer must be placed in a position where the plant roots can contact it during early plant growth, since P is generally immobile in the soil. Placing the P in a band close to the seed allows the young root system to access the band early in the season (Kalra and Soper 1968; Soper and Kalra 1969).

Conversely, if soil test P levels are moderate to high, the germinating seeding may be able to access enough P from the seed reserves and the soil P to optimize early season growth. In that case, the precise position of the bands may not be as important as on soils with very low reserves of plant-available P. As a result, mid-row or deep-placement of P may also be effective in maintaining crop yield when soils are not excessively low in available P. In studies with winter wheat in Saskatchewan, yields were similar when P was seed-placed or mid-row banded on soils with moderate levels of P (Campbell et al. 1996).

Year to year and site to site variability in soil temperature and moisture conditions can also influence the performance of different P placement methods. In a 12 year trial at the Ellerslie Experimental Farm in Alberta, the effects of 36 lb P_2O_5/acre, placed either in the seed-row, or dual banded with N at a depth of 7.5 to 10 cm depth or 15 to 17.5 cm, or split between the seed-row and dual bands, with half applied in the seed-row and half placed in the dual band, were compared for their effects on canola and barley yield (Karamanos et al. 2008). When temperatures in the month after seeding were cool, seed-row placed P produced higher crop yields, but when temperatures were warmer than normal, dual-banded P produced higher yield. Barley yield was generally greater with shallow than deep banding, related to the cool soil temperature. Deep placement was only superior to shallow placement in the one year of the study where canola was seeded late in the season, when temperatures were higher than normal, and precipitation was well below normal. A four-year field study near Melfort, SK compared deep-banded to seed-placed P in canola and wheat (Nuttall and Button 1990). With wheat, the two placements generally produced similar yield; with canola, seed-placed P produced higher seed yield than deep-banded P in one year when conditions were dry and soil test P level was very low. The results of this study confirm the idea that placement of P in or near the seed-row is important with cool temperatures and that dual-banding the P away from the seed-row can be effective under warm, dry conditions. When surface soils are dry, deep placement of P into moist soils, where roots are active, may avoid the issue of surface stranding of P (Fixen 1992).

A study in Alberta evaluated the response of canola, wheat and barley to P banded prior to seeding as compared to seed-placed phosphate on a wide range of soils (McKenzie et al. 1995). The seed-placed P fertilizer tended to produce higher yields than banded P at 33 of 55 sites that were responsive. Pre-plant banded P was superior to seed-placed P at only eight of the 55 sites and the responsive sites tended to occur where surface soils were drier. A long-term experiment to examine P fertilization effects on crop yield in a wheat–canola–triticale–pea–barley rotation under conventional and no-till/direct-seeding conditions was established in 1979 at the Breton and Ellerslie experimental farms in Alberta (Karamanos et al. 2013). Over the 20 years that barley was grown, yield increases were greater with seed-placed than mid-row banded P only under the direct-seeding system, while wheat, canola, triticale, and pea yield increases were greater with in-row than mid-row placement of P under both tillage systems.

Similarly and as mentioned previously, starter P fertilizer was extremely important for corn on low testing soils in Minnesota (Randall and Vetsch 2004). Yield response and economic return on the low-testing soil were lower with deep-banded P than with the starter P placed in the seed-row. However, on high-P soils, there was essentially no benefit of any form of P fertilization.

If the plant-available P in soil is very low, moving the banded P even small distances away from the seed-row may reduce access. Also, positioning the fertilizer in or near the seed-row is particularly important for crops such as flax, which have poorly developed root systems early in the growing season (Sadler and Bailey 1981; Sadler 1980; Strong and Soper 1974a). In Ontario studies, corn biomass yield and P concentration at the 4- to 5-leaf stage were increased by seed-placed, but not by side-banded P on soils containing 4 ppm Olsen P, although rates of side-banded P were 79 lb P_2O_5 per acre while the seed-placed rate was only 14 lb P_2O_5 per acre (Lauzon and Miller 1997). The biomass yield differential between placement methods persisted through the 6- to 7-leaf stage. By maturity, corn grain yield was slightly but non-significantly ($p<0.15$) greater with the high rate of side-banded P as compared to the low-rate of seed-placed P on the 4 ppm P soil, but was significantly greater with seed-placed fertilizer than side-banded when both were applied at a similar rate on a soil containing 17 ppm soil test P.

Greenhouse and field experiments in Ontario showed that alfalfa and bromegrass seedlings were better able to access fertilizer P when it was placed directly below the seed-row rather than displaced to the side by 3, 6 or 9 cm, because the roots did not access the P placed away from the seed row early enough in the growing season (Sheard et al. 1971). Field studies in Alberta showed that barley early season growth and final yields were generally greater when TSP fertilizer was placed in the row or 2.5 cm away rather than 5.0 cm away (Nyborg and Hennig 1969). At low rates (15 lb P_2O_5/acre or 7 kg P/ha), barley yield was greater from seed-row placement than if the fertilizer was placed 2.5 cm away. At 60 lb P_2O_5/acre (29 kg P/ha), yields were greater if the fertilizer was placed in the row or 2.5 cm below than if placed 2.5 cm to the side. Positional access will generally be greatest near the base of plant, where root density is highest, but optimal placement will differ with root geometry and response. For example, tap rooted crops may be more likely to intercept a band placed directly below the seed-row, while cereal crops that have a fibrous seminal root system may be able to readily intercept P banded below and to the side of the seed-row (Figure 2).

7.3 Seedling Toxicity Issues Related to Seed-Placed Phosphorus

While placement of P in the seed-row can be an effective method of placement to ensure early-season plant access to the fertilizer, many crops may experience seedling toxicity if the rate of application is too high (Grenkow 2013; Nyborg and Hennig 1969; Randall and Hoeft 1988; Swiader and Shoemaker 1998). The damage from P fertilizer is related both to salt damage from the dissolution of the fertilizer salt in the soil solution and to ammonia toxicity from the ammonium counterion that is usually applied with the phosphate.

The salt effect is related to the salt index of the fertilizer which is the effect that the fertilizer has on the osmotic potential of the soil solution (Rader et al. 1943). Growth chamber studies conducted in Minnesota using corn showed that damage to emergence and growth of corn from starter fertilizer was related to the salt index of the fertilizer multiplied by the rate of application

(Kaiser and Rubin 2013). A higher salt index produces a higher osmotic potential of the solution and a greater tendency to damage the emerging seedling. Osmotic damage occurs by reducing the ability of the crop to absorb water, so restricting germination and early growth. Very high osmotic potential may desiccate young roots. Superphosphate has a lower salt index than MAP and both have substantially lower salt indices than more soluble fertilizers such as potassium chloride, ammonium nitrate or ammonium sulphate. However, even TSP can lead to some delay in emergence with cereal crops as rates of application increase (Nyborg and Hennig 1969).


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Figure 2. Taproot of soybean (http://corn.agronomy.wisc.edu/Crops/Soybean/L004.aspx) on the left, as compared to fibrous roots of wheat seedling (http://agropedia.iitk.ac.in/content/wheat-root-system) on the right.

Ammonia in either the gaseous phase or the soil solution can lead to direct seedling toxicity, particularly affecting the metabolically active parts of the plant (Dowling 1998). Growth chamber studies in Australia ranked a range of crops for their sensitivity to MAP, DAP, TSP urea and ammonium nitrate, related to the ammonium level in the applied fertilizer (Dowling 1998). Urea and DAP produced greater reductions in crop stand than equivalent ammonium-N rates from MAP or ammonium nitrate. About 20 to 30% more ammonium was tolerated as MAP than as DAP. The risk from DAP is greater than from MAP because of the higher ammonium concentration and the increased pH associated with DAP prior to nitrification. As pH increases, the equilibrium between ammonium and ammonia shifts to favour ammonia formation, increasing its concentration and hence the risk of direct ammonia toxicity. Field studies on corn in Colorado indicated that damage from starter P applications was related to the N concentration of the starter material (Rehm and Lamb 2009). Similarly, field studies in South Dakota demonstrated that seedling damage in corn increased with the amount of N in the fertilizer, so that use of ammonium polyphosphate (APP, 10-34-0) led to less seedling damage than 9-18-9, due to the higher rates of N and K and the greater proportion of urea N applied with the latter fertilizer source, when both sources are applied at the same rate of P (Gerwing et al. 1996). The increased damage with higher N concentration in the P source would be a function of both the salt index and the production of ammonia by the fertilizer material.

Several factors influence the rate of fertilizer that can be safely applied with the seed. Any factor that affects the osmotic potential or the ammonia concentration at the seed will affect degree of seedling damage. Slowing the release of the fertilizer into the soil solution will lower the concentration and reduce both the osmotic potential and the ammonia concentration. Therefore, controlled release products can be less damaging than uncoated products at the same rate of application. The effect of a polymer coated controlled release MAP product and conventional MAP on seedling damage was assessed in greenhouse studies with ten different crops in Saskatchewan (Qian et al. 2005; Schoenau et al. 2005). The controlled release MAP greatly increased the tolerance to seedling damage in ten crops to high rates of seed-placed P, with rates of 70 lb P_2O_5/acre (35 kg P/ha) placed in the seed row producing no significant injury for most crops. Controlled release MAP also produced much less seedling damage than conventional MAP in growth chamber studies with canola in Manitoba (Katanda et al. 2019). Field studies in Manitoba also showed that the controlled release MAP product reduced the risk of seedling damage in canola as compared to use of MAP or APP (Grant 2011).

Soil characteristics will influence the toxicity of seed-placed fertilizer. Soil moisture will dilute the fertilizer, lowering the concentration in soil solution. Therefore, moist soils or rainfall received soon after seeding will decrease the degree of seedling damage. If ammonium is adsorbed by the soil, the concentration of ammonium in the soil solution will decrease, shifting the equilibrium between ammonium and ammonia in favour of ammonium and reducing the concentration of ammonia present. Therefore, risk of seedling damage is less on soils with a high cation exchange capacity (CEC) than soils with a low CEC. The CEC of a soil is high on soils with a high silt or clay content and also on soils with high concentrations of organic matter. Conversely, risk of damage is greater on coarse- than fine-textured soils, due to their low CEC and tendency to be drier, which would increase concentrations of both ammonia and salt in the solution. Therefore, risk of seedling damage is less on fine-textured and/or high organic matter soils than on coarse-textured and/or low organic matter soils (Dowling 1998; Gerwing et al. 1996; Kaiser and Rubin 2013; Rehm and Lamb 2009). Soil pH will influence the balance between ammonium and ammonia in solution, with more ammonia being present at high pH levels. Therefore, damage from fertilizers containing ammonium will tend to be higher on high pH soils (Dowling 1998).

Crop species and even cultivars will differ greatly in their tolerance to seed-placed fertilizer. In growth chamber studies in Australia, corn and sunflower were found to be more tolerant than soybean to TSP, MAP and DAP (Dowling 1998). Studies in Saskatchewan, conducted at Outlook, Melfort and Saskatoon, showed that sensitivity to seed-placed MAP was in the order pea > lentil >> faba bean (Henry et al. 1995). Pea stand count was reduced by 50% with 88 lb P_2O_5/acre (44 kg P/ha) while faba bean stand was not affected. Seed yield of peas was higher with side-banded rather than seed-placed at all locations, while seed yield of lentil was higher with side-banded than seed-placed at two of three locations.

In field studies in Alberta, seed-row placement of MAP at up to 40 lb P_2O_5/acre (20 kg P/ha) increased barley yield without reducing stand density while emergence of flax or rapeseed was greatly decreased by seed-row applications of either TSP or MAP at rates of 30 to 60 lb P_2O_5/acre (15 to 29 kg P/ha) (Nyborg and Hennig 1969). Seed-row application at 80 lb P_2O_5/acre (39 kg P/ha) decreased barley stand slightly but non-significantly, and grain yield was similar with P seed-placed or banded below the seed. Increasing the rate of seed-row application to 160 lb P_2O_5/acre (78 kg P/ha) decreased stand density by 1/3, resulting in no greater yield than for the unfertilized control. However, when the same rate of P fertilizer was placed 2.5 cm below the seed-row, the yield was double that of the control. Yield of rapeseed and flax was also greater when the fertilizer was placed below the seed-row rather than in the seed-row.

In growth chamber studies in Saskatchewan wheat, canola, flax, canary seed, pinto bean, or chickpea showed no reduction in emergence at rates of seed-placed MAP from 0 to 35 lb P_2O_5/acre (0 to 17 kg P/ha), but emergence was reduced at rates above 9 lb P_2O_5/acre (4 kg P/ha) for yellow pea and alfalfa, 18 lb P_2O_5/acre (9 kg P/ha) for mustard, and 35 lb P_2O_5/acre (17 kg P/ha) for bromegrass (Qian et al. 2005; Schoenau et al. 2005). Additional studies showed that pea, flax, and mustard were most sensitive to high rates of seed placed MAP, while wheat and oat were least sensitive. Use of a controlled release phosphorus fertilizer product greatly increased the tolerance of crops to high rates of seed-placed P, with rates of 70 lb P_2O_5/acre (35 kg P/ha) placed in the seed row producing no significant injury for most crops (Qian and Schoenau 2010; Qian et al. 2005; Schoenau et al. 2005). Further growth chamber studies evaluated the sensitivity of different *Brassica* species to seed-placed MAP and APP and found that small-seeded cultivars were more prone to germination damage than larger seeded *B. napus* cultivars and yellow-seeded canola was slightly more prone to reduced emergence than black-seeded cultivars (Qian et al. 2012; Urton et al. 2012; Urton et al. 2013).

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 (Roberts and Harapiak 1997). A higher SBU means that the fertilizer is more diluted 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 spread for the fertilizer band or by reducing the row spacing between fertilizer bands. Therefore, SBU will vary considerably with different types of seeding and fertilizing equipment (McKenzie and Middleton 2013). Single- and double-disc openers and narrow knife-openers place the seed and fertilizer together in the bottom of a relatively narrow furrow. The SBU of such drills or planters is small and the concentration of fertilizer in contact with the seed is high, increasing the risk of damage to sensitive crops (Figure 3). With hoe-type or shovel-type openers, the seed and fertilizer are spread across a wider furrow, giving a higher SBU and a lower concentration of fertilizer close to the seed, reducing the risk of damage. For example, some air seeders are equipped with sweep-type shovels that scatter the seed in wide bands with high SBU, so that higher rates of seed-placed P rates can safely be used. At low rates of fertilizer application, response to seed-placed P may be slightly less when the seed and fertilizer are spread out in broad bands as compared to narrower bands. In studies in Manitoba, wheat uptake of MAP increased slightly as area of application increased from very narrow bands to 2.5 cm wide bands, likely by enlarging the region that can be accessed by the root, but increasing the band width from 2.5 to 15 cm had little further effect (Hammond 1997). Increasing the row spacing will also decrease SBU, as the fertilizer and seed will be applied in fewer rows per unit area. Therefore, the risk of seedling toxicity is particularly high with row crops planted at 30 inch (75 cm) row spacings.

