4R Management of Phosphorus Fertilizer in the Northern Great Plains

Cynthia A. Grant and Don N. Flaten*

Abstract
Phosphorus (P) fertilizer has played a vital role in increasing the productivity of crop production in the northern Great Plains for approximately 100 years. Throughout this period, agricultural production practices have changed dramatically, while our knowledge of P behavior and beneficial management practices has improved. Some of the more recent and substantial changes in farming practices on the northern Great Plains include 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 P dynamics, and growing concern for the effects of P on water quality. 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. Classic principles and new P fertilizer technologies and management practices must be integrated into packages of 4R practices that optimize crop yield and agronomic efficiency while minimizing negative environmental impact and conserving P resources. Although a wide range of products and practices can be combined for this approach, placing ammonium phosphate fertilizer in a band, in or near the seed-row, at the time of seeding and at a rate that matches P removal by the crop generally provides the greatest P efficiency, long-term sustainability, and environmental protection for small grain, oilseed, and pulse crop production in the northern Great Plains.

Core Ideas
• 4R stewardship for P fertilization is vital for sustainable crop production.
• The most efficient sources of P fertilizer for this region are ammonium phosphates.
• Long-term sustainable crop production requires P fertilizer rates that match crop removal.
• Banding P fertilizer in or near the seed-row is agronomically and environmentally beneficial.

Phosphorus (P) is essential for all forms of life, including food, feed, fiber, and bioenergy crops. Over the long term, sustainable crop production requires that rates of P application match rates of P removal in cropping system and that P must be recycled from postconsumer sources back into the food system. However, for the short-, medium-, and long-term agronomic and environmental sustainability of crop production, all forms of fertilizer P, regardless of source, must be used as efficiently as practically possible.

Toward these goals, the basic strategy of 4R fertilizer stewardship is to apply the right fertilizer source at the right rate, right time, and right place to achieve the economic, social, and environmental goals for each situation. The challenge for 4R stewardship is to develop an effective management package that works within a site-specific, dynamic, and complex system. The 4R practices use science-based fertilizer management principles that have been developed and tested over time but can be modified as knowledge and technology evolve. The 4R tools interact with one another and will be affected by the agronomic, environmental, economic, and logistical considerations for the farm, field, or management zone. Tillage, cultivar selection, weather, pest management practices, land tenure, equipment and labor availability, and a range of other factors will influence 4R choices. Therefore, the 4R framework is adaptable and allows a producer to make nutrient management decisions based on site-specific conditions such a soil type, climate, and cropping history, as well as the local sustainability imperatives (Flis, 2018).

Most soils in the northern Great Plains of North America are deficient in P for crop production (Halvorson and Black, 1985a; IPNI, 2015). In addition, the climate of the northern Great Plains is characterized by cold winters and a short growing season (Padbury et al., 2002). So, when crops are planted in early spring, soils are usually cold, which restricts plant access and uptake for soil P even further, increasing the risk of P deficiency. As a result, P fertilization has played a vital role in increasing the productivity of crop production in the northern Great Plains for approximately 100 years. Throughout this period, agricultural production practices have changed dramatically, as have improvements in our knowledge of P behavior and beneficial management practices. This review outlines the principles and practices of 4R stewardship for optimizing fertilizer P efficiency...
in northern Great Plains cropping systems, for both short- and long-term sustainable production.

**Agronomic Drivers**

Building a 4R management program on the farm must take into account 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. However, some practices will have more specific impacts on 4R management decisions.

**Farm Size and Tenure**

Farm size in the northern Great Plains has increased substantially over the last 30 yr, while the number of farms has decreased (MacDonald et al., 2013; Staciwa, 2019). In addition, a smaller proportion of land is owned by the operator, while an increasing proportion is rented (Statistics Canada, 2019a). There has also been a movement toward greater specialization, with fewer mixed farms and more farms concentrating on either crop production or livestock production (MacDonald et al., 2013). These changes influence fertilizer management practices. For example, larger farmers may prefer broadcast fertilizer to increase speed of operations during the critical seeding period. Farmers with short-term rental agreements may select fertilizer application rates based on short-term crop response rather than managing to maintain soil P fertility near desirable levels (Kastens et al., 2000). Lack of access to nearby manure as a P source will increase the reliance on fertilizer P inputs.

**Reduced Tillage**

A major shift in agriculture on the northern Great Plains over the past 30 yr has been the widespread reduction in tillage. In the Canadian prairie provinces, for example, the proportion of land prepared for seeding using no-till or conservation tillage practices has increased substantially, particularly in Alberta and Saskatchewan, with a corresponding decrease in conventional tillage (Table 1).

