8.0 Phosphorus Fertilizer Timing

Key Messages

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

Summary

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

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

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

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

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

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

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

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

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

Detailed Information

8.1 Importance of Early Season Supply

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

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

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

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

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

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

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

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

8.2 Requirement for P Supply During Grain Fill/Flowering

An early season P supply can have long-lasting impacts of final crop yield potential, but an external supply of P later in crop growth may also be important, particularly if the plant has not had the opportunity to store surplus P reserves. Early studies suggested that the maximum quantity of P uptake of spring wheat was obtained by heading, with P accumulation in the grain primarily resulting from redistribution of P from the vegetative tissue (Boatwright and Haas 1961). Later work with hard red spring wheat grown under irrigation showed that only 45% of the total P in the above-ground tissue had accumulated by anthesis (Miller et al. 1994), possibly indicating that continued uptake of P may occur if moisture supplies are adequate. Studies conducted at Melfort, SK showed that about half of the P accumulation in wheat occurred by about 41 days after emergence, with the maximum <u>quantity</u> of P accumulation at full flowering to late milk or ripening, depending on the environmental conditions during the growing season (Figure 1) (Malhi et al. 2006). Maximum <u>rate</u> of P uptake was at tillering. The maximum rate of P uptake and the maximum total P accumulation occurred earlier than the corresponding values for biomass accumulation, indicating that P uptake preceded biomass accumulation and that the supply of nutrients must be adequate in early stages to support biomass production. However, P accumulation continued until as late as the early ripening stages. A similar pattern of nutrient accumulation preceding biomass accumulation occurred for pulse crops (Malhi et al. 2007b) and oilseed crops (Malhi et al. 2007a).

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

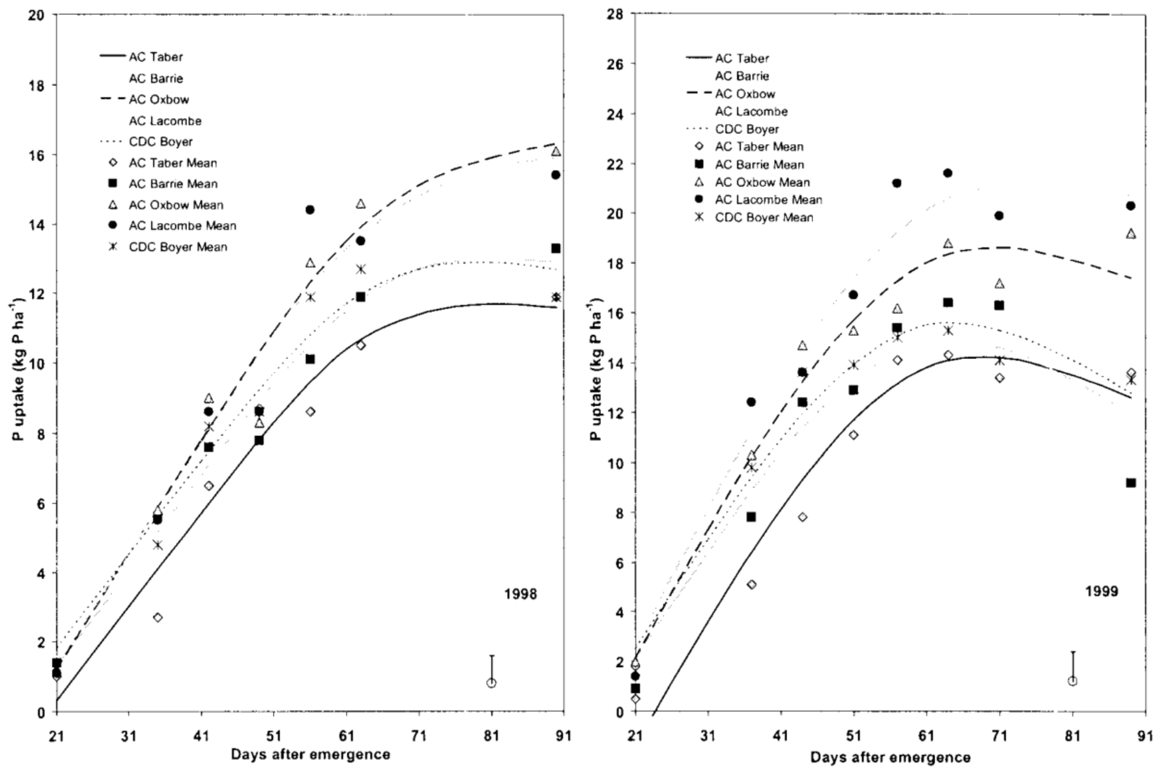

Figure 1: Changes in P uptake (kg P/ha) of spring wheat and barley with days after emergence in field experiments at Melfort, Saskatchewan. Standard error of the mean is shown by line bar. (Malhi et al. 2006).

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

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

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

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

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

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

8.3.1 Soil Temperature

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

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

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

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

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

8.3.2 Amount and Concentration of P in the Seed

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

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

8.4. Implications for P Fertilizer Management

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

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

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

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

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

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

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

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

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

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

Placement in or near the seed-row is most important in low-P soils where the plant cannot access enough P from the soil to meet its early-season growth requirements. Therefore, benefits from starter P are greatest and most frequent where soil test P concentrations are low (Barber 1958; Scharf 1999). Reduced tillage may also increase response to P in or near the seed-row, because soils may be slightly denser and cooler in the spring when undisturbed rather than cultivated (Gauer et al. 1982; Grant and Lafond 1993; Vetsch and Randall 2000). If soils are not extremely deficient in P, application of P as a dual band, deep-placed with N may be effective.

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

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

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

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

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

Gaps in Knowledge

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

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

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