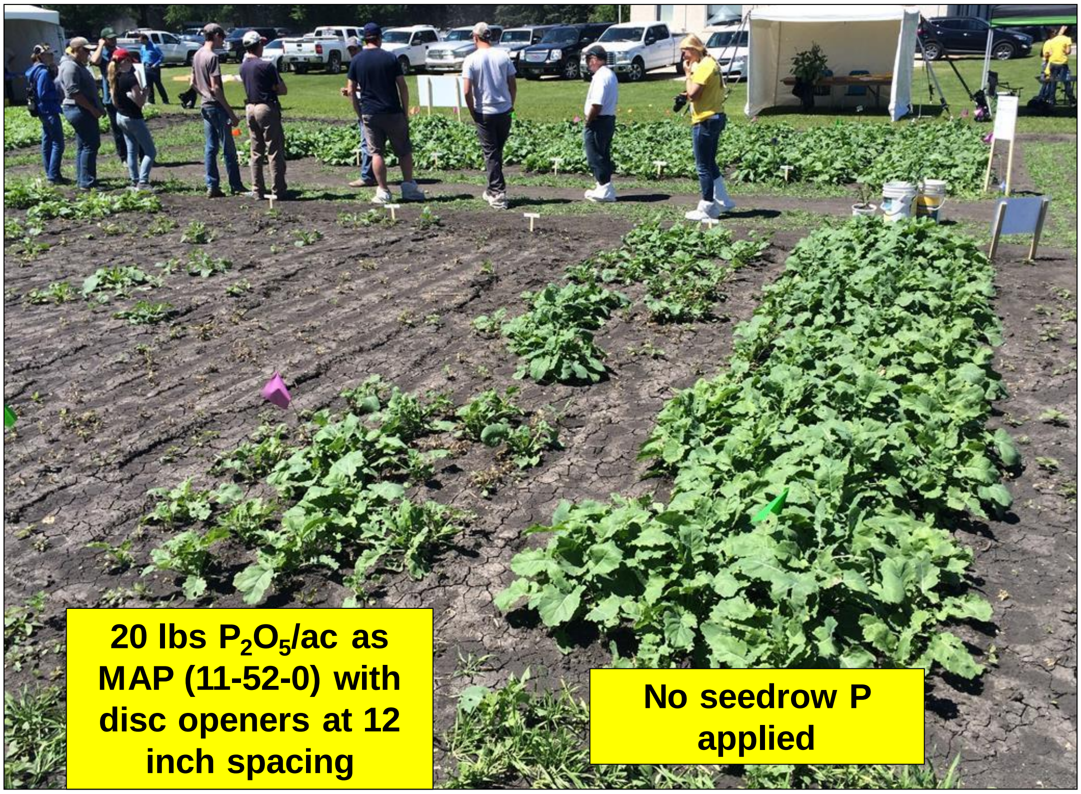

Figure 3. Seed-placed phosphorus fertilizer can lead to seedling damage in sensitive crops (e.g., canola) and low seedbed utilization (e.g, wide row spacings and narrow openers) as shown at the Portage la Prairie AAFC research station in Manitoba (Photo credit: Don Flaten).

Safe rates of seed-placed P are recommended considering the type of crop grown, soil and moisture characteristics, type of fertilizer used and the seed-bed utilization of the seeding equipment being used (McKenzie and Middleton 2013). While the specific recommendations vary from region to region, recommended safe rates are higher for cereal crops than oilseed crops, higher on fine- than coarse-textured soils, and higher with wide openers and narrow row-spacings than with seeders that have higher SBU. A web-based calculator has been developed by the South Dakota Cooperative Extension system to make recommendations for the safe rate of seed-row placement of fertilizers for various crops, based on soil type, moisture, fertilizer type and SBU (http://seed-damage-calculator.herokuapp.com, accessed August 28, 2018).

Where rates of P required to optimize crop yield or maintain P fertility create a risk of seedling damage, that risk may be reduced by moving the fertilizer away from the seed-row with side-banding or mid-row banding or by applying P in a separate operation. Side-banding effectively reduces the concentration of P in contact with the seed. While some studies have shown that under very P-deficient situations, yield may be reduced by moving the P away from the seed-row (Lauzon and Miller 1997; Nyborg and Hennig 1969; Sheard et al. 1971), placement of P below or close to the side of the seed-row is generally an effective form of placement that enables substantial rates of P fertilizer to be applied without a substantial risk of seedling toxicity.

Nevertheless, the relative performance of side-banded as compared to seed-placed fertilizer will depend on the risk of seedling damage from the seed-row P. Canola and rapeseed are more sensitive to seed-placed P than cereal crops; therefore, placing the fertilizer away from the seed-row in these oilseed crops will frequently provide an advantage at higher rates of application. Studies on calcareous and non-calcareous soils in Manitoba showed that seedling damage occurred in rapeseed when the rate of seed-placed MAP application increased above 30 lb P_2O_5/acre (15 kg P/ha) (Bailey and Grant 1990). Applying the fertilizer 2.5 cm away from the seed-row reduced seedling damage and led to the highest seed yield and P uptake. A one-year study near Swift Current, Saskatchewan evaluated rates of side-banded, seed-placed and broadcast P, finding that side-banded P at 22 lb P_2O_5/acre (11 kg P/ha) gave higher stand density and yield of canola than seed-placed MAP. The highest rate of seed-placed P reduced stand, resulting in lower canola yield than the other P treatments or the unfertilized control (Wheatland Conservation Area 2018). In other studies, conducted at Indian Head, Saskatchewan, a control plus five rates (20 to 90 lb P_2O_5/acre) of MAP were either side-banded or seed-placed for canola. Canola emergence and stand density were not reduced by either placement, although seed-row P rates were more than 3x the maximum recommended amounts. Seed-row placement resulted in greater early season growth relative to side-banding; however, yields for the two placement methods were equal despite low residual P levels and strong response to fertilization. Both seed-row and side-band placement were effective in supplying P to canola, without significant damage to seedlings under these conditions (Holzapfel 2016). In field studies across Alberta and Saskatchewan using side-banded and seed-placed MAP rates of 0, 30, 60, 90 or 120 lb P_2O_5/acre (0, 15, 30, 45, and 60 kg P/ha) the higher rates of seed-placed application led to stand thinning in canola, but final yield did not differ due to P application or fertilizer placement (Karamanos et al. 2014; Karamanos et al. 2017).

Certain legume crops may also show a better response to side-banding if seed-placement produces seedling damage. Studies conducted at Outlook, Melfort and Saskatoon on lentils, peas and faba beans showed that side-banded MAP generally produced higher stand density than seed-placed MAP in lentil and pea, but not in faba bean (Henry et al. 1995). The sensitivity of the crops to seedling damage was in the order pea > lentil >> faba bean. Pea stand count was reduced by 50% with 90 lb P_2O_5/acre while faba bean stand was not affected. Final seed yield of pea was greater with side-banded rather than seed-placed at all locations, while with lentil, seed yield was greater with side-banded than seed-placed at two of three locations. Seed yield of faba bean was not affected by placement. This reflected the relative sensitivity of the three crops to seedling damage from the seed-placed P. In field studies near Swift Current in a wet year, faba bean showed substantial responses to MAP phosphate applications at rates up to 55 to 70 lb P_2O_5/acre with either seed-placed or side-banded MAP fertilizer (Wheatland Conservation Area 2017). Stand establishment was not affected by seed-placed fertilizer at 2 weeks after seeding, but at 4 weeks after seeding, stand establishment was reduced by seed-placement of 70 lb P_2O_5/acre of MAP. Seed yield of faba bean was lower with 70 lb P_2O_5/acre seed-placed than side-banded or than if a lower rate of seed-placed P was used.

Crops such as cereals, that are more tolerant than canola or pulse crops to seed-placed fertilizer, may not show an advantage for side-banding over seed-placement. Studies in Saskatchewan using one-pass seeding systems with either side-banded or seed-placed P in wheat showed similar performance for the two placements, except under very dry conditions, where side-banding was superior (Mooleki et al. 2010). In studies in Alberta and Saskatchewan, side-banded and seed-placed P fertilizer rates of 0, 30, 60, 90, and 120 lb P_2O_5/acre (0, 15, 30, 45, and 60 kg P/ha) increased yield of barley and winter wheat with increasing rate of application, regardless of placement (Karamanos et al. 2014; Karamanos et al. 2017). Spring wheat responded more to high rates of side-banded than seed-placed MAP, even though there was no evidence of seedling damage from the seed-placed P. In studies conducted over a three-year period at Indian Head, SK, durum wheat yield increased with application of 18 or 35 lb P_2O_5/acre (8.5 or 17 kg P/ha) in one year and tended to increase ($p<0.07$) in another year of a three year trial, but there was no difference in yield whether the MAP was seed-placed or side-banded (May et al. 2008).

In general, on soils that are not extremely deficient in P, side-banding of P will be as effective as seed-row placement in increasing crop yield under conditions experienced in the Northern Great Plains. Side-banding can yield to higher yields by avoiding seedling damage and allowing the application of higher rates of P to optimize crop yield and/or to maintain long term P fertility.

7.4 Dual Banding of N and P Fertilizer

Dual banding refers to the application of N and P fertilizer in a single band, placed deep in the soil either prior to seeding or in side- or mid-row bands at planting. The deep dual bands are positioned far enough from the seed that seedling damage will not occur and, if banded before seeding, 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 fertilizers can increase the availability of the P for plant uptake. Ammonium ions increase uptake of phosphate, with the effect being attributed to several different mechanisms. Uptake of ammonium by plants leads to the excretion of H^+ that lowers pH in the rhizosphere and can increase the solubility of $CaHPO_4.2H_2O$ near the root surface and thus improve P availability (Blair et al. 1971; Miller et al. 1970; Miller and Ohlrogge 1958). Studies at the University of Manitoba showed that addition of urea with MAP in a dual band increased the mobility and uptake of P (Flaten 1989). Ammonium has also been shown to increase root proliferation in the fertilizer reaction zone which would increase the ability of the plant to absorb the applied P (Grunes 1959; Grunes et al. 1958; Miller and Ohlrogge 1958).

Many years ago, studies in Saskatchewan showed that dual banding of ammonium-N with P will tend to increase the uptake of P as compared to application of the N and P separately (Rennie and Mitchell 1954; Rennie and Soper 1958). Field and greenhouse studies with winter wheat in Colorado showed that dual banding of APP with anhydrous ammonia or UAN gave higher yields than broadcast application and that ammonium-N sources gave higher P uptake than nitrate-N sources when banded with APP (Leikam et al. 1983). Banding N and P separately resulted in lower P uptake than banding them together. In growth chamber studies conducted in Manitoba, addition of urea or ammonium sulphate to MAP increased P solubility (Beever 1987). The uptake of P by canola, flax and wheat from dual bands placed 7.5 cm to the side and below the seed-row was equal to or greater than uptake from P placed 2.5 cm below and to the side of the seed-row. Field studies conducted on calcareous soils in North Dakota showed that adding ammonium sulphate and ammonium bisulphate with APP increased early season plant growth and P uptake as compared to APP applied alone (Goos and Johnson 2001). Adding elemental S and ammonium thiosulphate to the APP band also increased P uptake as compared to APP applied alone. The acid-forming materials increased the early season P uptake, but by the end of the season the effects had dissipated. Grain yields were increased by the starter P at 6 of 8 site-years, but there was no increase in yield in response to use of the sulphate products with the APP.

While dual banding of P may increase the availability of P as compared to separate placement of the P and N, banding P with high rates of urea or anhydrous ammonia may delay fertilizer P uptake because the high concentration of ammonium, nitrate, nitrite and salt can prevent root penetration and proliferation in the band. Field and growth chamber studies in Manitoba showed that placing urea in the band with the MAP delayed the initiation of fertilizer P uptake by the seedling, likely because the high concentration of ammonia in the band prevented the roots from entering the fertilizer reaction zone (Figure 4) (Flaten 1989). Early season P uptake was greater for P placed in the seed-row, in 18 cm-spaced dual bands, or in 36 cm-spaced separate bands than for 36 cm-spaced dual bands, indicating a delay of P uptake from the wide dual bands due to N toxicity. In a subsequent study in Manitoba, fertilizer uptake by wheat, canola and flax from dual bands located 7.5 cm below and to the side of the seed-row was similar to uptake from MAP placed 2.5 cm to the below and to the side of the seed-row with the urea placed 7.5 cm to the side and below the seed-row (Beever 1987). The study also showed that initiation of fertilizer P uptake from the dual bands was delayed, especially for canola and flax as compared to wheat and especially when urea was in the band. This initial delay was followed by enhanced P uptake, resulting in similar or greater P utilization from the urea-MAP bands by 25 days after emergence. Incubation of the bands for 10 days prior to seeding reduced the delay in uptake of P from the band. Field studies with irrigated soft white wheat in Alberta also showed that response to dual bands of N and P improved when the bands were allowed to age for several weeks, presumably because the high concentrations of ammonia in the band would dissipate over time, reducing toxicity (Harapiak and Flore 1986). Manitoba studies showed that dual banding of MAP with ammonium sulphate was sometimes more effective than dual banding with urea because the delay in P uptake was not as great as with urea (Hammond 1997).

Generally, on severely P-deficient soils, phosphate should not be banded with N fertilizer if the N rate is higher than 60 to 70 lb N/acre, to avoid reduced early-season uptake efficiency of the P fertilizer from inhibition of root growth in the dual band (McKenzie and Middleton 2013). Alternatively, a low rate of starter P in the seed-row could be beneficial if some P needs to be diverted to the N band to avoid seedling toxicity.

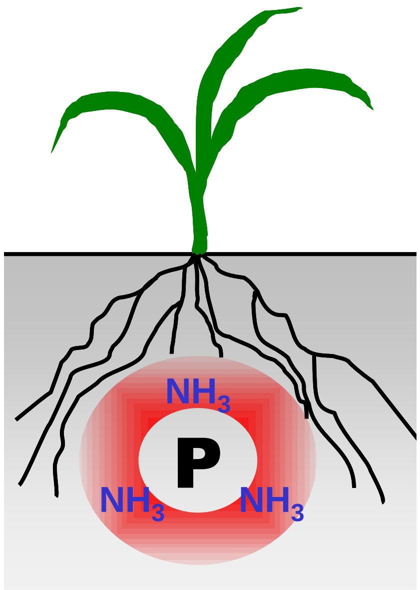

Figure 4. High rates of N fertilizer may delay fertilizer P uptake in "dual" bands, because the high concentration of N delays root penetration and proliferation in the band.