With reduced tillage, crop residue retained 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 warmer during the fall and winter (Gauer et al., 1982). The surface residue 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 et al., 1992). The standing stubble will retain snow on the field, further increasing available moisture and winter soil temperatures.

Cooler soil temperatures during spring and summer, along with lack of aeration with reduced tillage, may slow soil organic matter decomposition. Tillage also exposes occluded organic matter, enhancing its decomposition, so reduced tillage will slow the breakdown of this protected organic matter. The slower organic matter decomposition and lack of soil mixing leads to accumulation of organic matter under no-till, particularly in the surface soil (Campbell et al., 1996a, 1997, 1998a, 1998b; Halvorson et al., 2016; Lafond et al., 2011; Liebig et al., 2004; Sainju et al., 2015), increasing soil aggregation and water-holding capacity, while improving tilth and resistance to wind and water erosion. Under long-term no-till, the accumulated organic matter will provide an increased reservoir for nutrient cycling (Lafond et al., 2011).

In a reduced tillage system where soil mixing is minimal, P stratification may occur, with the P accumulating near the zone of placement, near the surface with broadcast application (Holanda et al., 1998) or at banding depth with in-soil banding (Grant and Lafond, 1994; Mallarino and Borges, 2006). Retention of the fertilizer bands may lead to challenges in soil testing, since getting a representative soil sample becomes difficult (Mallarino and Borges, 2006), but it may improve the long-term availability of P fertilizer by slowing reaction of P fertilizer with Ca and Mg in high-pH soils or Al and Fe in lower-pH soils. Stratification of P near the soil surface with broadcast applications may also reduce the availability of residual P for crop uptake if the surface soil dries, “stranding” the P. Continuous cropping with no-till can lead to accumulation of organic P in the labile and moderately labile P pools near the soil surface (Selles et al., 1999). 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, 1987).

**Table 1. Percentage of land prepared for seeding using various tillage systems in the Canadian prairie provinces from 1991 to 2016. Adapted from Statistics Canada (2019b).**

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<td>48</td>
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† Tillage systems in the Statistics Canada census questionnaires were defined for conventional, conservation, and no-till, respectively, as tillage that incorporates most of the crop residue into the soil, no-till or zero-till seeding (including direct seeding into undisturbed stubble or sod), and tillage that retains most of the crop residue on the surface (including minimum tillage) Statistics Canada (2019b).
Enhanced mycorrhizal associations due to undisrupted mycelial networks under reduced tillage may increase P availability for some crops (Bittman et al., 2006; Grant et al., 2005; Miller, 2000). In Manitoba field studies, flax (Linum usitatissimum L.), a highly mycorrhizal crop, produced greater mycorrhizal colonization under reduced tillage as compared to conventional tillage (Monreal et al., 2011). However, tillage system did not influence early season availability of $P$ or crop response of canola and wheat to $P$ fertilizer application (Grant et al., 2009). While the potential of no-till for enhancing mycorrhizal colonization should be considered, particularly for mycorrhizal-dependent crops such as corn (Zea mays L.) or flax (Grant et al., 2005), 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 environmentally and economically sustainable results.

### Increased Cropping Diversity and Intensity

Cropping sequence and intensity will have a major effect on $P$ fertilizer management decisions. For long-term sustainability, $P$ removal in the crop should be balanced by $P$ applications to ensure that $P$ in the soil is not depleted to deficiency or increased to excess. In the absence of $P$ addition, long-term continuous cropping led to greater reductions in plant-available $P$ than did wheat–fallow systems because of the greater removal of $P$ that occurred when a crop was harvested every year (McKenzie et al., 1992a, 1992b; Selles et al., 1999). However, continuous cropping with $N$ and $P$ fertilizer additions to compensate for $P$ removed in the grain increased several soil pools as compared to fallow-based systems (Bowman and Halvorson, 1997; McKenzie et al., 1992a, 1992b; Selles et al., 1995, 1999). The residual $P$ fertilizer enriched the inorganic labile pools, the $P$ held in the microbial biomass, and the moderately labile inorganic $P$. Factors that increase crop yield, such as improved genetics, higher $N$ applications, better agronomic practices, or more favorable weather conditions, will also increase $P$ harvest and the need for $P$ applications to balance $P$ removal (Selles et al., 1995).

Most plant species enhance uptake of $P$ by forming 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). Mycorrhizal colonization can be reduced if a crop is grown on fallow or after a nonmycorrhizal crop such as canola (Grant et al., 2005; McGonigle et al., 1999, 2011; 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, crop management practices for flax or corn production should include careful positioning of these crops in the rotational sequence to encourage mycorrhizal associations and effective use of soil $P$. Phosphorus fertilization also tends to reduce mycorrhizal colonization as high plant $P$ concentration reduces the ability to form the association (Clapperton et al., 1997; Grant et al., 2005). Restriction of $P$ supply to encourage mycorrhizal association is not normally beneficial for crop yield, but in situations where $P$ supply is limited, mycorrhizal associations may help the crop access $P$ from the soil.

