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.

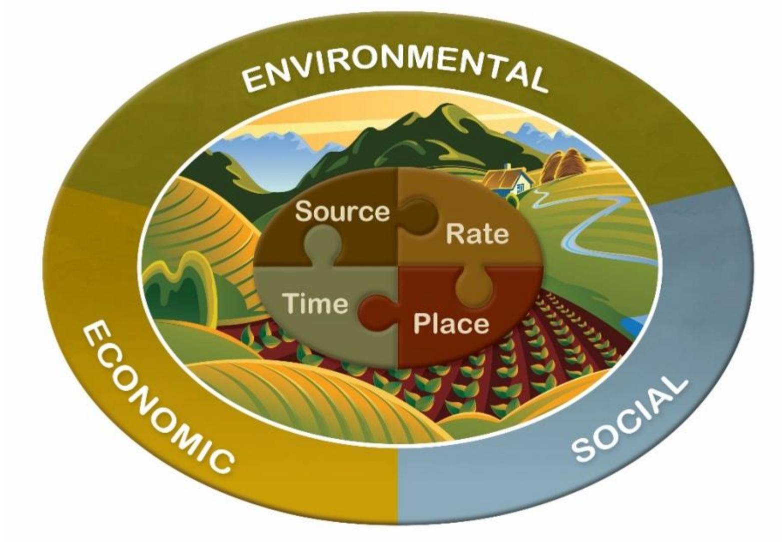

Figure 1. The 4R nutrient stewardship concept defines the right source, rate, time, and place for plant nutrient application as those producing the economic, social, and environmental outcomes desired by all stakeholders to the soil-plant ecosystem (Roberts 2010) figure credit: http://www.ipni.net/ipniweb/portal/4r.nsf/article/communicationsguide

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).

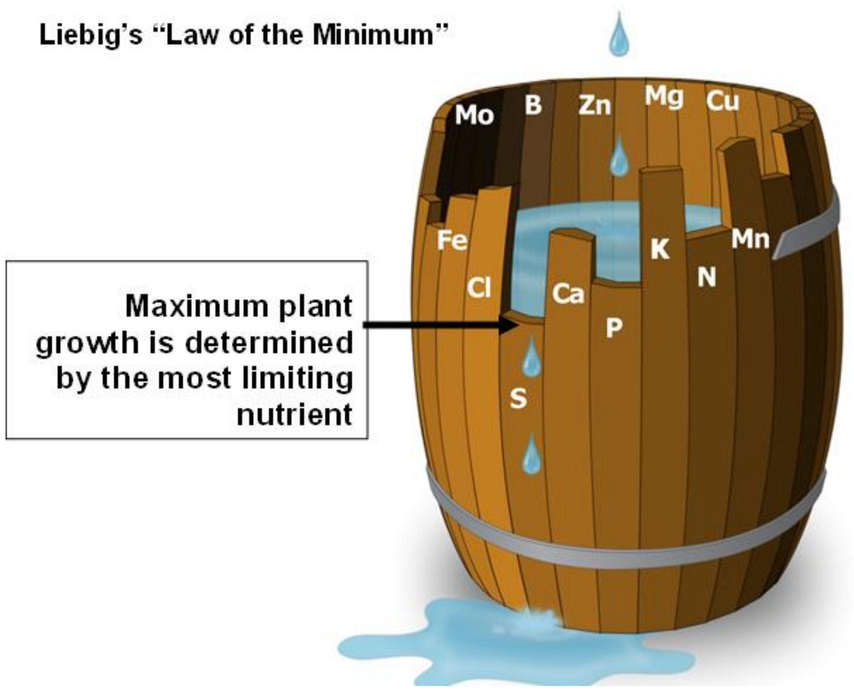

Figure 2. Yield will be limited by the nutrient in the shortest supply (Source: Sask. Ministry of Agriculture).

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.