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

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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 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.

Detailed Information

8.1 Importance of Early Season Supply

The supply of P available to the plant early in the growing season is critically important for optimum yield in many crop species (Grant et al. 2001). Restrictions in P supply during the early stages of crop growth can lead to a cascade of physiological effects that limit final crop yield. Restricted P supply later in the growing season tends to have a smaller impact on crop production than do early season nutrient deficiencies. Studies from the 1920s showed that wheat grew well if it was raised with complete nutrient solution for 4 weeks, then transferred to solutions containing all the known essential nutrients except P (Gericke 1924; Gericke 1925). Withholding P from the wheat plants after 4 weeks did not decrease yield. However, if the solutions were deficient for the first 4 weeks of growth, wheat yield was very restricted. The authors concluded that P was critical for early season growth but not needed for later growth periods. However, at that time, only seven nutrients were considered essential for growth, so micronutrient deficiencies may well have influenced the results of this early study.

Similar conclusions about the importance of an early P supply were shown in solution cultures with barley, where P supply between the second and fourth week of growth had the greatest impact on barley yield, while P supply after six weeks of growth had no further impact (Brenchley 1929). Phosphorus supply in the first four to six weeks of growth seemed to be critical for tiller production. Eliminating P from the solution during the first two weeks of growth or after six weeks of growth had no impact on the number of heads produced but eliminating it between four and six weeks of growth led to total absence of head production. Eliminating P in the first two weeks of growth did not affect the total number of flowers produced, but grain number declined because of a greater number of sterile florets. Brenchley (1929) suggested that the early season P requirement of barley was mainly for head production. He also noted that if enough P was present in the solution, sufficient P was taken up by the plant in the first six weeks of growth to allow the plant to produce optimum final dry matter yield, even though only a small amount of the final dry matter yield was attained by six weeks. Phosphorus that was absorbed by the plant in later stages increased tissue P concentration but did not affect final dry matter yield.

These early solution culture studies may have had some problems because of incomplete knowledge of the essential nutrients required for crop; however, many of the observations of the early studies have been repeated in more recent work in solution studies. For example, in the 1970s, restrictions in P supply for barley in the first 24 days of growth reduced plant size and tillering (Green et al. 1973; Green and Warder 1973). If P was added to the solution after about 24 d of P deprivation, the final plant yield was no greater than for plants that had never received P. Limitations in P supply between planting and the six-leaf stage also reduced dry matter and grain yield of field corn (Barry and Miller 1989).

Maximum tiller production of spring wheat and intermediate wheat grass occurred when P was present in nutrient solution for the first five weeks (Boatwright and Viets 1966). Having P available for longer did not increase tillering and P had to be supplied for at least one week for any tillers to be produced. Limiting P for three or more weeks reduced final tiller production. Secondary root development showed the same pattern of response as tiller development, with early availability of P being important for maximum root development. Providing P for only the first five weeks produced spring wheat and intermediate wheatgrass final dry matter as high as when it was applied for longer periods. If P was supplied for the first four weeks of growth, dry matter yield was 80 and 66% of maximum for wheat and intermediate wheat grass, respectively. Yields dropped to 50 and 25% of maximum, respectively, if P was supplied for only the first three weeks of growth. On the other hand, withholding P for 2 weeks then returning it to the solution led to dry matter yields of 80 and 59%, and grain yields of 42%, of the maximum. Withholding P for 3 weeks led to dry matter yields of 30%, and grain yield of 19%, of the maximum. Only 15% of maximum P was absorbed by wheat and 5% by intermediate wheat grass during the first 2 weeks of growth, but the small amount accumulated was critical for maximum dry matter and grain yields at maturity.

In other solution culture studies with wheat, high P supply in the 30 days between Feekes stages 6 and 9 led to more fertile heads, more grains per head and more P in the vegetative parts that could be mobilized during grain filling than if the same P concentration was supplied in the 30 days from Feekes stage 11 to 17 (Römer and Schilling 1986). In field studies with spring wheat conducted in North Dakota, early P deficiency inhibited tillering in wheat, reducing the development of T1 and T2 tillers that are normally initiated around the 2.5 leaf stage (Goos and Johnson 1996).

Restrictions in early season P supply may depress subsequent plant growth because of restrictions in C nutrition of the plant. In field-grown corn, P deficiency slowed the rate of leaf appearance and reduced leaf size, especially in the lower leaves (Colomb et al. 2000). The slower leaf growth and lower photosynthetic capacity would decrease C nutrition influencing subsequent root growth and the ability of the plant to access P from the soil (Mollier and Pellerin 1999; Pellerin et al. 2000; Plénet et al. 2000a; Plénet et al. 2000b). Restriction of axillary meristem development by seedling P deficiency could reduce kernel number and yield potential in corn (Barry and Miller 1989). Meristem formation occurs by the six- or seven-leaf stage, so P deficiency prior to this stage could decrease meristem size, leading to fewer initiated kernels per ear. A similar mechanism may occur in other species since reductions in seed number with P deficiency are seen in many different crops (Crafts-Brandner 1992; Elliott et al. 1997a; Elliott et al. 1997b; Elliott et al. 1997c; Hoppo et al. 1999).

While early P supply has been shown to be important in a range of plants, different species will differ in their sensitivity to early season P stress. Radish (*Raphanus sativus* sp.), lettuce (*Lactuca sativa* sp.) and foxtail millet (*Setaria italica*) were grown in vermiculite with varying concentrations of P for a period of 2 weeks, then transferred to soil containing varying concentrations of P (Avnimelech and Scherzer 1971). The effect of the early P stress persisted in radish, with early P nutrition having a greater effect than P content of the soil for twenty-five days after the seedlings were transplanted. Similarly, with lettuce, the P supply during the first 18 d of growth had a greater effect on later growth than did the later P supply in the soil. The lettuce seedlings grown with adequate P during their initial growth produced final yields five times greater than plants that were P-restricted during early growth. In contrast to lettuce and radish, foxtail millet was not negatively affected by the lack of P during early growth (Avnimelech and Scherzer 1971). Peppers were also able to recover from restrictions in early season P supply, showing classical deficiency symptoms when grown with low P for the first 15 days, but if they were then transferred to a full P supply, they showed the same the root and top growth at twenty-eight days of growth as plants that had been provided with full P throughout the growth period (Bar-Tal et al. 1990).

Effects of early season P stress may be more severe for early season dry matter production than grain yield. In field studies in Manitoba, P deficiency reduced the early-season dry matter yield of spring wheat by about 25-50% as compared to the P-fertilized treatment, but the final yield at the end of the season was reduced by only about 12 to 25% (Tomasiewicz 2000). Similarly, in Manitoba field trials with corn, early season corn biomass at V4 was doubled by starter P side-banded at planting, but grain yield was increased by only 10% at maturity (Rogalsky 2017). Other growth-limiting factors may inhibit yield as the season progresses so that the yield potential provided by the adequate early season P may not be attained. Under these conditions, the yield gap between the P-deficient and the P-sufficient plants will narrow due to other stresses. However, early season P deficiency can set a limit to the maximum potential yield (Barry and Miller 1989).

8.2 Requirement for P Supply During Grain Fill/Flowering

An early season P supply can have long-lasting impacts of final crop yield potential, but an external 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. Early studies suggested that the maximum quantity of P uptake of spring wheat was obtained by heading, with P accumulation in the grain primarily resulting from redistribution of P from the vegetative tissue (Boatwright and Haas 1961). Later work with hard red spring wheat grown under irrigation showed that only 45% of the total P in the above-ground tissue had accumulated by anthesis (Miller et al. 1994), possibly indicating that continued uptake of P may occur if moisture supplies are adequate. Studies conducted at Melfort, SK showed that about half of the P accumulation in wheat occurred by about 41 days after emergence, with the maximum quantity of P accumulation at full flowering to late milk or ripening, depending on the environmental conditions during the growing season (Figure 1) (Malhi et al. 2006). Maximum rate of P uptake was at tillering. The maximum rate of P uptake and the maximum total P accumulation occurred earlier than the corresponding values for biomass accumulation, indicating that P uptake preceded biomass accumulation and that the supply of nutrients must be adequate in early stages to support biomass production. However, P accumulation continued until as late as the early ripening stages. A similar pattern of nutrient accumulation preceding biomass accumulation occurred for pulse crops (Malhi et al. 2007b) and oilseed crops (Malhi et al. 2007a).

The P present in the seed of cereal grains is largely provided by redistribution of nutrients accumulated in the vegetative tissue during the early stages of growth. As the plant develops, P is transported from leaves and stems to the grain until 75 to 80% of the plant P is present in the grain at maturity (Mohamed and Marshall 1979). Nevertheless, some of the seed P in spring wheat is supplied from post-anthesis soil uptake, to augment internal redistribution of P accumulated during early growth (Mohamed and Marshall 1979).

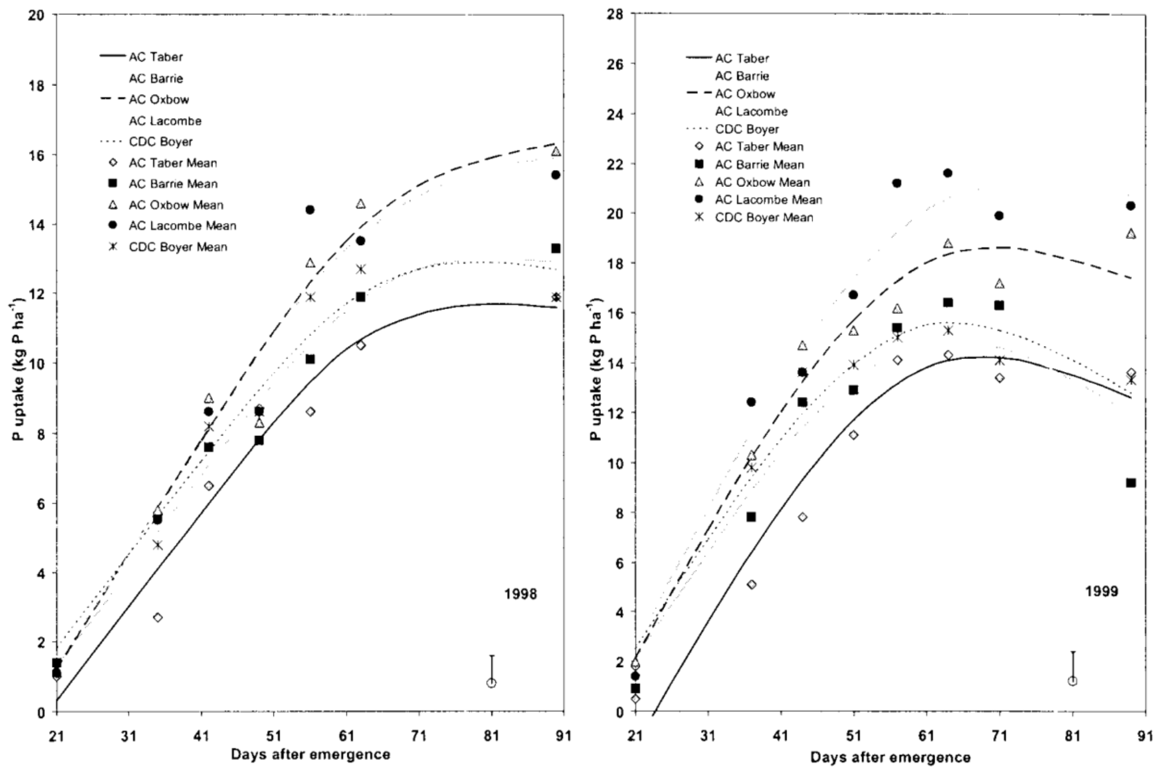

Figure 1: Changes in P uptake (kg P/ha) of spring wheat and barley with days after emergence in field experiments at Melfort, Saskatchewan. Standard error of the mean is shown by line bar. (Malhi et al. 2006).

Uptake of P from the soil will continue during later growth stages if environmental conditions permit, but the effect of later season P supply on crop yield will vary, depending on the initial P status of the plant. There may still be a requirement for some external supply of P at later stages of crop growth to ensure optimum grain yield, particularly if early-season supply was limited. In solution culture, maximum dry matter production of winter wheat occurred if P was supplied until the first node stage, but maximum grain yield occurred only if P was supplied through the mealy-ripe stage (Feekes' scale 11.2) (Sutton et al. 1983). Absence of P in the growth medium during later growth stages did not inhibit dry matter production, but reduced grain yield, possibly because carbohydrate translocation was limited. A small amount of P was needed through ripening to allow enough carbohydrate translocation to maximize grain yield. Sutton et al. (1983) suggested that if late season soil P was limited, a small foliar application of P during grain filling could improve grain filling and optimize grain yield.

Dry soils during grain fill could restrict P uptake from the soil and inhibit translocation during grain fill. Where late season supply of P is inadequate, rapid remobilization of P and N from wheat tissue to the grain may restrict photosynthesis before maximum grain weight is achieved, limiting final seed yield (Batten and Wardlaw 1987). If P is limiting for the plant, it may be possible to extend photosynthesis with foliar application of P fertilizer. In solution culture experiments, foliar application of P did not affect leaf function or grain development in wheat plants that had been adequately supplied with P in early growth, but P applied to the flag leaf of P-deficient plants delayed leaf senescence and the breakdown of photosynthetic tissue (Batten and Wardlaw 1987). However, these foliar applications did not increase grain yield.

In contrast, when plants were under stress due to crowding or high temperatures, foliar application of monopotassium phosphate (KH_2PO_4) slowed leaf senescence and increased wheat grain yields under field conditions in Morocco (Benbella and Paulsen 1998a; Benbella and Paulsen 1998b). In field and greenhouse studies in Oklahoma, corn yield occasionally increased with foliar application of P at the V8 stage if soil P levels were low (Girma et al. 2007). Conversely, studies with winter wheat in Oklahoma using rates of foliar P from 2 to 40 lb P_2O_5/ac (1 to 20 kg P/ha) applied from second node of stem formation (Feekes 7) to flowering completed (Feekes 10.54) showed that grain yield was higher with only pre-plant soil-applied P and not with only foliar P (Mosali et al. 2006). Occasionally, application of foliar P in addition to pre-plant P gave higher yields than application of pre-plant P, alone. Also, where no pre-plant P was applied, foliar P increased yield as compared to no foliar P, but yields were still substantially lower than when pre-plant P was applied. Earlier applications of foliar P led to larger grain yield increases than later applications. Responses to foliar application also tended to be greater under moisture stress.