Plants can mobilize $P$ from subsoil reserves and deposit it at the surface in crop residues. In addition, legume crops have been reported to increase soil $P$ availability by modifying rhizosphere pH and secretion of carboxylic acids and/or $P$ solubilizing enzymes (Hinsinger, 1998, 2001; Hinsinger and Gilkes, 1995). The $P$ made available by legumes may be utilized by the crops following in the rotation. Therefore, crop sequencing may be used as a way of increasing $P$ availability of sparingly soluble $P$, especially in organic farming systems.

### Balanced Crop Nutrition

Crop yield will be limited by the nutrient in the shortest supply. So, if other nutrients are limiting crop production, the
crop cannot effectively use applied P, restricting both yield and P use efficiency. Similarly, P deficiency will reduce the ability of the crop to attain optimum yield, decreasing use efficiency of water and other nutrients (Kröbel et al., 2012).

Nitrogen is the most commonly limiting nutrient for crop yields 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 (Grant et al., 1985; Grant and Bailey, 1998; Havlin et al., 1990; Selles et al., 2011). In field studies of winter wheat in Saskatchewan, application of N at optimum levels increased maximum yield and the response to applied P (Fig. 1) (Campbell et al., 1996b). Similarly, optimum yields of canola were obtained when P plus N and S deficiencies were corrected (Grant et al., 2003; Karamanos et al., 2005; Nuttall et al., 1990). In studies with barley (Hordeum vulgare L.) in Manitoba, maximum yield on a sandy soil was attained only when P fertilizer was applied with N and KCl (Grant et al., 1995). Canola is especially subject to S deficiency, so S applications may be necessary when canola is grown on low-S soils to ensure efficient use of P and optimum crop yield (Grant et al., 2003, 2004; Grenkow et al., 2013; Karamanos et al., 2005).

In addition to P use efficiency benefits, other nutrients may have a direct effect on P availability. Using ammonium-based instead of calcium-based P fertilizers can increase the availability of the P for plant uptake, through changes in rhizosphere pH (Blair et al., 1971; Flaten, 1989; Miller et al., 1970; Miller and Ohlrogge, 1958) or encouragement of root proliferation in the fertilizer reaction zone (Grunes, 1959; Grunes et al., 1958; Miller and Ohlrogge, 1958). Dual banding of ammonium N, urea, or ammonium sulfate in the same band as P fertilizer may improve the uptake of P as compared to separate application of the N and P (Beever, 1987; Goos and Johnson, 2001; Rennie and Mitchell, 1954; Rennie and Soper, 1958). However, very high rates of N banded with P may delay fertilizer P uptake because the high concentration of ammonium, nitrate, and salt can prevent root penetration and proliferation in the band (Beever, 1987; Flaten, 1989). Therefore, if soil P levels are very low, P fertilizer should not be banded with N fertilizer rates higher than 65 to 75 kg ha⁻¹ to avoid reduced uptake efficiency of the P fertilizer from inhibition of root growth in the dual band, unless some starter P is also applied (McKenzie and Middleton, 2013).

Phosphorus fertilization may also interact with trace elements, both chemically and nutritionally. Phosphorus fertilizers normally contain Zn as a contaminant and so may increase soil Zn concentration over time (François et al., 2009; Grant et al., 2014; Sheppard et al., 2009). However, application of P fertilizer can reduce Zn concentration in the tissue and induce Zn deficiency in many crops (Cakmak and Marschner, 1986, 1987; Gao et al., 2010; Grant et al., 2010; Jiao et al., 2007; Marschner and Cakmak, 1986; Moraghan, 1984; Mortvedt, 1984). Yield reductions from P effects on Zn availability are likely to occur only in situations where the tissue Zn concentration decreases below critical levels. In Manitoba studies on soils low in both P and Zn, canola would respond to P application only when applied with Zn (Tu, 1989). Although Zn deficiency is rare on the northern Great Plains, it 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-leveling, or on soils where P has accumulated to high levels (MAFRD, 2019). 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.

The 4R Package of Management Practices

The 4Rs do not stand alone but interact both with the other agronomic factors on the farm and also with one another. The goal of 4R P stewardship is to improve the overall sustainability of the cropping system by providing 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. Selection of the right combination of source, rate, timing, and placement will be site-specific and driven by the environmental and management factors present at each location.

