7.0 Phosphorus Fertilizer Placement

Key Messages

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

Summary

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

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

Band applications place the fertilizer in narrow zones, usually below the soil surface, that provide a concentrated source of P. Band applications may be placed any time before planting, at the time of planting, or after planting. Fluid sources may also be dribble-banded on the soil surface. Unless the bands of P are disturbed by tillage, they remain intact through the growing

season. Under no-till systems or with perennial crops, the bands may remain intact over several years because of the lack of soil disturbance. The contact between the banded fertilizer and the soil is low, which reduces the retention of P through soil-fertilizer reactions, so the fertilizer P remains in a plant-available form for longer than with a broadcast, incorporated application, particularly on soils with a high capacity for P retention. The volume of soil fertilized in a band is smaller than with broadcast applications, so there is a smaller region of high-P soil where the plant roots can grow. However, many plants can intensify root development when they contact a high P zone, increasing their ability to use the banded fertilizer P.

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

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

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

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

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

Detailed Information

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

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

7.1 Efficiency of Band versus Broadcast Application

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

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

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

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

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

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

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

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

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

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

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

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

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

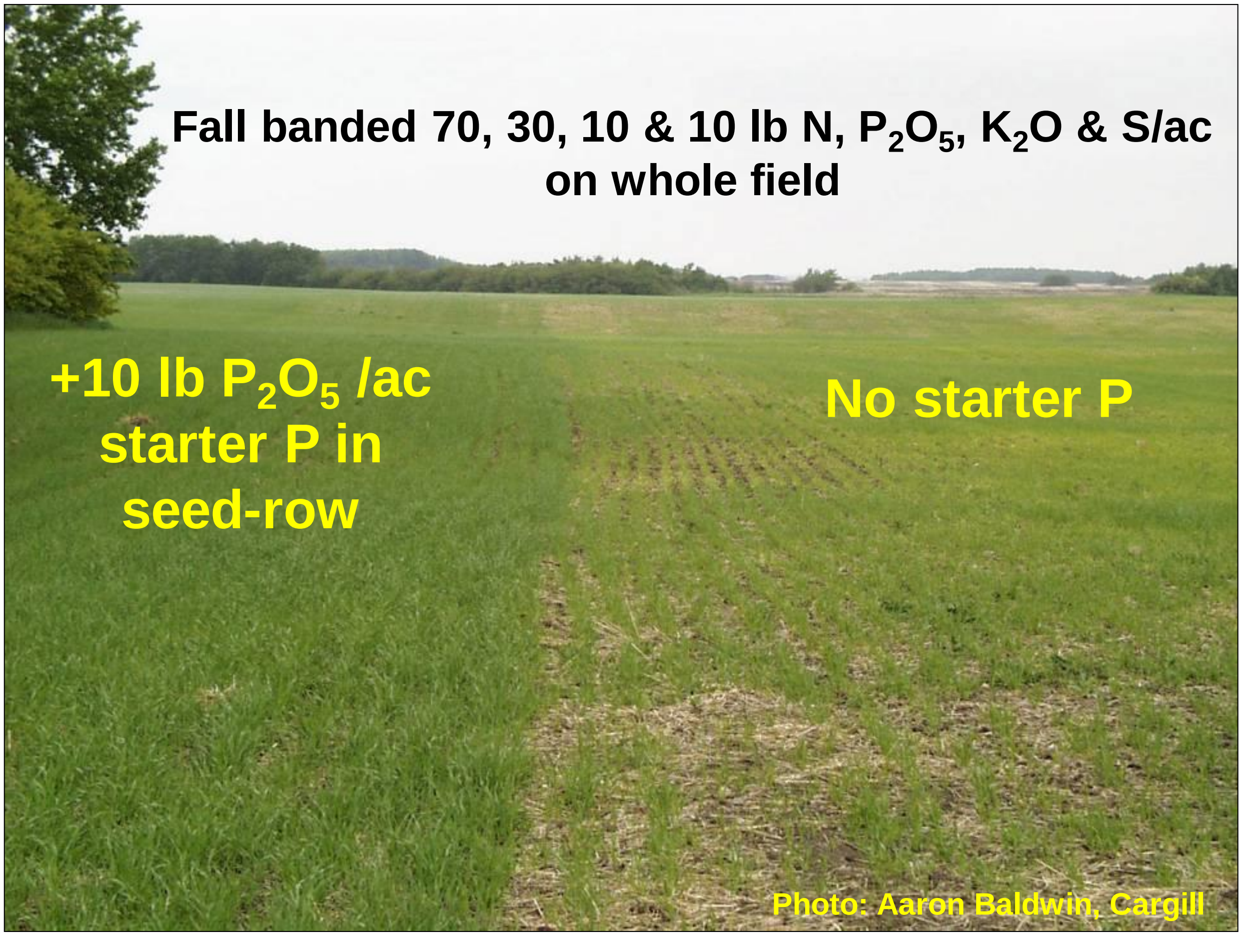

Figure 1. Placement of P in or near the seed-row can improve early growth on cold soils, as shown in this picture of starter P response in Saskatchewan. On the left, a low rate of starter P was applied in the seed-row during spring seeding; both areas of the field received a fall banded application of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

7.2 Effect of Band Position