Field studies in Manitoba showed that foliar application of P at the five to six leaf stages, at early tillering, could increase yields of spring wheat if they had not received sufficient P in the seed-row at planting (Green and Racz 1999). Later, field studies in spring wheat and canola showed that foliar applications of monopotassium phosphate did not increase crop yield regardless of the initial P status of the plants (Chambers and Devos 2001). Recent field and growth chamber studies in SK with canola, wheat and field pea showed that in-season foliar applications of monopotassium phosphate increased tissue P concentration, particularly in canola, but was less effective than seed-placed P in increasing crop yield P (Froese 2018; Schoenau 2018). Uptake of foliar P fertilizer by plant leaves was not large enough to be of benefit to crop yield in this study. Therefore, situations where foliar P applications will increase crop yield are likely to be rare in the Northern Great Plains.

8.3 Factors Affecting Early-Season Supply of P to the Plant

The ability of the plant to access P during the early stages of growth will have an important influence on the crop yield potential. However, many factors make it difficult for the plant to access the early-season P that it requires under the growing conditions of the Northern Great Plains. Plant uptake of P is a function of the area of the root absorptive surface and the concentration of P that is in contact with that absorbing surface. Therefore, the chemical, physical and biological factors that affect the solubility of P and its movement to the root surface as well as those that influence root growth and function will determine plant P supply. In general, factors that restrict root growth, such as soil compaction, salinity, or other stress factors will reduce early season P uptake. Similarly, factors reducing P concentration in the soil solution at the root surface, including low background P level, dry or compacted soils, low or high soil pH, or soils with a large capacity to retain P will reduce the ability of the plant to access soil P.

8.3.1 Soil Temperature

While many environmental factors will influence the ability of crops to access P, soil temperature is particularly important on the Northern Great Plains, where annual crops are frequently planted into cold soil in early spring. Cold soil temperatures can restrict P uptake by the plant by reducing root growth and soil P extractability. In studies conducted in Manitoba, extraction of soil P with 0.5 N $NaHCO_3$ (similar to the Olsen soil test) was as much as 40% less at 10°C than 25°C, with the effect being greater on soils with a lower background P concentration (Sheppard and Racz 1984a; Sheppard and Racz 1984b). Effects of temperature differed in fertilized versus unfertilized soil. In the unfertilized soil, extractability of P increased with increasing temperature, while in the fertilized soil, extractability decreased with increasing temperature (Sheppard and Racz 1984a). In the unfertilized soil, increasing temperature increased release of soil P, increasing P supply, while in the fertilized soils, increasing temperature accelerated retention reactions of between fertilizer P and soil, decreasing P supply. It is important to note that the practical impact of temperature on solubility of native soil P is opposite to the effects on fertilizer P, even though the cold temperatures slowed P reactions in both cases. In cold soil, the native soil P is less available than on warm soils, because dissolution is slower. In contrast, applications of fertilizer P will remain available for longer on cold than warmer soils because retention reactions will be slower. Therefore, the relative benefit of fertilizer P is greater on cold than warm soils.

Low soil temperatures decreased both the equilibrium soil solution P concentration and the P-desorption buffer capacity, indicating that both the intensity and capacity of P supply from the bulk soil decreased with decreasing temperature. Increasing soil temperature from 10 to 25°C increased the root growth of wheat seedlings and increased plant uptake of P in some, but not all soils (Sheppard and Racz 1984a; Sheppard and Racz 1984b). Capacity for P uptake by the plant will depend on how quickly the concentration of P in the soil solution at the root surface can be replenished by P release and diffusion. At low soil temperature, the replenishment of the soil solution will be slowed. This slower replenishment combined with slower root growth will to reduce the rate of plant P uptake at low temperature.

As well as affecting overall root growth, temperature may also more specifically affect root proliferation in the fertilizer band. With many crop species, when the roots contact an area of high P concentration, as is found in the reaction zone of a fertilizer band, root growth preferentially increases in the nutrient-enriched area (Sheppard and Racz 1985; Strong and Soper 1974a). The proliferation increases the absorbing area in the area of high nutrient concentration, improving the P uptake efficiency (Kalra and Soper 1968; Soper and Kalra 1969; Strong and

Soper 1973; Strong and Soper 1974a; Strong and Soper 1974b). The relative increase in rooting in a high-P area of the soil is greater at cooler than warmer soil temperatures. In studies conducted in Manitoba using band and broadcast fertilizer applications, wheat showed little root proliferation in the band at warm soil temperatures, but root mass was up to 3.6 times greater in the band than the adjacent soils at 10°C (Sheppard and Racz 1985). Therefore, preferential root exploitation is another reason why band placement provides a greater benefit to plants under cool than warm soil conditions.

In summary, band application of P fertilizer in or near the seed-row at planting is most beneficial under the cold soil conditions as are often experienced in the Northern Great Plains. During early season crop growth, P supply tends to be restricted because of slow diffusion of soil P, slow general root growth, and lower availability of native soil P. Under these conditions, fertilizer P may be necessary to ensure adequate crop growth and may be more available for crop uptake because of slower retention reactions.

8.3.2 Amount and Concentration of P in the Seed

Fertilizer P and soil P are not the only sources of P for crops. High concentrations of P in the seed may provide enough P to the seedling to support the first few weeks of growth. More than 70 years ago, Saskatchewan researchers used ^{32}P tracers to determine that wheat seedlings did not take up any appreciable amount of soil P until they were two weeks old (Spinks and Barber 1948). However, smaller-seeded crops with smaller P reserves may require external P more quickly after seeding. For example, rapeseed seedlings could grow on seed reserves of P until approximately 7 days of age, but growth was restricted by P deficiency if P was absent 7 to 12 days after transplanting (Schjørring and Jensén 1984).

Higher concentration of P in the seed may increase the benefit of the seed-borne P to the plant. In greenhouse studies, wheat seeds of the same weight that had higher P concentration produced higher dry matter yields after as long as 35 days of growth, while field studies in Australia showed a benefit in wheat growth that persisted until 67 days after seeding (Bolland and Baker 1988). Other greenhouse studies in SE Australia showed that heavier wheat seeds had higher P concentration than lighter seeds and had greater germination and higher root and shoot dry weight after three weeks of growth (Derrick and Ryan 1998). Similarly, growth chamber studies showed that wheat seeds with higher P concentration emerged more rapidly and had greater early shoot and root growth than seedlings with lower P concentration (De Marco 1990). Increasing total seed P content, calculated by seed mass by seed P concentration, seemed to be important, with the effects of seed weight and seed P concentration being additive. In greenhouse studies in Alberta, barley plants grown from high-P seed had greater shoot height and biomass accumulation at 21 days than plants grown from low-P seed (Zhang et al. 1990). Imbibing the low-P seed through a solution of monosodium phosphate (NaH_2PO_4) led to greater shoot growth and dry matter accumulation than with the untreated low-P seed, but less than for the plants grown from seed high in P without imbibition. Increasing seed P concentration also increased the ability of the seedling to accumulate P from the soil, likely because of better root development (Zhu and Smith 2001). Improved early season shoot growth will increase photosynthetic capacity while greater early root establishment will increase the ability of the plant to access water and nutrients from the soil, potentially leading to an increase in final crop yield potential.

8.4. Implications for P Fertilizer Management

Effective fertilizer P management must provide an adequate amount of P to the plant when required for optimum yield. Therefore, early-season access by the plant to P is critical. If plant-available P in the soil is high, the soil may supply enough P to the young plant to optimize crop growth (Nyborg et al. 1999). Where the amount of plant-available P present in the soil is small or the ability of the crop to access the native soil P early in the growing season is compromised, applications of P fertilizer will be required to optimize crop yield potential. Fertilizer amendments must be managed in a way to ensure that the P can be accessed by the crop in the first few weeks of growth, when it will have the greatest effect on crop yield.

Research conducted in Saskatchewan in the 1940s showed that application of P fertilizer to wheat at the time of seeding led to the greatest increase in crop growth (Dion et al. 1949). Fertilizer application at the time of seeding led to vigorous early growth and later growth could be largely completed from P taken up from the bulk soil. Radiotracer studies in Saskatchewan confirmed that the main uptake of P from fertilizer applications occurred prior to heading (Spinks and Barber 1947; Spinks and Barber 1948; Spinks and Dion 1949; Spinks et al. 1948). The rate of uptake of fertilizer P was greatest between two and six weeks after emergence, while the rate of uptake of soil P was initially low but increased over time. Therefore, uptake of fertilizer P is much more rapid that that of soil P for the first four weeks of growth but after four weeks the plant takes up soil P much more rapidly (Spinks and Barber 1948). Uptake of P from the bulk soil increases as the plant root system expands, so that more and more of the absorbing surface of the root is accessing P from the unfertilized soil. In the early stages of growth, practically all the P taken up by the fertilized plant comes from the fertilizer, because the high concentration of P allows significant uptake with the limited root surface of the young seedling. While fertilizer P uptake may continue after heading, most of the later uptake is from the reserves of soil P, with a much smaller amount being taken up from the fertilizer application because the effects of the larger root area in the unfertilized soil dominates absorption. These and later radiotracer studies in Saskatchewan showed that wheat took up most of the P from fertilizer early in growth and took up soil P later in the season (Mitchell 1957). Plant access to early season fertilizer P and an adequate supply of P in the bulk soil ensures adequate P nutrition throughout the entire growing season, which is important for optimum yield. Therefore, in studies evaluating the effects of residual and annual applications of P fertilizer, spring wheat crops were not able to attain maximum yield on low-P soils, even with high rates of seed-placed fertilizer (Wagar et al. 1986).

Greenhouse studies in Manitoba evaluated the pattern of uptake of P by rapeseed (*Brassica napus* L.), oats (*Avena sativa* L.), flax (*Linum usitatissimum* L.) and soybean (*Glycine max* L. Merr.) from fertilized and unfertilized soil (Kalra and Soper 1968). Rapeseed began to absorb fertilizer P early in the growing season, while flax used very little of the fertilizer P. The proportion of soil to fertilizer P used by the crops increased from 35 days after seeding to harvest for rape, oats and soybean, but remained constant for flax. Rapeseed was more efficient than the other crops in absorbing fertilizer P, while soybean was more efficient in absorbing soil P. As other researchers had observed, absorption of soil P continued later in growth than did the uptake of fertilizer P, likely because as the root system expanded it could contact and utilize more of the P in the bulk soil. Also, as time progressed, the fertilizer P was probably depleted and/or retained by soil to become less plant-available, so the concentration of soluble P in the fertilizer reaction zone probably decreased.

The optimum timing for P fertilizer application is strongly interconnected with the optimum placement for P. The ability of the plant to use fertilizer P early in the growing season is improved by precisely 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. Phosphorus will react with calcium and magnesium in high pH soils and with iron and aluminum in low pH soils to form increasingly less soluble compounds and limit the distance that the P will move in solution. Placing the fertilizer in a concentrated band in or near the seed-row at planting 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 may also reduce the contact between the soil and the fertilizer, reducing P retention (Havlin et al. 2014; Tisdale et al. 1993).

However, there is a balance required between reducing the volume of soil fertilized in order to reduce retention and having a large enough volume of soil fertilized to allow adequate access of the roots to the fertilized soil (Barber 1977; Randall and Hoeft 1988). Studies in Manitoba showed that oats and flax were able to use more P if the fertilizer was mixed with a portion of soil rather than applied in a concentrated point, while buckwheat and rape were more capable of using the P from the concentrated zone (Soper and Kalra 1969). The enlarged reaction zone created by blending the fertilizer with more soil allowed more roots to contact the fertilizer, which was important for the oats and flax. However, many plants, including canola, rapeseed and buckwheat, are able to increase the density of rooting when they contact a high concentration of P as is found in a fertilizer reaction zone (Strong and Soper 1974a; Strong and Soper 1974b). The combination of a high root density with a high fertilizer concentration will increase the ability of the plant to take up P during early growth. Differences among species in their ability to proliferate roots in a high-P fertilizer reaction zone will influence their ability to respond to P placed in a concentrated band.

In soils with a high P retention capacity, placing the fertilizer in a concentrated band near or with the seed during the seeding operation as “starter P” increases the opportunity for the young seedling to contact and use the fertilizer during the critical early stages of growth. In a Saskatchewan study, wheat plants used a greater proportion of fertilizer P if it was banded near the seed than if the seed and fertilizer were separated. Placing the P near the seed-row may be especially important for crops such as flax that have limited early-season root development (Sadler 1980).

Corn grown in the cold soils of the Northern Great Plains frequently shows a response to application of starter P in or near the seed-row. As mentioned previously, in field trials in Manitoba with corn, starter P side-banded at planting increased early season corn biomass at V4 twofold and grain yield by 10% (Rogalsky 2017). In the same trials, starter P advanced silking dates by 2-7 days and reduced grain moisture contents by 2-3% on an absolute basis. Similar studies were conducted in Brookings, South Dakota to evaluate the effect of starter fertilizers on corn yield (Osborne 2005; Osborne and Riedell 2006). Starter fertilizer with only P and K increased yield, oil production, and N removal in all years compared with no starter fertilizer treatment. In Minnesota, starter fertilizers containing P increased corn yield on low and very low testing soils (Randall and Hoeft 1988; Randall and Vetsch 2008; Vetsch and Randall 2002). Additionally, growth chamber studies in Minnesota showed that corn plant mass was increased by in-row fertilizer blends containing P, even though the temperature in the chambers was above that normally occurring in the Northern corn-growing region (Kaiser and Rubin 2013). Sweet corn yields in Illinois were also increased with seed-row or side-banded P fertilizer, but only if rates were not high enough to cause seedling toxicity (Swiader and Shoemaker 1998).

Genetic differences may result in different responses to application of starter P in corn. In studies in Kansas, two of four hybrids assessed showed yield increases in response to a starter fertilizer blend containing P (Gordon and Pierzynski 2006). During the cool spring conditions, the two hybrids that responded to starter fertilizer had poorer rooting than the non-responsive cultivars but produced higher yield than the non-responsive cultivars when both were fertilized. The starter P may have helped the poorer-rooting cultivars overcome the lack of early-season root growth and express their inherent higher yield potential. Starter fertilizer consistently reduced the number of thermal units needed to go from emergence to mid-silk for the responsive cultivars, but not for the non-responsive cultivars. This type of accelerated maturity can be especially important in short season areas, such as in the Northern Great Plains. A similar hybrid x starter fertilizer interaction was found with APP applications in a previous no-till dryland corn study in Kansas (Gordon et al. 1997).

As mentioned in the section on P fertilizer placement, position of the band in relation to the seed-row can also be important. Corn yield in Ontario studies was increased more if P fertilizer was seed-placed rather than banded below and to the side of the seed-row when soil P levels were very low (Lauzon and Miller 1997). Greenhouse and field experiments in Ontario showed that alfalfa and bromegrass seedlings were better able to access fertilizer P when it was placed directly below the seed-row rather than placed to the side by 3, 6 or 9 cm, because the roots did not access the P placed beside the seed row early enough in the growing season (Sheard et al. 1971). Similarly with flax, P uptake was greater when fertilizer was placed directly below the seed and decreased as the fertilizer band was moved further from the seed-row (Sadler and Bailey 1981; Sadler 1980).