Phosphorus Fertilizer Rate

The rate of P fertilization should be selected to ensure that the crop can access the P that it requires as it is needed to optimize crop growth. An effective soil test should be used to determine the need for fertilizer application and estimate fertilizer application rate. The Olsen test is effective across a wide range of neutral to high pH soils, including high pH calcareous soils, while the Bray test is effective only in neutral to lower pH, noncalcareous soils (McKenzie et al., 1995). Kelowna and modified Kelowna tests are also effective on many of the soils in the northern Great Plains (Ashworth and Mrazek, 1995; McKenzie et al., 1995; Qian et al., 1994). Soil test P information can estimate the average probability of response to P application and assess the accumulation or depletion of P from a field over time but will not predict precisely how much P to apply or if a response will occur in a specific field and a specific year (Karamanos, 2007).
The short-term sufficiency approach to rate determination for P aims to optimize net returns in the year of application based on the regionally calibrated critical threshold, measured soil test values, and the probability of response to P by the crop in the current year (Howard, 2006). This approach 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). If the soil P can provide an adequate supply to the plant throughout the growing season, application can be reduced or eliminated, although on the cold soils of the northern Great Plains, a response to starter P may occur even when soil P levels are relatively high (Alessi and Power 1980). 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. Likelihood and magnitude of a response to P will tend to increase with the yield potential of the crop (Grant et al., 2009; Zentner et al., 2010), but the response also varies substantially from year to year, depending on environmental conditions (Fig. 2) (Campbell et al., 2005).

The appropriate rate for P fertilizer must be selected to fit properly with the method of placement, to maximize agronomic efficiency and avoid toxicity. While the efficiency of P fertilizer is normally greatest when applied as a band in or near the seed-row, particularly under cold soil conditions, many crops such as canola or flax are sensitive to seed-placed fertilizer and placement of high rates of monoammonium phosphate or ammonium polyphosphate in or too close to the seed-row, reducing stand density and limiting yield response (Nyborg and Hennig, 1969; Qian et al., 2005, 2012; Sadler, 1980; Schoenau et al., 2005; Urton et al., 2012, 2013). Safe rates for seed-placed P in sensitive crops will often be less than removal in the harvested crop, leading to a P deficit. For sensitive crops such as soybean [Glycine max (L.) Merr.], flax, and canola, rates of application may be increased by using broadcast, side-band, or midrow-band placement or by applying higher rates of P to preceding crops in the rotation. This strategy of “rotational fertilization” is supported by field studies at two locations in Manitoba, where P concentration in the tissue of flax at 6 wk was increased by application of P fertilizer to preceding wheat or canola crops (Grant et al., 2009).

An alternate, long-term sustainability approach to P rate determination aims to ensure that the background level of P in the soil is neither depleted to levels that limit crop production nor increased to levels that may pose an environmental risk. The decision to build, replace, or draw down the P in the soil is based on the critical level of soil P below which a yield response to fertilizer P application is likely to occur, reported to be from approximately 15 mg kg⁻¹ using Miller Axley extraction (Malhi et al., 1993; Miller and Axley, 1956) to more than 30 mg kg⁻¹ using the Kelowna extraction (McKenzie et al., 2003, 2001) on the northern Great Plains. On low P soils, small surplus applications of P fertilizer banded near the seed-row to optimize efficiency can be applied annually or through the crop rotation to gradually increase soil P (Selles et al., 2011; Syers et al., 2008). If low-cost sources of P are available, it may be desirable to add larger amounts of P as a separate band or broadcast application, to quickly increase the soil P level (Wagar et al., 1986a, 1986b). If the concentration of soil test P exceeds the agronomic optimum range (e.g., in some manured fields), the soil’s P reserves can be depleted by reducing P fertilization to “starter” rates that are less than removal in the harvested crop.

The long-term sustainability approach assumes that P applied to the soil will not be lost from the system in appreciable amounts except through crop removal. This approach is suited to land with long tenure arrangements and where capital is available to carry the operation through the building phases, or if the present cost of P fertilizer is lower than anticipated future cost, or if low-cost P sources such as manure are readily available. High rates of broadcast P should be avoided in areas where seasonal runoff may move P to surface water. 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 (0.50 kg total P ha⁻¹) were for the high rate of application (80 kg P O₅ ha⁻¹) for surface broadcast treatments, with half or less of this amount of loss for the unfertilized and 20 kg P O₅ ha⁻¹ treatments.