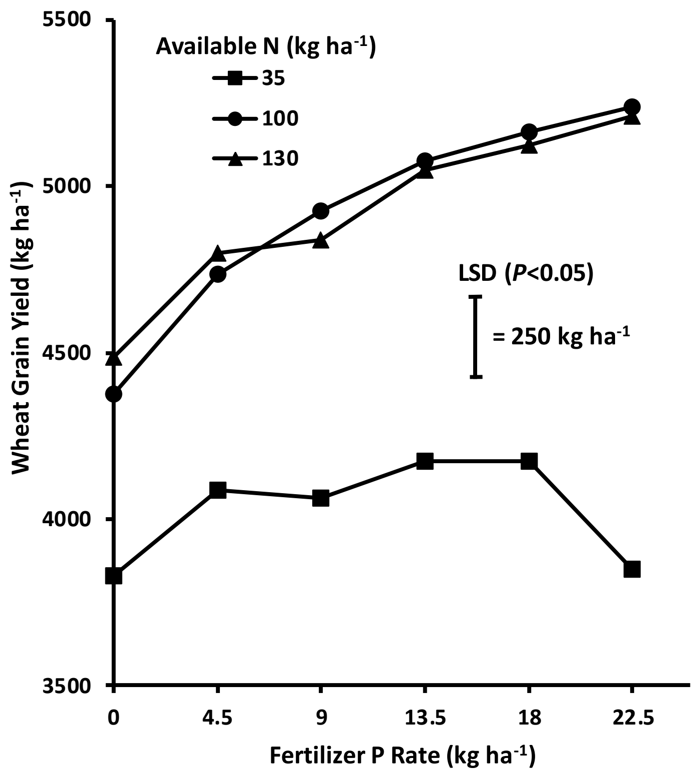

Figure 3. Response of winter wheat to P application increased when optimum levels of N fertilizer were applied (Campbell et al., 1996b).

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.

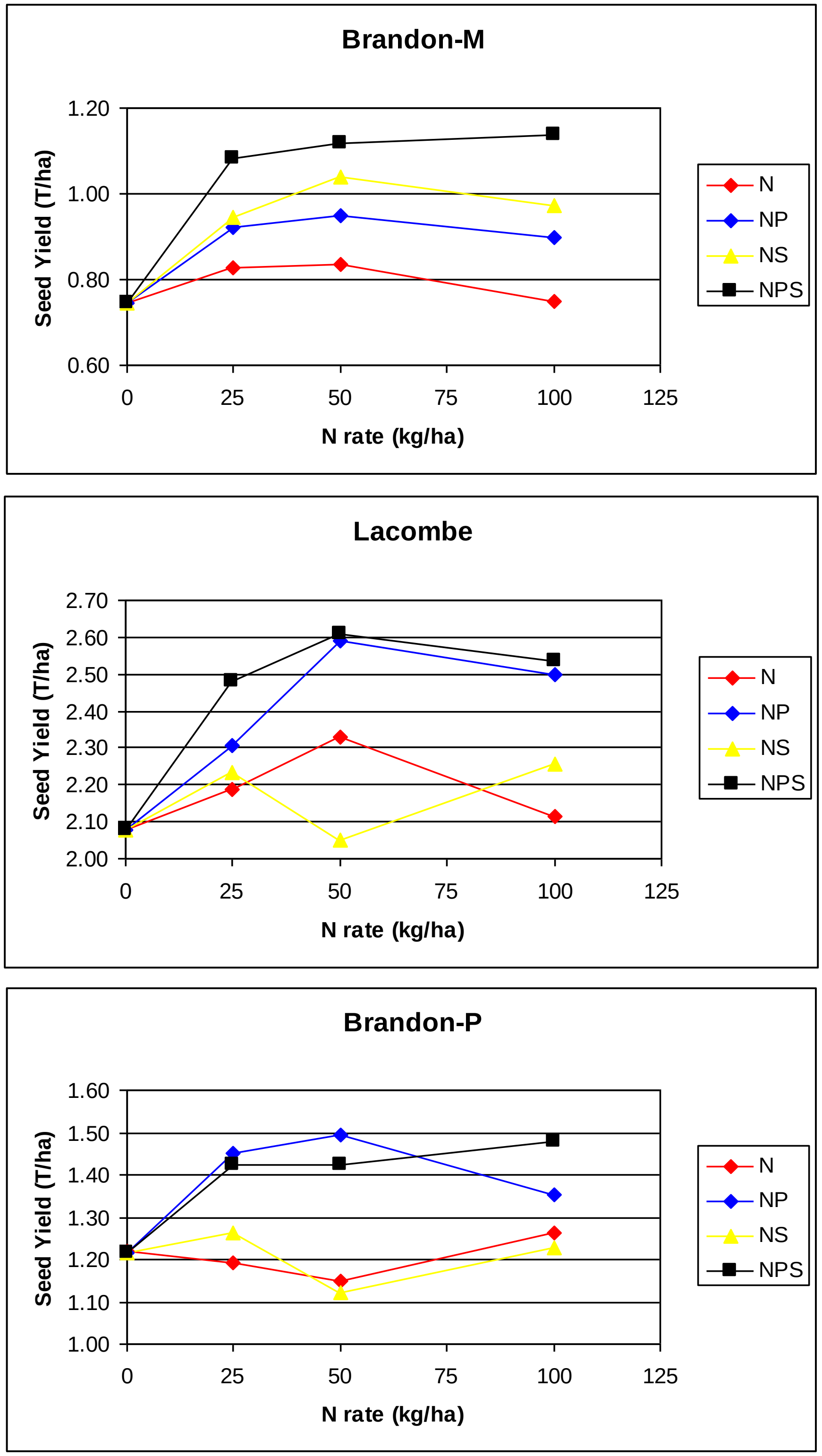

Figure 4. Canola seed yield as affected by N, P and S fertilization at three locations (averaged over cultivars). (Grant et al. 2003b).

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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