Soluble P fertilizer may lead to seedling damage if excess amounts are placed in or too near to the seed-row (Nyborg and Hennig 1969; Qian and Schoenau 2010; Qian et al. 2007; Randall and Hoeft 1988; Richards et al. 1985; Swiader and Shoemaker 1998). Damage is more likely with ammonia-forming sources such as diammonium phosphate, because the ammonia contributes to seedling toxicity (Allred and Ohlrogge 1964). Banding the fertilizer below or below and slightly to the side may reduce the risk of seedling damage in sensitive crops while maintaining the benefit of banding, especially in crops with wide spacing between seed-rows.

Placement in or near the seed-row 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 (Barber 1958; Scharf 1999). Reduced tillage may also increase response to P in or near the seed-row, because soils may be slightly denser and cooler in the spring when undisturbed rather than cultivated (Gauer et al. 1982; Grant and Lafond 1993; Vetsch and Randall 2000). If soils are not extremely deficient in P, application of P as a dual band, deep-placed with N may be effective.

If the P concentration in the soil is high, plants may be able to access enough P early in the season from the bulk soil to satisfy their P demand. Therefore, an alternative strategy for P management may be to build P to a sufficiency level, then balance P applications with removal over time to maintain soil P level. Many studies on the Northern Great Plains have evaluated the effect of single large applications of P fertilizer to build background soil P concentrations as compared to smaller annual applications, or to a combination of the two practices (Bailey et al. 1977; Halvorson and Black 1985a; Halvorson and Black 1985b; Read et al. 1977; Read et al. 1973; Selles 1993; Wagar et al. 1986).

At four sites on Chernozemic soils in Manitoba and Saskatchewan, a single large application of phosphate fertilizer at rates from 0 to 800 lb P_2O_5/acre (0 to 400 kg P/ha) was broadcast and incorporated at the initiation of the study (Read et al. 1973). Superimposed over the base treatment were annual applications of monoammonium phosphate placed with the seed at 7 rates from 0 to 100 lb P_2O_5/acre (0 to 50 kg P/ha). The study continued for 6 years of a wheat-flax rotation in Manitoba and a wheat-fallow rotation in Saskatchewan. Where no P had been applied at the initiation of the study, wheat yield increased with increasing rates of P placed with the seed. However, at three of the four locations, there was no increase in yield with seed-placed fertilizer on the blocks that had received 200 to 800 lb P_2O_5/acre (100 to 400 kg P/ha) at the beginning of the study. On one soil, there was a response to seed-placed P in 3 of 6 years on the block that had received 200 lb P_2O_5/acre (100 kg P/ha) at the beginning of the study. Increase in yield per lb or kg P applied over the six years was similar for an initial application of 200 lb P_2O_5/acre (100 kg P/ha) and application of 20 lb P_2O_5/acre (10 kg P/ha) seed-placed each year. Soils were taken from the field sites and used in greenhouse studies where 19 successive crops were grown to evaluate the persistence of the residual effect of the P applied. The P concentration in the soil decreased to the level of the control after three to five crops on the 200 lb P_2O_5 treatment and after 11-13 crops on the 800 lb P_2O_5 treatment, but the available P in the 800 lb P_2O_5 treatment was still higher than that of the control after 19 consecutive crops. A total of 87, 81 and 70% of the P applied was recovered in the harvested plant material from the 200, 400 and 800 lb P_2O_5/acre applications, respectively, indicating that the broadcast applications were used efficiently over time. The field studies were continued for two more years and the residual effect of the high rates of P application persisted, with higher yields and higher soil P concentrations occurring with the 400 and 800 lb P_2O_5 rates. Adding P with the seed did not increase the yield on plots that had received 200 lb P_2O_5/acre or more, except at one of the four test sites. Over the 8 years of cropping, 200 lb P_2O_5/acre as a single application at the initiation of the study produced the greatest cumulative grain yield and increasing application rate above this level or providing additional seed-placed P did not generally provide a further grain yield increase. By the final year of the study, the Olsen soil test extractable P level of the 200 lb P_2O_5/acre treatment was reduced to about 4 ppm which was similar to the control and would be too low to support optimum crop yield. However, soils treated with 400 and 800 lb P_2O_5/acre contained between 10 and 27 ppm Olsen soil test extractable P and would be expected to continue to support optimum grain yield for several more years with minimal likelihood of grain yield response to additional P fertilizer applications (Bailey et al. 1977; Read et al. 1977).

In a similar study conducted in Montana, concentrated superphosphate was applied once, at study initiation, at rates of 0, 45, 90, 180, and 360 lb P_2O_5/acre (0, 22, 45, 90, and 180 kg P/ha) and crops were grown for the following 17 years without additional fertilizer P application (Halvorson and Black 1985a; Halvorson and Black 1985b). A wheat-fallow system was used for the first six wheat crops (*Triticum aestivum*) and then a continuous annual cropping system including wheat, barley *(Hordeum vulgare*), and safflower (*Carthamus tinctorius* L.), was used for remainder of the study. Fertilizer P recovery in the grain for the 45, 90, 180, and 360 lb P_2O_5/acre treatments averaged 32, 25, 23, and 13%, respectively, without N fertilization and 45, 38, 37, and 24% with 45 kg N/ha. Even after 17 years, the P recoveries at the higher P rates (>90 lb P_2O_5/acre) were < 50% of that applied and cumulative recovery of fertilizer P was still increasing at the higher P rates through to harvest of the last crop in 1983. The researchers concluded that a one-time broadcast application of P fertilizer at rates as high as 180 lb P_2O_5/acre was an efficient way to manage P fertilizer. The 180 and 360 lb P_2O_5/acre treatments with N fertilization had the greatest accumulated grain yields over the duration of the study (Halvorson and Black 1985b)

A slightly later six-year study in Saskatchewan on a Brown Chernozemic clay soil used single broadcast P applications at 5 rates from 0 to 320 lb P_2O_5/acre (0 to 160 kg P/ha) and annual seed-placed P applications at 5 rates from 0 to 40 lb P_2O_5/acre (0 to 20 kg P/ha) in a 6-yr study (Wagar et al. 1986). The single broadcast application of 80 lb P_2O_5/acre increased yields over 5 years and had an average yield and P uptake similar to that of the annual seed-placed applications of 20 and 40 lb P_2O_5/acre. Initial broadcast applications of 160 and 320 lb P_2O_5/acre increased yields over 6 years and soil levels of Olsen soil test extractable P were still high enough after 6 years to indicate that future yield increases could occur. Annual application of seed-placed fertilizer also had a residual effect over time, indicating that even relatively low rates of seed-placed P can remain available for crop uptake over time.

Field studies on a low and high testing clay loam soil in Minnesota compared annual broadcast P applications versus larger P applications every three years for 12 years of application and 8 further years of residual testing (Randall et al. 1997a; Randall et al. 1997b). Phosphorus fertilizer was applied annually for 12 years at rates of 0, 50 and 100 lb P_2O_5/acre (0, 25, and 50 kg P/ha) and compared to 150 lb P_2O_5/acre (75 kg P/ha) applied every third year. Corn and soybean yields were improved by the annual 50 lb P_2O_5/acre rate in 6 of 12 years when the soil test P was <22 ppm and in 8 of 12 years when the soil test P was 10 ppm. Increasing the rate of application to 100 lb P_2O_5/acre did not increase yield above the 50 lb P_2O_5/acre rate of application. Corn and soybean yield for the 150 lb P_2O_5/acre rate applied every three years were equal to that for the annual application of 50 lb P_2O_5/acre in all years on the high testing soil and in 11 of 12 years on the low testing soil, so there were no differences between annual and triannual applications in 23 of 24 site years. Residual benefits of the P applications persisted for the 8 years of study after fertilizer application was ceased. During the 8-year residual period, yields were increased above the control in all site-years by carryover from the 50 lb P_2O_5/acre rate. While this study did not assess whether further yield increases could be obtained by some starter placement of P fertilizer at the time of seeding, it does indicate that increasing soil test P through large broadcast applications of P can be as beneficial as annual applications, if the soil test P level is increased to adequate levels. The amount of fertilizer P required to maintain or increase soil test P levels and the critical soil test P level required for optimum yield is not well-defined and will depend on soil characteristics (Randall et al. 1997b).

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.

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9. 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 1).

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 a soil type, climate, cropping history, as well as the local sustainability goals.

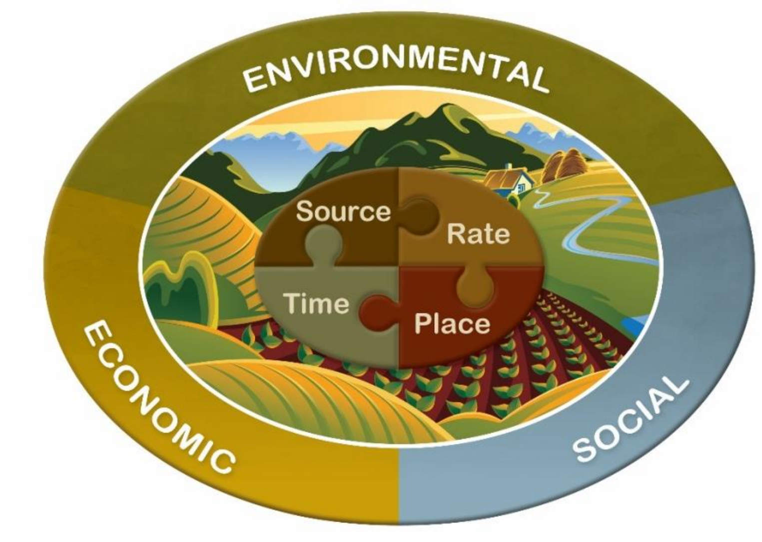

Figure 1. The 4R nutrient stewardship concept defines the right source, rate, time, and place for plant nutrient application as those producing the economic, social, and environmental outcomes desired by all stakeholders to the soil-plant ecosystem (Roberts 2010) figure credit: http://www.ipni.net/ipniweb/portal/4r.nsf/article/communicationsguide

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 types of 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.

Detailed Information

The basic principle of 4R fertilizer management is to apply the right source at the right rate, right time and right place to achieve the economic, social and environmental goals for each location. The challenge for 4R management is to develop an effective and cohesive management package that works within a dynamic and complex system.

The 4R tools interact with one another and are affected by the agronomic, environmental, economic and logistical considerations on the farm. Tillage, cultivar selection, weather, pest management practices, land tenure, equipment and labour availability and a range of other factors influence 4R choices.

The 4R practices are science-based fertilizer management principles that have been developed and tested over time, but can be modified as knowledge and technology evolve. The 4R framework is adaptable and allows a producer to make nutrient management decisions based on site-specific conditions such a soil type, climate, cropping history, as well as the local sustainability imperatives (Bruulsema 2017; Bruulsema et al. 2009; Bruulsema et al. 2008; Flis 2018; IPNI 2012).

9.1 The 4R Package - Fitting the Pieces Together

The goal of 4R management of P fertilization is to provide the optimum amount of P to the growing crop at the time it is required, in the most cost-efficient manner, with the least environmental risk. However, as mentioned in the beginning of this review, each of the 4Rs does not stand alone; they interact with each other, as well as other agronomic factors on the farm (Figure 1).

An effective soil test is the first step in the 4R package. Soil testing provides an estimate of the plant-available P in the field and the likelihood of a yield response to fertilizer P. Based on the sustainability goals and the crop requirements, the producer can estimate the rate of P application required. The rate required will be affected by, crop type, yield potential, residual soil nutrient levels, crop sequence, and other management factors, as well as the other 3Rs.

Rate of application and fertilizer placement are closely interrelated. Efficiency of use of low rates of P fertilizer is much higher with banded than broadcast fertilizers, so if low rates of P targeted to optimize yield are being used, band application is preferable (Bailey and Grant 1990; Campbell et al. 1996b; Grant and Bailey 1993b; Karamanos et al. 2002; Wagar et al. 1986; Wheatland Conservation Area 2018). In contrast, if higher rates of fertilizer P are being used to build soil P, broadcast and banded applications may provide similar yield.

Early-season P supply is critical to establish optimum yield potential, so in some cases P responses to starter fertilizer placed in or near the seed-row may occur, even on soils that are moderate to high in available P. Since P is not mobile in the soil, P fertilizer should be placed in a position where the crop roots can access it early in the growing season. Seed-row placement or side-banding P at planting can ensure that the crop roots contact the fertilizer early in the season if the background level of P is too low to optimize early-season P supply.

In the Northern Great Plains, P supply for annual spring-seed crops is often restricted early in the growing season by cold soil temperatures. Cold soil reduces the already low mobility of P and also slows root growth, further restricting the ability of the crop to access P from the soil. Therefore, the likelihood of seeing a response to starter P will increase as soil temperature decreases, so starter P is often more important with early seeding into cold soils (Alessi and Power 1980; Grant et al. 2001; Sheppard and Racz 1984a; Sheppard and Racz 1984b; Sheppard and Racz 1985; Sheppard et al. 1986; Vetsch and Randall 2000).

Similarly, the lower the plant-available P soil, the greater the potential benefit of placing the fertilizer near or in the seed-row. However, 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. Studies in Alberta showed that when temperatures in the month after seeding were cool, seed-row placed P produced higher barley yields, while when temperatures were warmer than normal, dual-banded P with N, away from the seed, produced higher yield (Karamanos et al. 2008). Similarly, in a field study near Melfort, SK, deep-banded and seed-placed P produced similarly yield in canola and wheat, except when conditions were cool and dry and soil test P was low (Nuttall and Button 1990). With wheat, the two placements generally produced similar yield, while with canola seed-placed produced higher seed yield than deep-banded P in one year when conditions were dry and soil test P level was very low. Therefore, optimal placement can also be affected by time of seeding and weather conditions as well as by soil test P.

Source, placement and rate of application will also interact with crop type due to risk of seedling toxicity. 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 (Nyborg and Hennig 1969; Qian et al. 2005; Schoenau et al. 2005; Urton et al. 2012; Urton et al. 2013). Placement of rates of P above safe limits can reduce crop yield. Toxicity risk tends to be higher with diammonium phosphate (DAP, e.g., 18-46-0) than MAP or APP, while triple superphosphate (TSP, e.g., 0-45-0) tends to be somewhat safer (Dowling 1996; Dowling 1998). While not commercially available for broad-acre cropping, an experimental form of polymer coated MAP was substantially safer than other immediately available P sources (Grant 2011; Katanda 2019; Qian and Schoenau 2010; Qian et al. 2007). When growing crops that are sensitive to seed-placed fertilizers, options include applying a low rate of fertilizer in the seed-row, building P in the soil in the preceding years, moving the fertilizer band away from the seed-row, using an opener system with higher seed-bed utilization, or choosing a fertilizer source with lower toxicity.