Available P will differ substantially across a field, so uniform fertilizer application based on an average soil test P value may result in over- and under-fertilization in different areas of the field. More detailed site-specific information to vary P applications within a field based on available P or risk of P movement to water bodies could be beneficial to reduce 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 (Franzen and Peck, 1995). Available P tends to be highly correlated with topography, being greater in depressional
areas and smaller on knolls, so sampling may be based on topographical zones (Manning et al., 2001; Wilson et al., 2016). High rates of P may be applied to remediate eroded knolls and make the P concentrations more uniform across the field (Larney et al., 2011; Larney and Janzen, 1996). Optical sensors linked to variable rate applicators are being tested to measure soil P and adjust fertilizer rate on the go (Maleki et al., 2008). In a long-term sustainability system, where P removal is balanced by P inputs, variable P inputs could be based on a yield map to correct the rate for crop removal, assuming lower yields were not caused by P deficiencies.

Phosphorus Fertilizer Source

Selection of a fertilizer source on the northern Great Plains is driven by the soil characteristics. The availability of a P fertilizer source is directly related to its solubility (Chien et al., 2011). The phosphate in the soil solution will react with Ca and Mg in neutral to alkaline soils and Fe and Al in more acid soils to form increasingly less soluble compounds that affect the volume and nature of the reaction zone around the fertilizer granule and influence the ability of the plant to access the fertilizer P (Bertrand et al., 2003, 2006; Chien et al., 2011; Lombi et al., 2004; Racz and Soper, 1967, 1970). The effectiveness of various fertilizer sources will therefore be affected both by their initial content of plant-available P and by the type and speed of reactions of the soluble P with soil constituents.

Phosphate rock is the original source for production of most agricultural fertilizers, but because its solubility decreases with increasing soil pH and Ca content, 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 (Kucey and Bole, 1984). However, rock phosphate may be used in organic farming because it is considered a permissible fertilizer source, while other, more soluble phosphate fertilizers are prohibited.

Monoammonium phosphate (MAP, \(\text{NH}_4\text{H}_2\text{PO}_4\)) is the most common form of P fertilizer used on the northern Great Plains (AAPFCO and TFI, 2015; Statistics Canada, 2019c). It is highly water soluble and provides both ammonium and orthophosphate ions for plant uptake. The solution around the fertilizer granule is moderately acidic, which increases the availability of the phosphate on neutral to high pH soils. The ammonium ions 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 reaction zone (Miller et al., 1970; Miller and Ohlrogge, 1958). While diammonium phosphate (DAP, \(\text{(NH}_4\text{)}_2\text{HPO}_4\)) also contains orthophosphate and ammonium, its solution pH is higher than that of MAP, reducing its mobility and plant availability on calcareous soils (Beaton and Read, 1963; Bouldin and Sample, 1959; Lewis and Racz, 1969). The high pH of DAP and its high ammonium content also produce a high solution concentration of ammonia that can lead to toxicity if too much is placed in the seed-row (Allred and Ohlrogge, 1964).

Another form of ammoniated phosphate fertilizer that has recently become available is struvite (magnesium ammonium phosphate hexahydrate). One advantage of struvite is that it can be manufactured from municipal wastewater or liquid manure, providing a concentrated source of P recovered from the waste stream that can be conveniently recycled back into the production of food or feed. Struvite is not nearly as soluble as MAP (Degryse et al., 2017), so the risk of salt toxicity to seedlings is much less for struvite (Katanda et al., 2019). Growth chamber experiments in Manitoba demonstrated that the P nutritional value of struvite derived from liquid manure was variable, being similar, slightly less, or slightly greater than that for MAP, depending on the soil and crop (Ackerman et al., 2013; Katanda et al., 2016).

The most common fluid phosphate fertilizer on the northern Great Plains is ammonium polyphosphate (APP), which provides both polyphosphate and orthophosphate forms of P. As with MAP and DAP, the ammonium in the fertilizer increases P availability. Plants take up P as orthophosphate, but because the polyphosphates rapidly hydrolyze in the soil to orthophosphate, the P in APP is readily available (Chang and Racz, 1977). Research in Australia showed greatly improved efficiency with fluid formulations such as APP or even dissolved MAP solutions instead of dry granular fertilizer (Lombi et al., 2004, 2005). With fluid sources, the fertilizer was not precipitated as rapidly as with granular forms, increasing the size of the reaction zone and enhancing fertilizer availability (Bertrand et al., 2006). While similar reactions and benefits have been reported on a few occasions in Manitoba soils (Spratt, 1973), fluid forms have generally not produced large benefits on the northern Great Plains, possibly because the soils are not as dry or as calcareous as in Australia (Goh et al., 2013; Racz and Soper, 1967, 1970).