In a one-pass seeding and fertilizing operation, phosphorus fertilizer can be band applied precisely in the seed-row, near the seed-row, or in a mid-row band. Phosphorus can also be applied in a separate operation in random bands alone or dual banded with nitrogen. The bands can be placed deep in the soil or on the soil surface. With precision GPS technology, bands applied in a separate operation from seeding may be positioned at a specific distance from the seed-row.

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

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

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

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

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

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

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

7.3 Seedling Toxicity Issues Related to Seed-Placed Phosphorus

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

7.4 Dual Banding of N and P Fertilizer

Dual banding refers to the application of N and P fertilizer in a single band, placed deep in the soil either prior to seeding or in side- or mid-row bands at planting. The deep dual bands are positioned far enough from the seed that seedling damage will not occur and, if banded before seeding, deep enough in the soil that they are not disrupted during the seeding operation. Deep placement can also position the fertilizer where the soil stays moist long into the growing season and where shallow-rooted weeds are slow to contact it.

Placement of the phosphate with ammonium-based fertilizers can increase the availability of the P for plant uptake. Ammonium ions increase uptake of phosphate, with the effect being attributed to several different mechanisms. Uptake of ammonium by plants leads to the excretion of H^+ that lowers pH in the rhizosphere and can increase the solubility of $CaHPO_4.2H_2O$ near the root surface and thus improve P availability (Blair et al. 1971; Miller et al. 1970; Miller and Ohlrogge 1958). Studies at the University of Manitoba showed that addition of urea with MAP in a dual band increased the mobility and uptake of P (Flaten 1989). Ammonium has also been shown to increase root proliferation in the fertilizer reaction zone which would increase the ability of the plant to absorb the applied P (Grunes 1959; Grunes et al. 1958; Miller and Ohlrogge 1958).

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

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

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

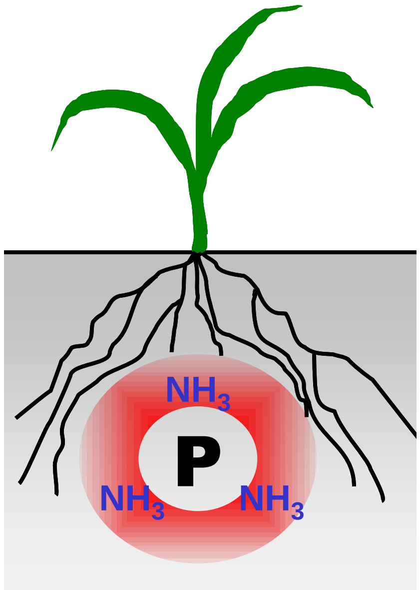

Figure 4. High rates of N fertilizer may delay fertilizer P uptake in "dual" bands, because the high concentration of N delays root penetration and proliferation in the band.

Gaps in Knowledge

More information is required on:

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

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References

Alessi, J. and Power, J. 1980. Effects of banded and residual fertilizer phosphorus on dryland spring wheat yield in the Northern Plains. Soil Science Society of America Journal 44(4):792-796.