9.2 Agronomic Drivers for Phosphorus Management on the Northern Great Plains

The 4R management system must consider the total agronomic package on the farm. Fertilizer management interacts with other agronomic practices and total management must be optimized if nutrient use efficiency is to be optimized. Building a 4R management program on the farm must consider a wide range of agronomic 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 4R management program will deliver maximum benefits only if the rest of the pieces in the management "puzzle" are working well and all the pieces are fit together.

A healthy, vigorous crop is an important factor for high nutrient use efficiency. This requires selection of a crop cultivar suited to the location, proper seed-bed preparation, optimum seeding rate and depth, effective pest control, timeliness of operations, and attention to the other details of agronomic management that establish and maintain good crop growth. Unless these fundamentals of agronomic management are in place, the 4R nutrient management plan will not reach its full potential. However, some practices will have more specific impacts on decisions regarding 4R management of P fertilizer.

9.2.1 Tillage system and crop sequence

A major shift in agriculture on the Northern Great Plains over the past thirty years has been the widespread reduction in tillage. In the Canadian prairie provinces, the area of land prepared for seeding using no-till or conservation tillage practices has increased substantially, particularly in Alberta and Saskatchewan, while area of land prepared using conventional tillage practices has declined (Table 1).

Table 1. Percentage of land prepared for seeding using various tillage systems in the Canadian prairie provinces from 1991 to 2016 (compiled from Table 32-10-0162-01: Selected land management practices and tillage practices used to prepare land for seeding, historical data. Statistics Canada, Ottawa, ON. https://www150.statcan.gc.ca/t1/tbl1/en/cv.action?pid=3210016201)

Province	Tillage System	1991	2006	2011	2016
		------ % of land seeded to crops ------			
Manitoba	Conventional	66	43	38	41
	Conservation	29	35	38	39
	No-Till	5	21	24	20
Saskatchewan	Conventional	64	18	10	7
	Conservation	26	22	20	19
	No-Till	10	60	70	74
Alberta	Conventional	73	25	13	12
	Conservation	24	28	22	19
	No-Till	3	48	65	69

With reduced tillage, residue from previous crops is left on the soil surface rather than incorporated into the soil. Residue accumulates at the soil surface as a mulch which affects soil physical properties and microclimate. Presence of crop residue on the soil surface reflects light and insulates the soil moderating changes in soil temperature. The soil will generally be slightly cooler during the spring and summer (Carefoot et al. 1990; Gauer et al. 1982), but will stay warmer during the fall and winter (Gauer et al. 1982). The mulch and standing stubble will reduce evaporation and may increase water retention, so soil moisture content is generally greater under reduced tillage than under conventional tillage (Carefoot et al. 1990; Lafond 1992). The standing stubble will also trap snow and retain it on the field, further increasing available moisture and winter soil temperatures.

Surface residue tends to break down more slowly than incorporated residue because the microclimate at the surface is less favourable for decomposition than in the soil and because contact between surface residue and the soil microorganisms that decompose the crop residue is restricted. Breakdown of the organic matter already incorporated into the soil may also be affected. The slightly cooler soil temperatures during the spring and summer with reduced tillage may slow organic matter decomposition. In addition, organic matter in the soil is frequently occluded within macro-aggregates, where it is protected from decomposition. Tillage exposes this protected organic matter, enhancing its decomposition. Aeration of the soil with tillage also hastens microbial breakdown. The slower decomposition of organic matter and lack of soil mixing leads to accumulation of organic matter under no-till, particularly in the surface soil horizon (Campbell et al. 1996a, 1997, 1998a, 1998b; Halvorson et al. 2016; Lafond et al. 2011; Liebig et al. 2004; Sainju et al. 2015).

The increase in organic matter is beneficial in terms of increased soil aggregation, improved water-holding capacity, improved tilth, and enhanced resistance to wind and water erosion. Under long-term no-till, the accumulated organic matter will provide an larger reservoir for nutrient cycling (Lafond et al. 2011); however, in the initial years of a reduced tillage system, as soil organic matter is building, nutrient release from mineralization may be lower under no-till than under conventional tillage. Continuous cropping with no-till can lead to an accumulation of organic P in the labile and moderately labile P pools near the soil surface due to crop residue accumulation (Selles et al. 1999b). Leaching of the soluble P from the surface crop residues into the soil may allow available P to be released into the soil below the residue even though mineralization is restricted (Gares and Schoenau 1994; Schoenau and Campbell 1996). In studies in Saskatchewan, no-till systems that were evaluated appeared to generally have a positive effect on soil P availability in the short and long-term, with benefits that increased over time (Schoenau et al. 2007).

Reduced tillage will also have specific impacts on P dynamics and 4R P management. Phosphorus is relatively immobile in the soil and so remains near the site of fertilizer placement. In a reduced tillage system where soil mixing is minimal, P stratification may occur with the P accumulating near the zone of placement (Grant and Bailey 1994; Grant and Lafond 1994; Schwab et al. 2006; Selles et al. 1999b; Smith et al. 2017). If the fertilizer is broadcast, the accumulation will be near the soil surface (Holanda et al. 1998), but with in-soil banding the accumulation will be near the depth of fertilizer banding (Grant and Lafond 1994; Mallarino and Borges 2006). Retention of the fertilizer bands may lead to problems in soil testing, since it makes it difficult to get a representative soil sample (Kitchen et al. 1990; Mallarino and Borges 2006). But retention of intact bands may improve the long-term availability of P fertilizer under reduced tillage by slowing reaction of the P fertilizer with the Ca and Mg in high pH soils or the

Al and Fe in low pH soils. The impact of stratification on P availability may differ depending on the specific conditions. In field studies at three sites in Saskatchewan where P had been seed-placed, long-term no-till led to accumulation of P in the 0 to 5 cm depth, while tillage decreased stratification; however, there was no difference among tillage treatments in crop P uptake (Baan et al. 2009). In contrast, stratification of P near the soil surface with broadcast applications may reduce the availability of residual P for crop uptake if the surface soil dries, “stranding” the P.

An additional concern with stratification of P near the soil surface under no-till is the increased risk of P movement in surface runoff. In many areas of the Northern Great Plains, P movement is mainly in the form of dissolved P during snowmelt runoff (Tiessen et al. 2010). While no-till management can reduce the risk of particulate loss of P through erosion, loss of dissolved P from crop residues and the stratified P retained at the surface from broadcast applications can increase the total P in runoff (Li et al. 2011; Tiessen et al. 2010). In-soil placement of P can reduce the amount of P retained at the soil surface, reducing the risk of P movement in no-till systems, although runoff of P that is leached from vegetative residues may still be a concern, especially in snowmelt-runoff dominated watersheds such as those in the Northern Great Plains.

In-soil banding of P may provide additional benefits under no-till. In-soil banding of P can reduce the contact between the soil and the fertilizer, slowing the transformation of soluble P to more sparingly soluble, less available forms. Banding P fertilizer can also improve the access of plants to the P fertilizer. Many plants can proliferate their roots when they contact a concentrated source of P, such as a fertilizer band (Strong and Soper 1973; Strong and Soper 1974a; Strong and Soper 1974b). This allows the plant to effectively mine the P from the band, utilizing the P efficiently. Also, as roots cannot take nutrients up from dry soil, placing the band in a position where the soil does not dry out early in the season avoids having the fertilizer "stranded" at the soil surface, where the roots cannot use it.

Since P will not move through the soil, it must be in a position where the plant roots can contact it during early plant growth, when P is very important for crop development (Grant et al. 2001). Placing the P in a band close to the root allows the root to contact and utilize the band. Therefore, fertilizer P is most efficiently used when seed-placed or placed in a band close to the seed. Placing the P fertilizer in or near the seed-row is most important in soils with low P or under cool soil conditions, conditions that occur frequently in the Northern Great Plains, since low P supply and slow root growth will combine to cause severe P stress early in the season. Thus, the plant demand for P can outstrip the soils ability to supply the nutrient. Benefits from in-soil banding in or near the seed-row may occur more frequently under reduced tillage, where the soil is slightly slower to warm up in the spring and where bulk densities in the soil surface may be increased to some extent (Grant and Lafond 1993). However, in studies in Manitoba, early season uptake of P by canola and wheat seedlings was not affected by tillage system, nor was the response of either crop to P application (Grant et al. 2009).

The availability of P under no-till systems may be increased for some crops due to enhanced mycorrhizal associations (Grant et al. 2005). Mycorrhizae are fungi which form associations with certain crops under low-P situations, enhancing the uptake of P by the crop. Tillage disrupts the mycorrhizal network and reduces the effectiveness of this association. Research at

Guelph, ON (Miller 2000) and Agassiz, BC (Bittman et al. 2006) showed that corn produced on summer fallow or under intense tillage was restricted in its ability to access P, while corn which followed a mycorrhizal crop, particularly under no-till, showed improved early season P nutrition. The greater P absorption was largely a result of the undisrupted mycelium present in an undisturbed soil. The mycelium remains viable over extended periods in frozen soil and so can acquire P from the soil and deliver it to the plant immediately upon becoming connected to a newly developing root system in the spring. This early season development of mycorrhizal associations is important, because the P status of the crop in the first 4 to 6 weeks of growth has a major impact on final crop yield (Grant et al. 2001). In studies conducted at Brandon, flax, a highly mycorrhizal crop, produced greater mycorrhizal colonization under reduced tillage as compared to conventional tillage (Monreal et al. 2011).

Therefore, both cropping sequence and tillage system may have important impacts on the crop P status and potentially the crop response to applied P. However, in studies evaluating rate of P fertilization in canola and wheat under no-till or conventional till in Manitoba, tillage system did not influence early season availability of P or crop response to P fertilizer application (Grant et al. 2009). Seed yield of canola and wheat was not consistently affected by tillage and there was no interaction between tillage system and P fertilization for either canola or wheat, indicating that tillage had little effect on P availability for these two crops. Canola is non-mycorrhizal, and wheat is not highly dependent on mycorrhizal colonization, so changes in mycorrhizal potential may not have been important. While the potential of no-till for enhancing mycorrhizal colonization should be considered, particularly for mycorrhizal-dependent crops such as corn or flax, these shifts are unlikely to have a large effect on the selection of 4R practices. Under no-till, in-soil 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.

9.2.2 Crop type, rotation and yield

Crop type, rotation and yield will have a major effect on P fertilizer management decisions. Removal of P from the system and hence the need for P to replace the nutrients removed will be affected by the type of crop grown and by the harvested yield. Crops differ in their P concentration in the grain and hence in the amount removed in each bushel or kg of the harvested material. For example, grain P concentration tends to be higher in flax and lentil than in cereal crops, but P exported from the cropping system was greater from cereals than from the lower yielding flax and lentil because P removal is proportional to the crop yield and the concentration of P in the harvested material (Selles et al. 1995). Studies at four locations in SK showed that soybean had higher grain P concentration than pea and lentils, but total grain P uptake of soybean and pea were similar to one another and both had P uptake that was greater than that of lentil (Xie et al. 2017). A twelve-year field study in Scott, SK showed that crop diversity did not influence extractable P, but application of P fertilizer led to slightly higher concentrations of extractable P than production without P fertilizer input (Malhi et al. 2009).

If a long-term sustainability strategy for P management is followed, the P removal in the crop should be balanced by P applications to ensure that P in the soil is not depleted. Intensification of crop production in the absence of P inputs from fertilizer or organic amendments can deplete available soil P. Long-term field studies in Saskatchewan showed that P removal was directly proportional to grain yield and changes in available P in the soil were related to the balance between P fertilizer inputs and P removal (Selles et al. 1999a; Selles et al. 1999b).

The amount of P removed in the grain tends to decrease with increasing fallow frequency because more P is harvested when crops are grown more frequently in the rotation (Selles et al. 1995; Selles et al. 1999a). Long-term field studies in Alberta showed that in the absence of P addition, continuous cropping led to greater reductions in plant-available P than did wheat-fallow systems because of the greater removal of P when a crop was harvested every year (McKenzie et al. 1992a; McKenzie et al. 1992b). However, if continuous cropping is combined with addition of N and P, there is a positive effect on P availability. Continuous cropping with N and P fertilizer additions to compensate for P removed in the grain increased the soil's labile P pools as compared to fallow-based systems (McKenzie et al. 1992a; McKenzie et al. 1992b; Selles et al. 1995; Selles et al. 1999a). The residual P fertilizer enriched the inorganic labile pools, the P held in the microbial biomass and the moderately labile inorganic-P. In studies conducted in Colorado, continuous cropping increased P availability as compared to a wheat-fallow system, even though P inputs were greater in the latter system, possibly due to redistribution of soil P from lower depths through biocycling in crop residue in the continuous cropping system (Bowman and Halvorson 1997).

As P removal is proportional to the harvested yield, removal will be affected not only by crop type, but also by other factors that influence the final crop yield. Long-term studies in Saskatchewan showed that during a period of several years when precipitation was low and yields were reduced due to drought, the P removed in the grain was less than the P applied as fertilizer and the Olsen-P in spring samples increased, reflecting the positive P balance (Selles et al. 2011). In a period when grain yields increased due to more favourable moisture conditions, crop removal of P exceeded P fertilization and Olsen-P concentration remained relatively stable. Studies with durum and bread wheat in four environments in Saskatchewan showed that uptake of P was strongly related to grain yield, so environments that encouraged high yield also encouraged high P removal (Clarke et al. 1990). Similarly, P removal was increased by use of N fertilizer because of the higher grain yield attained when N deficiencies were corrected (Selles et al. 2011).

Specific crops may have additional effects on P management decisions. Efficiency of P fertilizer is normally greatest when applied as a band in or near the seed-row, particularly under cold soil conditions. However, many crops such as soybean, field pea, flax or canola are sensitive to seed-placed fertilizer and placement of high rates of MAP or APP in or too close to the seed-row can reduce stand and limit yield response (Katanda 2019; Nyborg and Hennig 1969; Qian et al. 2005; Qian et al. 2012; Sadler 1980; Schoenau et al. 2005; Urton et al. 2012; Urton et al. 2013). Producers will often restrict the amount of P fertilizer applied with these crops or move the fertilizer away from the seed-row to avoid seedling damage. The amount of P that can safely be seed-placed with sensitive crops will be less than removal in the seed, leading to a P deficit (Table 2). If sensitive crops are grown frequently in the crop rotation and P inputs are restricted to levels that can be safely seed-placed, soil may be depleted over time due to the negative P balance for P input and removal. The deficit can be offset by applying higher rates of P to other crops in the rotation such as wheat or barley that are less susceptible to seedling damage and often produces a P surplus if the maximum safe rates of seed-placed P are used. Field studies at two locations in Manitoba showed that P concentration in the tissue of flax at six weeks was increased by application of P fertilizer to preceding wheat or canola crops (Grant et al. 2009). Other strategies for reducing P deficits in rotations with high proportions of crops such as those that are sensitive to seed-placed fertilizer include using less damaging P sources, using broadcast, side-band or mid-row band placement, selecting seeding implements with higher seed-bed utilization, and applying P fertilizer separately from the seeding operation. The P deficit may also be counteracted by building soil P levels through intermittent application of high rates of P as large bulk inputs fertilizer P or livestock manure.