Additives and coatings have been evaluated to improve P fertilizer efficiency. As mentioned previously, the application of ammonium N with P fertilizer generally improves fertilizer P uptake by the plant (Miller et al., 1970; Miller and Ohlrogge, 1958). Decreases in pH related to the oxidation of elemental S and the presence of the sulfate ion may also improve P availability on calcareous soils (Kumaragamage et al., 2004; Mitchell et al., 1952). Therefore, blending monoammonium phosphate, ammonium sulfate, and elemental sulfur into a single granule could theoretically lead to increased availability of the P. However, field and growth chamber studies with Manitoba soils did not show increases in P uptake for this type of product compared with MAP and ammonium sulfate applied as separate fertilizer sources (Kroeker, 2005).

A maleic-itaconic copolymer applied as an additive to either granular or liquid P fertilizer is marketed with the aim of sequestering antagonistic metals in the soil around the fertilizer granule to reduce the tie-up of P (Chien and Rehm, 2016; Degryse et al., 2013). While some studies have reported benefits from inclusion of this type of product in starter P formulations (Gordon and Tindall, 2006), most field studies in the northern Great Plains have not shown a benefit (Chien et al., 2014; Grant, 2011; Karamanos and Puurseven, 2011). Polymer coatings have also been evaluated to control the release of P into the soil solution, slow the formation of sparingly soluble P compounds, and increase the supply of crop-available P (Pauly et al., 2002). Polymer-coated P compounds are not commercially available at present, but in field research trials they performed similarly to uncoated products in promoting yield, with the benefit of producing significantly lower seedling damage.
Phosphorus Fertilization Timing

Early-season P supply is important for optimum crop yield (Grant et al., 2001). As noted above, especially on the northern Great Plains, cold soils during early spring can slow root growth and reduce the solubility and mobility of soil P, limiting the plant’s ability to take up P from the soil (Sheppard and Racz, 1984a, 1984b). Phosphorus is relatively immobile in soil, and P fertilizer will remain close to the site of application (Lombi et al., 2005), so early-season plant access to P will be improved by placing the fertilizer where the roots will contact it soon after germination. 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 (Kalra and Soper, 1968; Strong and Soper, 1973, 1974a). 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.

Placement 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 growth requirements, although yield responses from starter applications may still occur even on high P soils with early seeding into cold soils (Bailey et al., 1977; Barber, 1958; Halvorson and Black, 1985a, 1985b; Read et al., 1973, 1977; Scharf, 1999; Selles, 1993). The slightly denser and cooler soil conditions under reduced tillage, a common practice in this region, may also increase response to starter P (Gauer et al., 1982; Grant and Lafond, 1993; Vetsch and Randall, 2000). However, research with corn in Ontario demonstrated that no-till or zero-till improved the effectiveness of mycorrhizal symbiosis and increased plant uptake of P (Miller, 2000), and research in Western Canada has shown that application of starter P does not seem to compensate for restriction in mycorrhizal colonization due to fallow, tillage, or nonmycorrhizal preceding crops (Bittman et al., 2006; Grant et al., 2009).

Uptake of P from the soil will continue during later growth if environmental conditions permit (Malhi et al., 2006), and later P supply may be important depending on the initial P status of the plant (Sutton et al., 1983). As the plant root system grows, it accesses more P from the bulk soil and less from a fertilizer band (Kalra and Soper, 1968). Lack of late-season P supply on severely depleted soils may reduce maximum yield even with high rates of seed-placed P (Wagar et al., 1986a). Some studies in wheat and corn indicate that foliar application of P may provide a benefit as a top-up treatment if P uptake from seed-placed P applications or from the soil is restricted because of moisture stress or low soil P level (Benbella and Paulsen, 1998a, 1998b; Girma et al., 2007; Green and Racz, 1999; Mosali et al., 2006). However, benefits to foliar application under conditions experienced on the northern Great Plains are rare.

Phosphorus Fertilizer Placement

Optimum fertilizer placement depends on the background levels of P in the soil, the rate of P being applied, and the environmental conditions. 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 establishing perennial forage crops or in a long-term sustainability management approach. Broadcast and incorporation of P fertilizer distributes the P relatively uniformly throughout the surface soil, providing a large zone of fertilized soil with extensive fertilizer-soil contact that increases P fixation and frequently reduces fertilizer use efficiency (Fixen, 1992). Furthermore, if broadcasted P is not incorporated, soluble P is left at the soil surface, contributing to the risk of movement of P into water bodies (Wiens, 2017).

Band applications of P are generally more efficiently used by plants than are broadcast applications of P when applying low rates of P fertilizer, particularly on low P soils (Campbell et al., 1996b). Placing the fertilizer in a concentrated region where the reaction zones of the individual granules or droplets overlap minimizes the contact between the fertilizer and the soil, reducing fixation and maintaining the fertilizer in a plant-available form for longer than a broadcast incorporated application, particularly on high P-fixing soils (Fixen, 1992). Under no-till systems or with perennial crops, the undisturbed bands may remain intact over several years (Grant and Lafond, 1994; Selles et al., 1999). 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 (Barber, 1958; Claassen and Barber, 1976). However, many crops such as canola or buckwheat (Fagopyrum esculentum Moench) 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, 1974b). Placing the fertilizer band in a position where plant roots contact it early in the season and increase their root density in the high P zone, increases the ability of the plant to access adequate P when it is required (Strong and Soper, 1974a).

In the northern Great Plains, P supply for annual spring-seeded crops is often restricted early in the growing season by cold soil temperatures, so crop responses to P fertilizer banding in or near the seed-row may occur, even on soils that are moderate to high in available P. The likelihood of seeing a response to starter P will increase as soil temperature decreases, so starter P may be more important with early seeding into cold soils (Alessi and Power, 1980; Grant et al., 2001; Sheppard and Racz, 1984a, 1984b, 1985; Sheppard et al., 1986; Vetsch and Randall, 2000). Where soil P levels are moderate to high and the soils are warm, the soil P may be sufficient for supporting early plant growth, and deep- or midrow banding may be just as effective as seed-placement (Campbell et al., 1996b; Karamanos et al., 2008; McKenzie et al., 1995; Nuttall and Button, 1990). Therefore, optimal placement can be affected by time of seeding and weather conditions as well as by soil test P.

Placing the fertilizer below the soil surface into moist soil also reduces the risk of “stranding” the fertilizer in dry soil and may give the crop a competitive advantage against weeds for P uptake, as many weeds are shallow-rooted (Blackshaw and Brandt, 2009; Blackshaw et al., 2004). Field studies with wheat showed that 4 yr 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 with weed competition than in weedfree conditions. Banding below the soil surface also reduces the concentration of soluble P at the soil surface, reducing the environmental risk of movement of P to water bodies (Smith et al., 2016, 2017; Weiseth, 2015). Also, as noted previously, band placement of the phosphate with moderate
amounts of ammonium-based or urea fertilizers can increase the availability of the P for plant uptake (Blair et al., 1971; Flaten, 1989; Grunes, 1959; Grunes et al., 1958; Miller et al., 1970; Miller and Ohlrogge, 1958).

Many crops may experience seeding toxicity related to salt damage in the soil solution and to ammonia toxicity from the ammonium applied with the phosphate (Dowling, 1998; Nyborg and Hennig, 1969). 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 (Qian and Schoenau, 2010). Seedbed utilization (SBU) is the degree of dispersion of the fertilizer bands and is calculated as the percentage of the total soil area over which the fertilizer is spread. A higher SBU means that the fertilizer is diluted more than it would be with a lower SBU, reducing the concentration of the fertilizer in the solution and decreasing the risk of seeding 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 consider the type of crop grown, soil and moisture characteristics, type of fertilizer, and the SBU of the seeding equipment being used. Under conditions where a risk of seeding 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 midrow banding. Side banding or midrow banding can produce higher yields by avoiding seeding damage and allowing higher rates of P to optimize crop yield.

**Putting the 4R Package Together**

After the sustainability goals for a specific location have been identified, an effective, locally validated, and calibrated soil test is the first step in developing the 4R package. Soil testing provides an index 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.

In addition, the appropriate rate of application will be related to fertilizer placement and vice versa. Efficiency of use for low rates of P fertilizer is much greater 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., 1996a; Grant and Bailey, 1993; Karamanos et al., 2002; Wagar et al., 1986a; 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 yields. Rate, placement, and timing of P fertilizer application will also interact with crop type due to crop demand, ability to utilize fertilizer applications, and risk of seeding toxicity. If the crop requirement to optimize yield is greater than can be safely placed near the seed-row, options include building P in the soil in the preceding crops and/or years, moving the fertilizer band away from the seed-row or using an opener system with higher SBU, or choosing a fertilizer source with lower toxicity. Therefore, the choices for source, placement, timing, and rate of P fertilizer application should be carefully selected to form a coherent, cohesive package of practices that complement each other, to maximize synergies and minimize trade-offs.

The 4R management package must also consider environmental sustainability, in addition to agronomics and economics. The major environmental concern for P fertilizers is the risk of P movement to water bodies. In northern Great Plains soils, risk of P loss from soil to surface runoff increases linearly with the concentration of P near the soil surface (Fig. 3) (Sawka, 2009; Wright et al., 2006). Therefore, soil test P should not be built above the agronomic optimum range of available P, and when soil test P is within the optimal range, fertilizer application rates should match but not exceed crop removal. Furthermore, P fertilizer should be placed under the soil surface when possible, since broadcast applications tend to increase the concentration of fertilizer and soil test P at the soil surface, particularly in the absence of tillage.