Table 2. Phosphorus balance for moderate crop yields of selected crops, using maximum recommended safe rates of seed-placed fertilizer from the Manitoba Soil Fertility Guide (Grant 2012).

Crop	Yield (bu/acre)	P Removal (lb P_2O_5/acre)	Limit for Seed-Placed P (lb P_2O_5/acre)	Balance (lb P_2O_5/acre)
Wheat	40	29	50	+21
Canola	40	40	20	-20
Soybeans	40	32	10	-22
Barley	80	38	50	+12
Flax	32	20	20	0
Peas	50	38	20	- 18
Oats	100	29	50	21

Crop sequencing may also influence P dynamics through effects on mycorrhizal colonization. Fallow and production of non-mycorrhizal crops such as canola can reduce mycorrhizal colonization of the following crop (Grant et al. 2005; McGonigle et al. 2011; McGonigle et al. 1999; Miller 2000; Monreal et al. 2011). Sequencing a crop such as flax or corn that is highly reliant on mycorrhizal associations after canola or fallow can restrict P supply and final crop yield. Therefore, management of flax or corn should include proper placement in the rotational sequence to complement 4R management practices for P fertilizer. Phosphorus fertilization also tends to reduce mycorrhizal colonization as high plant P concentration discourages formation of the association (Clapperton et al. 1997; Grant et al. 2005). Restriction of P supply to encourage mycorrhizal colonization is not normally beneficial, but in situations where P supply is limited, mycorrhizal associations may help the crop.

Plants can mobilize P from sub-soil reserves and deposit it at the surface in crop residues. In addition, legume crops may increase soil P availability by modifying rhizosphere pH and by secretion of carboxylic acids and/or P solubilizing enzymes (Hinsinger 1998; Hinsinger 2001;

Hinsinger and Gilkes 1995). The P made available by legume green manure crops may be transferred to following crops in the rotation. Therefore, crop sequencing may be used as a way of increasing P availability from sparingly soluble P sources, especially in organic farming systems. If rock phosphate is used as a fertilizer, green manure crops may assist in mobilizing and releasing P the insoluble P source for the following crops in the rotation.

A field study on an organic farm in Ontario showed that the residues from a buckwheat (*Fagopyrum esculentum*) green manure crop grown with a sedimentary phosphate rock application increased in situ soil P supply and Olsen P (Arcand et al. 2010). However, the increase in available P due to the green manure was not large enough to be of agronomic benefit. Similar results were seen in studies on organic farms in Montana, where rock phosphate was applied to spring pea, buckwheat and yellow mustard grown as green manure crops to mobilize P from applications of rock phosphate for a subsequent winter wheat crop (Rick et al. 2011). Although P applied to the preceding crops increased the winter wheat yield, there was not a specific effect of the preceding green manure crop. Among the preceding crops, spring pea had about three- to five-fold more P uptake than mustard or buckwheat, but there was no effect of preceding crop on wheat, indicating that the extra P in the pea biomass was not an advantage for the following crop. The P from the residue may have been immobilized rather than mineralized and therefore might be of long-term rather than short-term benefit.

While it appears that green manure crops can utilize some sparingly soluble P, the benefit of this practice for providing P to following crops has not been large. Field studies in SK showed that P uptake of wheat and canola was sometimes increased by preceding alfalfa or red clover crops in the rotation, primarily because of higher crop yield following the N-fixing crops (Miheguli et al. 2018). Available soil P was not reduced by the legume rotations despite the higher P removal, indicating that the legumes in rotation may have been able to help maintain available P in the short-term. However, in the absence of fertilizer addition, the P balance was more negative for the legume-based rotations which could lead to long-term soil depletion, as has been demonstrated in a long term organic cropping systems trial in Manitoba (Welsh et al. 2009).

Field studies in Swift Current, SK also showed that fertilizer P applied near the soil surface could be moved to the 15 to 120 cm soil depths through uptake by the plant and deposition in root material in the lower soil horizons (Read and Campbell 1981). Sweet clover green manure and alfalfa-bromegrass hay crops increased Olsen-P in the subsoils, possibly through root decomposition (Campbell et al. 1993). The movement of P to lower depths may be of benefit under dry conditions.

In summary, crop rotation and intensification will influence the rate of P that should be applied through the crop cycle to optimize crop yield. These factors will also affect the amount of P required to balance input with removal and avoid excessive accumulation or depletion. Fertilizer rates and placement must consider factors such as crop sensitivity to seed-placed fertilizer and the ability of the crop to utilize soil and fertilizer P. Small seeded crops and pulse crops can be sensitive to seedling toxicity, so rates of P placed with the seed should be reduced to avoid the risk of damage. Phosphorus applications should be balanced with crop removal through the rotation to avoid excessive accumulation or depletion of P over time. The impact of preceding crops on the development of mycorrhizal populations should be considered when growing crops such as flax and corn that are highly dependent on mycorrhizal associations.

9.2.3 Weed Competition

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. Integrated weed management uses a systems approach to reduce weed populations and crop loss by enhancing crop competitiveness with weeds (O'Donovan et al. 2007). One tool for integrated weed management is effective fertilizer management to stimulate crop growth relative to weed growth.

Weeds compete with crops for P with the timing of uptake by weeds such as wild oats being similar to that for cereal crops (Schoenau et al. 2007); therefore, fertilizer management practices to provide a competitive advantage to the crop will improve fertilizer use efficiency and potentially reduce weed competition for light, water and nutrients. Weeds differ in their responsiveness to P fertilizer and in some cases fertilizer application can increase the competitive ability of the weeds over that of the crop. In a greenhouse study of 22 agricultural weeds in comparison to wheat and canola, most of the weeds increased shoot biomass more than wheat and canola in response to P applications (Blackshaw et al. 2004). In the unfertilized control, wild mustard, canola and kochia took up the most P, while wheat took up less than canola, but still more than all but four of the weeds. As rate of P fertilizer increased, canola, wild mustard and red root pigweed extracted the greatest amount of P, while wheat removed less than 17 of the 22 weed species at the highest fertilizer rate. Therefore, most of the weeds studied were superior to wheat in utilizing and responding to P applications.

In other greenhouse studies, two grass and two broadleaved weed species were grown with wheat in a replacement series design at P doses of 5, 15, and 45 mg P per kg soil to evaluate the competition between the weeds and the wheat as affected by P application (Blackshaw and Brandt 2009). The competitive ability of the low P-responsive species, Persian darnel and kochia, decreased as the P dose increased while that of the high P-responsive species, round-leaved mallow, progressively improved. The competitive ability of wild oat, with an intermediate responsiveness to P was not affected by the P fertilizer. Weed or crop species or even crop cultivars that are highly responsive to P fertilizer may gain a competitive advantage if they are provided with fertilizer P (Konesky et al. 1989).

Many weed species are shallow-rooted and therefore can readily access broadcast fertilizers that accumulate near the soil surface. Studies have shown that placing N fertilizers in a band application near the seed-row can improve the ability of the crop to access the fertilizer and allow the crop to out-compete the weeds (O'Donovan et al. 2007). Similarly, field studies with wheat showed that four years of seed-placing or midrow-banding P fertilizer resulted in higher wheat yields than broadcast applications when wheat was grown with competitive weeds (Blackshaw and Molnar 2009). The benefit of in-soil banding to wheat was greater in systems with weed competition than in weed-free conditions. The shoot P concentration of weeds was generally lower with seedrow- or midrow-banded P than with broadcast P, indicating that in-soil placement reduced the ability of the weeds to access the P fertilizer. In contrast, wheat tissue P concentration was highest with seedrow-placed P fertilizer.

In summary, applying fertilizer in a position where weeds can readily access it may increase the ability of the weeds to compete with the crop, especially early in the growing season. Conversely, applying the fertilizer in a manner that gives preferential access for the crop can increase the ability of the crop to compete with weeds. Therefore, 4R practices for integrated weed management would include in-soil band application of P fertilizers near or in the seed-row, as well as at the time of seeding at rates matched to crop demand, to ensure that the crop has 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 should be practiced for highest crop yield and fertilizer use efficiency.

9.2.4 Effects of other nutrients

A major principle of nutrient management is to address Liebig's law of the minimum. Crop yield will be limited by the nutrient in the shortest supply (Figure 2). If other nutrients are limiting crop production, the crop will not be able to effectively use the P that is applied, and both yield and P use efficiency will be restricted. Similarly, P deficiency will reduce the ability of the crop to attain optimum yield and will reduce use efficiency of water and other nutrients (Kröbel et al. 2012).

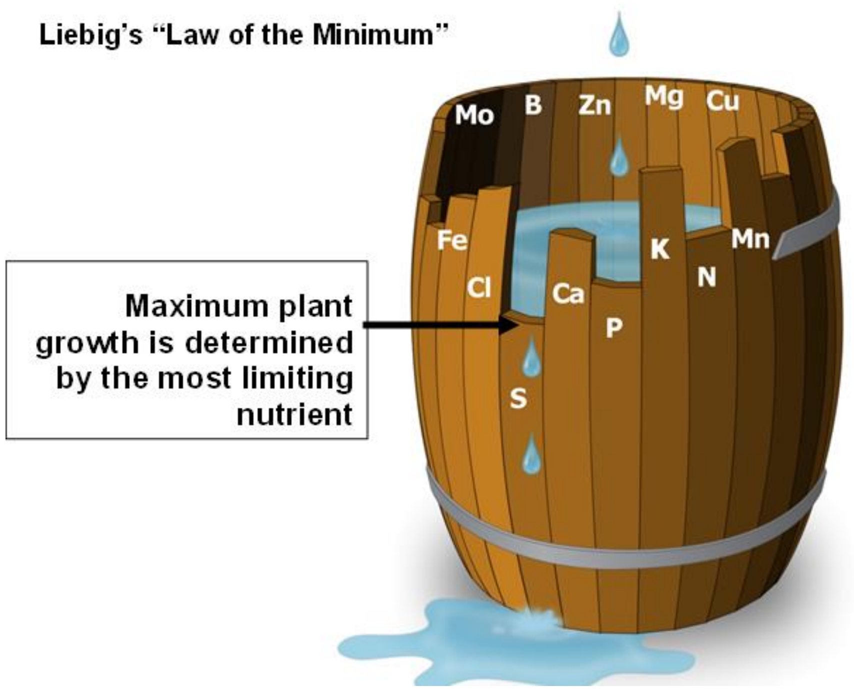

Figure 2. Yield will be limited by the nutrient in the shortest supply (Source: Sask. Ministry of Agriculture).

Nitrogen is the nutrient that is most commonly limiting for crop yield of non-legumes on the Northern Great Plains. Correction of N deficiency will lead to higher crop yields and allow the crop to more effectively utilize P applications. Numerous studies over the years have shown that both N and P must be present in adequate amounts to ensure optimum yield and nutrient use efficiency (Havlin et al. 1990). Long-term studies in Swift Current, SK demonstrated that cumulative efficiency of P use over time was increased by use of N fertilizer (Selles et al. 2011). In field studies conducted with durum wheat in Manitoba, maximum yield was obtained only when both N and P were applied (Grant and Bailey 1998). Yield response of no-till winter wheat to P application in Manitoba increased with increasing rates of N application (Grant et al. 1985). Similarly, in field studies with winter wheat in Saskatchewan, application of N at optimum levels led to a greater response to applied P and a higher maximum yield than in the absence of N fertilization (Figure 3) (Campbell et al. 1996b). In a 16 year study of N and P applications in canola, yields increased when P was applied alone but both N and P were required to attain optimum yield (Nuttall et al. 1990). Studies in Alberta with hybrid canola showed that optimum yields were obtained when N, P and S were all provided to correct deficiencies with no indication that a specific nutrient ratio in the fertilizer was required (Karamanos et al. 2005). On a very P deficient site, response to P application increased when N rate was increased as well.

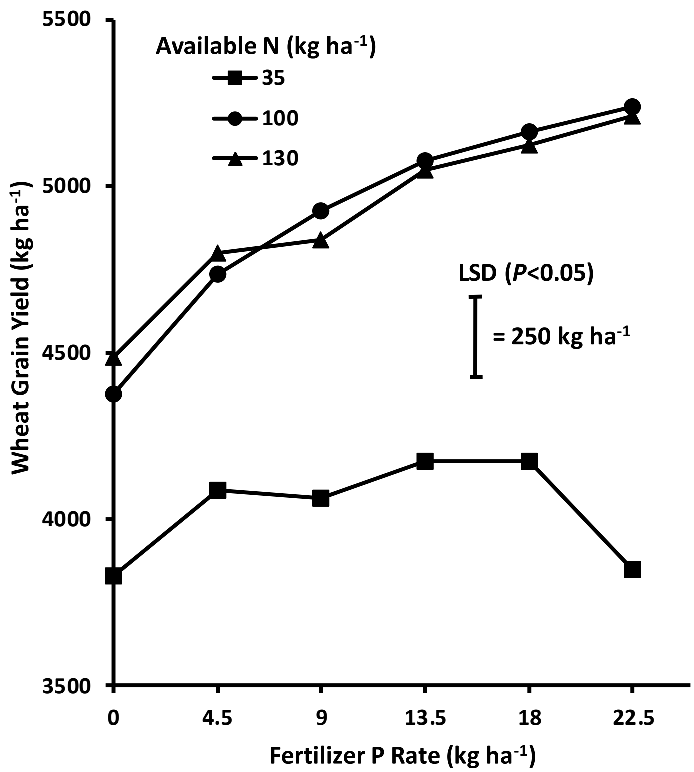

Figure 3. Response of winter wheat to P application increased when optimum levels of N fertilizer were applied (Campbell et al., 1996b).

While N is the most commonly limiting nutrient and the nutrient that generally has the greatest influence on crop yields on the prairies, deficiencies of other nutrients can also restrict crop yield and thus reduce the ability of the crop to effectively use P. Potassium is not often deficient on the Northern Great Plains due to the high native mineral K content in most soils in this region. However, it may be limiting to crop yield in some instances, particularly on coarse-textured soils, because of their low clay content. Correcting deficiencies will allow a crop to attain its yield potential and improve efficiency of use of P and other nutrients. In studies with barley near Brandon, maximum yield on a sandy soil was attained only when N, P and KCl were all applied (Grant et al. 1995). Canola is especially susceptible 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 (Grant et al. 2003a; Grant et al. 2004; Grenkow et al. 2013; Karamanos et al. 2005). Similarly, in studies near Brandon and Lacombe, maximum yield of canola was obtained with balanced N, P and S fertilization, even when yield was restricted due to dry conditions (Figure 4).