The environmental and agronomic co-benefits of precise placement and timing are optimized when fertilizer P is banded in or near the seed-row at planting, after the spring snowmelt, minimizing the risk of P loss to runoff (Weiseth, 2015). Risk of P movement increases with increasing rates of application particularly when applications closely precede runoff events. In many areas of the northern Great Plains, the major process for P movement from the field is through movement of dissolved P in snowmelt runoff (Tiessen et al., 2010). Applying P fertilizer at spring seeding, after snowmelt, both maximizes the efficiency of use and minimizes the risk of P movement. Conversely, fall broadcast applications of P are at high risk for P movement and should not be used in areas where spring runoff may reach sensitive water bodies. Fall banding is less desirable than spring banding because the fall-applied fertilizer is in the soil at the time of snowmelt runoff. Regardless of when the fertilizer is applied, however, placing the fertilizer in a band below the soil surface substantially reduces the surface concentration and the runoff risk, compared with broadcast applications (Smith et al., 2016).

In general, fertilizer P management practices 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 by reducing accumulation of P near the soil surface. For example, in-soil banding of P at rates

![Fig. 3. Relationships of soil test P and dissolved inorganic P flow-weighted mean concentration (DIP-FWMC) for six extraction methods for the first 30 min of simulated runoff in 38 Alberta soils (Wright et al., 2006).](image)
based on an effective soil test will minimize the accumulation of P at the soil surface. Furthermore, banding the fertilizer P in soil at or near the time of seeding will also minimize the amount of P required to optimize crop yield, reducing the long-term accumulation of P in the soil. Therefore, 4R P fertilizer management improves both the economic and the environmental sustainability of cropping systems in the northern Great Plains.

The principles of 4R nutrient stewardship for P fertilizer should also be integrated with other nutrient, soil, and water management practices. For example, application of livestock manure at rates that meet crop N requirements usually supplies enough P for several years of crop removal (Kumaragamage and Akinremi, 2018). Therefore, livestock manure management should be considered as a complement to 4R P fertilizer management.

Fungal inoculants such as Penicillium bilaiae or mycorrhizae are sometimes promoted as a means of increasing P uptake in field crops. Although benefits of Penicillium bilaiae have occasionally occurred under field conditions (Beckie, 1997; Beckie et al., 1998) those benefits have been erratic, and inoculation with this organism seems to be unreliable as a method of improving P nutritional status of crops on the northern Great Plains (Grant et al., 1999, 2002; Karamanos et al., 2010). Mycorrhizal inoculants are commercially used in horticulture and forestry as well as in organic production systems; however, their effectiveness in large-scale, commercial cropping systems on the northern Great Plains has been limited (Grant et al., 2005; Malhi et al., 2014). Therefore, although mycorrhizae clearly aid in P uptake for many crops, the populations provided in currently available inoculants may not be an improvement over a well-established native population. Furthermore, if inoculants are applied as a substitute for applying P at rates to match crop removal, soil P fertility will eventually decline.

Another important step in a 4R Nutrient Stewardship package is to ensure that appropriate soil and water conservation practices are used, to complement the beneficial nutrient management practices. Soil and water conservation practices should be selected to match local conditions, to ensure that they apply the “right strategy” in the “right place” (Dodd and Sharpley, 2016). The snowmelt-dominated runoff and relatively level landscapes of the northern Great Plains create unique challenges for selecting and using conservation strategies that are effective for reducing the risk of P loss in this region (Baulch et al., 2019; Kieta et al., 2018; Tiessen et al., 2010). These challenges also imply that conservation practices do not easily compensate for suboptimal nutrient management practices, which makes the latter group of practices especially important in this region.

**Summary and Conclusions**

The past several decades have seen 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 P dynamics, and growing concern for the effects of P on water quality. In this region’s predominantly large-scale, dryland farming systems, economically and environmentally sustainable agronomic P management requires science-based application of 4R management principles. As cropping systems, technology, and societal demands evolve over time, fertilizer P management practices must also evolve to address concerns and take advantage of emerging opportunities.

Looking ahead to the long-term future of crop production systems and the role of fertilizer P in the northern Great Plains region, many of the classic principles of P management will continue to apply. For example, over the long-term, sustainable crop production requires rates of P application that match rates of P removal by crops. However, new technologies to recycle postconsumer P back into the crop production system will need to be developed. Nevertheless, whatever source of P is used for crop production must be used as efficiently as possible. Using 4R stewardship practices to apply the right source at the right rate, time, and place will help to optimize crop yield and agronomic efficiency while minimizing negative environmental impacts and excessive depletion of this precious resource.

**Conflict of Interest**

The authors declare no conflict of interest.

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