In addition to the nutritional effects on efficiency of P use, other nutrients may also have a direct effect on P availability. Placement of the phosphate with ammonium-based fertilizers can increase the availability of the P for plant uptake. When the ammonium ion is taken up by the plant, H^+ is excreted, reducing pH in the rhizosphere which can improve P availability (Blair et al. 1971; Miller et al. 1970; Miller and Ohlrogge 1958). Studies at the University of Manitoba also showed that addition of urea with MAP in a dual band increased the mobility and uptake of P (Flaten 1989). Ammonium can also increase root proliferation in the fertilizer reaction zone, potentially increasing the ability of the plant to absorb applied P (Grunes 1959; Grunes et al. 1958; Miller and Ohlrogge 1958). Therefore, dual banding of ammonium-N fertilizer with P may improve the uptake of P as compared to application of the N and P separately (Rennie and Mitchell 1954; Rennie and Soper 1958). In growth chamber studies conducted in Manitoba, addition of urea or ammonium sulphate to MAP increased P solubility (Beever 1987). In field studies on calcareous soils in North Dakota, adding ammonium sulphate and ammonium bisulphate with APP increased early season plant growth and P uptake as compared to APP applied alone (Goos and Johnson 2001). Adding elemental S and ammonium thiosulphate to the APP band also increased P uptake as compared to APP applied alone. The acid-forming materials increased the early season P uptake, but by the end of the season the effects had dissipated, so there was no additional benefit in yield through use of the sulphate products as compared to use of the starter P alone.

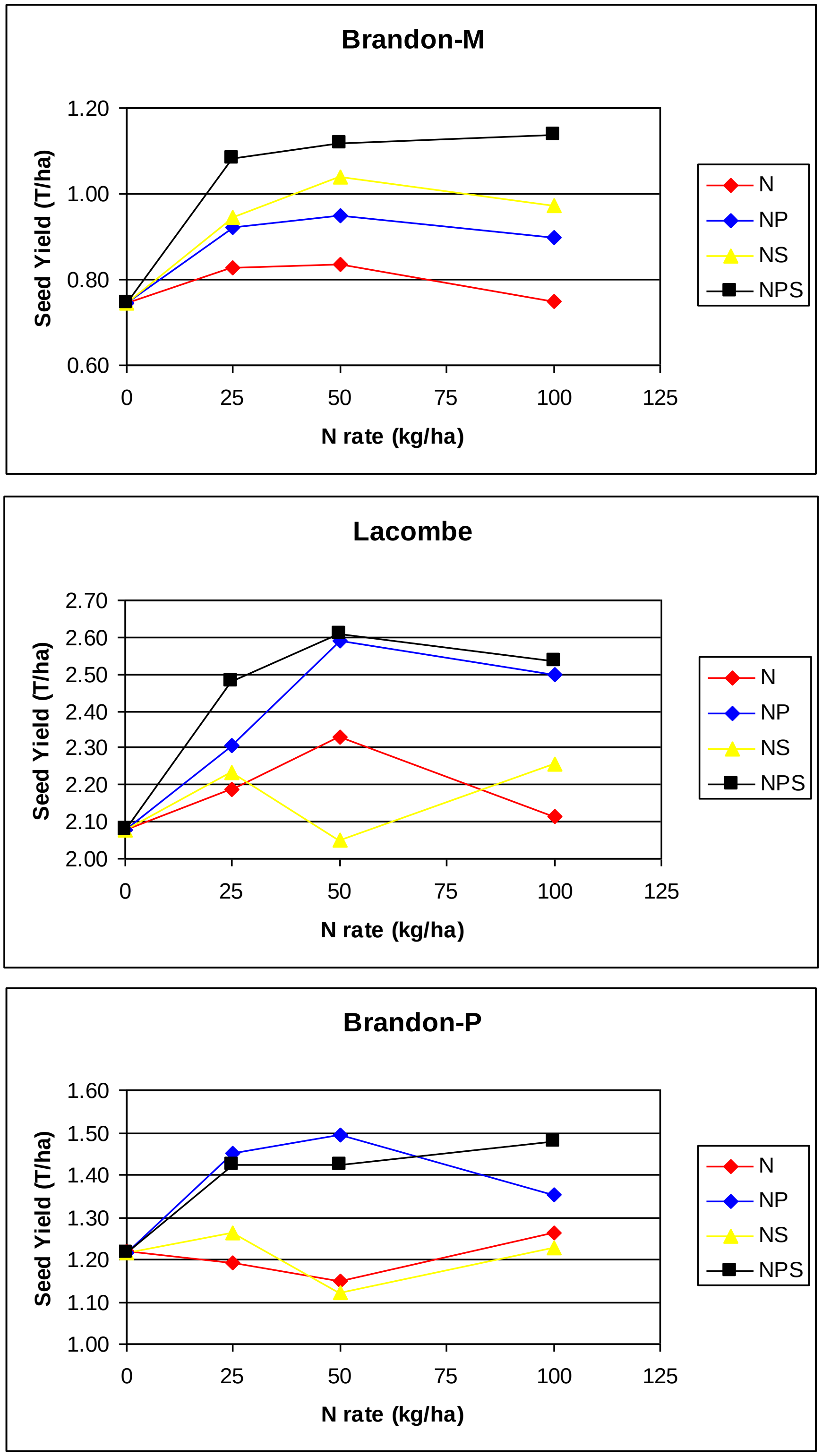

Figure 4. Canola seed yield as affected by N, P and S fertilization at three locations (averaged over cultivars). (Grant et al. 2003b).

Although dual banding of P may increase the availability of P as compared to separate placement of the P and N, banding P with high rates of urea or anhydrous ammonia may delay fertilizer P uptake because the high concentration of ammonia, ammonium, nitrite, nitrate and salt can prevent root penetration and proliferation in the band. Field and growth chamber studies in Manitoba showed that placing urea in the band with the MAP delayed the initiation of fertilizer P uptake by the seedling, likely because the high concentration of ammonia in the band preventing the roots from entering the fertilizer reaction zone (Flaten 1989). Fertilizer uptake by wheat, canola and flax from dual bands located 7.5 cm below and to the side of the seed-row was similar to uptake from MAP placed 2.5 cm to the below and to the side of the seed-row and urea placed 7.5 cm to the side and below the seed-row, but initiation of fertilizer P uptake from the dual bands was delayed, especially for canola and flax as compared to wheat and especially when urea was in the band (Beever 1987). This initial delay was followed by enhanced P uptake, resulting in similar or greater P utilization from the urea-MAP bands by 25 days after emergence. Incubation of the bands for 10 days prior to seeding reduced the delay in uptake of P from the band. Other Manitoba studies showed that dual banding of MAP with ammonium sulphate was sometimes more effective than dual banding with urea, because it did not lead to a delay in P uptake as the urea caused (Hammond 1997). The practical application of this research is that if soil P levels are very low, phosphate should not be banded with N fertilizer if the N rate is higher than 60 to 70 lb N/acre, to avoid reduced uptake efficiency of the P fertilizer from inhibition of root growth in the dual band (McKenzie and Middleton 2013). Alternately, a portion of the P fertilizer should be placed in or near the seed-row to satisfy P demand until the crop can access the P in the dual band.

Phosphorus fertilization may also interact with trace element nutrition, both chemically and nutritionally. Phosphorus fertilizer normally contains Zn as a contaminant, with an average concentration of 2290 ppm per unit P being reported in 195 samples of phosphate fertilizers collected from 12 countries in Europe (Nziguheba and Smolders 2008). These values are similar to those measured in Canadian fertilizer sources (Grant et al. 2014; Lambert et al. 2007; Sheppard et al. 2009). Therefore, P applications will also apply some Zn. However, P fertilization has been shown to reduce Zn concentration in the tissue and induce Zn deficiency in many crops (Cakmak and Marschner 1986; Cakmak and Marschner 1987; Gao et al. 2010; Grant et al. 2010; Marschner and Cakmak 1986; Moraghan 1984; Mortvedt 1984). Long-term studies at sites across the Canadian Prairie Provinces showed that although the Zn applied with P fertilizer increased soil Zn concentration at many locations, concentration of Zn in the plant was reduced with increasing P applications (François et al. 2009; Grant et al. 2014). In growth chamber studies with commercial and reagent grade P, application of P induced Zn deficiency symptoms in flax, but the severity of the symptoms was more severe with reagent-grade relative to commercial P fertilizer, presumably due to the presence of Zn as a contaminant in the commercial fertilizer (Jiao et al. 2007). Application of Zn fertilizers eliminated the symptoms and increased biomass and seed yield.

In some cases, reductions in growth from high rates of P application in the absence of adequate Zn have been due to excessive P accumulation in leaves and resulting P toxicity (Tu 1989). When Zn is adequately supplied, a shoot control signal apparently prevents excessive P uptake by the roots and transport to the shoots but this control is seems to be impaired in Zn deficient plants (Bagci et al. 2007; Cakmak and Marschner 1986; Cakmak and Marschner 1987). Phosphorus effects on Zn may also result from interactions between Zn and P in the soil, interference with the uptake, translocation and use of Zn in the plant, or dilution of tissue Zn levels from a yield response to applied P (Fageria 2001; Lambert et al. 2007).

Other studies have indicated that suppressed mycorrhizal association from high P levels may lead to a reduction of Zn and Cu uptake by the plant (Lambert et al. 1979; Singh et al. 1986; Thompson 1996; Tu 1989). Corn and flax are two crops where P-Zn interactions are frequently seen (Grant and Bailey 1993a; Moraghan 1984; Spratt and Smid 1978; Stukenholtz et al. 1966) and which are also highly dependent on mycorrhizal associations (Grant et al. 2005; Grant et al. 2010; McGonigle et al. 2011; Miller 2000; Monreal et al. 2011). Therefore, suppression of mycorrhizal activity may play a role in the P-Zn interactions seen in these crops (Lambert et al. 1979; Thompson 1996).

Applications of high rates of P fertilizer in an attempt to build soil P levels may lead to a reduction in Zn availability (Spratt and Smid 1978; Wagar et al. 1986). In studies in Saskatchewan and Manitoba, applications of high rates of P fertilizer decreased the concentration of Zn in flax tissue to near-critical levels, although application of Zn fertilizer did not increase seed yield under field conditions (Spratt and Smid 1978). In contrast, when the P-enriched soil was used in growth chamber studies, flax yields were increased by application of Zn fertilizer. Differences between the field and the pot studies may reflect the restricted soil volume in pot studies that may reduce the ability of the crop to access Zn from the soil. In other long-term field studies where soil P was increased by a single broadcast application of a large amount of P, application of Zn-chelate or Zn sulphate increased yield of wheat, while no Zn response occurred on the treatment that had not received P fertilizer (Singh et al. 1986). The Zn uptake in the tissue was reduced by the residual P and increased by either foliar- or soil-applied Zn.

Soils that are low or marginal in available Zn are the most likely situations where P fertilization may increase the risk of Zn deficiency in sensitive crops and lead to the requirement for Zn application for optimum yield. For example, in studies on Manitoba soils low in both P and Zn, canola would respond to P application only when applied with Zn (Tu 1989). Zinc deficiency is relatively rare on the Northern Great Plains, but may occur on soils low in organic matter, sandy soils, calcareous and high pH soils, soils with exposed subsoil due to erosion or land-levelling, or on soils where P has accumulated in high concentrations (https://www.gov.mb.ca/agriculture/crops/soil-fertility/soil-fertility-guide/print,micronutrients.html, accessed October 23, 2018). 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 and P response.

Phosphorus-induced Zn deficiencies can also occur at more moderate P levels. On sites in Manitoba that were marginal in both P and Zn, application of P fertilizer led to an increase in vegetative growth, decreasing the concentration of Zn in the tissue due to dilution and thus inducing a Zn deficiency (Grant and Bailey 1989b). Field studies in Saskatchewan also showed decreases in grain Zn concentration with moderate P applications which were attributed to biological dilutions due to the yield response to P (Schoenau 2018). Reduction in tissue Zn concentration with P application can also occur in the absence of dilution (Grant and Bailey 1989a). In field studies with flax in Manitoba, banded applications of P generally reduced tissue concentration of Zn with reductions also occurring from the residual effect in the year following broadcast P application (Grant and Bailey 1993a; Grant and Bailey 1993b). Applications of zinc sulphate increased tissue Zn concentration, but did not consistently increase crop yield. Yield reductions due to P effects on Zn availability are likely to occur only in situations where the tissue concentration is reduced below critical levels.

9.3 4R Management of P Fertilizer for the Environment

As mentioned in the review chapter on P fertilizer and the environment, the major environmental concern for P fertilizers is the risk of P movement to water bodies. Most of the 4R management practices for P fertilizer that increase the amount of P taken up by the crop will also reduce the risk of P losses from the field to water bodies. Therefore, efficient methods of P fertilizer management will generally improve agronomic, economic and the environmental sustainability.

Selection of fertilizer application rates that are closely matched to crop demand should be used to minimize the risk of P runoff. In simulated runoff studies on soils collected from a no-till field trial, P loss increased with the rate of broadcast P application (Wiens 2017; Wiens et al. 2019). The largest amounts of total P exported in snowmelt runoff (0.45 lb total P/acre) were from the high application rate (72 lb P_2O_5/acre) surface broadcast treatment, with half or less of this amount in the unfertilized and 18 lb P_2O_5/acre treatments.

Risk of P movement increases with the concentration of P near the soil surface (Sawka 2009; Wright 2006). Therefore, P fertilizer placement plays an important role in determining the risk of fertilizer P loss. Broadcast applications tend to increase the concentration of fertilizer at the soil surface, particularly in the absence of intensive tillage (Smith 2016). Risk of P movement will also increase with increasing rates of application and when applications closely precede run-off events. In many areas of the Northern Great Plains, the major path of P movement from the field is through movement of dissolved P in snowmelt runoff. Therefore, fall broadcast applications of P are at high risk for P movement and should not be used in areas where runoff may reach sensitive water bodies. Applying P fertilizer in the spring, at planting and after snowmelt, increases the efficiency of use and reduces the risk of P movement.

In general, fertilizer P management practices that are agronomically efficient also tend to reduce the risk of P movement to water. In-soil banding of P at rates based on an effective soil test and an accurate estimate of crop requirement for P will reduce the accumulation of P at the soil surface. In addition, applying fertilizer P in a subsurface band at or near the time of seeding and after spring snowmelt runoff will also reduce the amount of P required to optimize crop yield, reducing the long-term accumulation of P in the soil.

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?

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