Bailey, L. D. and Grant, C. A. 1990. Fertilizer placement studies on calcareous and non-calcareous chernozemic soils: Growth, P-uptake, oil content and yield of Canadian rape. Communications in Soil Science and Plant Analysis 21(17-18):2089-2104.

Bailey, L. D., Spratt, E. D., Read, D. W. L., Warder, F. G. and Ferguson, W. S. 1977. Residual effects of phosphorus fertilizer. II. For wheat and flax grown on chernozemic soils in Manitoba. Canadian Journal of Soil Science 57:263-270.

Barber, S. A. 1958. Relation of fertilizer placement to nutrient uptake and crop yield. I. Interaction of row phosphorus and the soil level of phosphorus. Agronomy Journal 50:535-539.

Beever, D. W. 1987. Effect of various nitrogen fertilizers on solubility and plant availability of phosphorus in dual NP bands M. Sc. Thesis, University of Manitoba, Winnipeg, MB. 115 pp.

Blackshaw, R. E. and Brandt, R. N. 2009. Phosphorus fertilizer effects on the competition between wheat and several weed species. Weed Biology and Management 9(1):46-53.

Blackshaw, R. E., Molnar, L. J. and Janzen, H. H. 2004. Nitrogen fertilizer timing and application method affect weed growth and competition with spring wheat. Weed Science 52(4):614-622.

Blair, G. J., Mamaril, C. and Miller, M. 1971. Influence of nitrogen source on phosphorus uptake by corn from soils differing in pH. Agronomy Journal 63(2):235-238.

Borges, R. and Mallarino, A. P. 2000. Grain yield, early growth, and nutrient uptake of no-till soybean as affected by phosphorus and potassium placement. Agronomy Journal 92(2):380-388.

Campbell, C. A., McLeod, J. G., Selles, F., Zentner, R. P. and Vera, C. 1996. Phosphorus and nitrogen rate and placement for winter wheat grown on chemical fallow in a Brown soil. Canadian Journal of Soil Science 76(2):237-243.

Claassen, N. and Barber, S. A. 1976. Simulation model for nutrient uptake from soil by a growing plant root system. Agronomy Journal 68(6):961-964.

Dowling, C. W. 1998. Seed and seedling tolerance of cereal, oilseed, fibre and legume crops to injury from banded ammonium fertilizers Ph. D. Thesis. Griffith University, Queensland, Australia. 193 pp.

Fixen, P. 1992. Optimum fertilizer products and practices for temperate-climate agriculture. Pages 77-85 *in* J. J. Schultz, ed. Phosphorus and the environment. International Fertilizer Development Center, Tampa, FL.

Flaten, D. N. 1989. The effect of urea on the solubility and plant uptake of monoammonium phosphate Ph. D. Thesis, University of Manitoba, Winnipeg, MB. 253 pp.

Gerwing, J., Gelderman, R. and Bly, A. 1996. Effects of seed-placed P studied. Fluid Journal Fall 1996. https://fluidfertilizer.org/wp-content/uploads/2016/05/15P14-15.pdf

Goos, R. and Johnson, B. 2001. Response of spring wheat to phosphorus and sulphur starter fertilizers of differing acidification potential. The Journal of Agricultural Science 136(3):283-289.

Grant, C. A. 2011. Impact of traditional and enhanced efficiency phosphorus fertilizers on canola emergence, yield, maturity and quality. Pages 10. Agriculture and Agri-Food Canada, Brandon, MB.

Grant, C. A. and Bailey, L. D. 1998. Nitrogen, phosphorus and zinc management effects on grain yield and cadmium concentration in two cultivars of durum wheat. Canadian Journal of Plant Science 78(1):63-70.

Grant, C. A., Flaten, D. N., Tomasiewicz, D. J. and Sheppard, S. C. 2001. The importance of early season phosphorus nutrition. Canadian Journal of Plant Science 81(2):211-224.

Grenkow, L. A. 2013. Effect of seed-placed phosphorus and sulphur fertilizers on canola plant stand, early season biomass and seed yield. M. Sc. Thesis. University of Manitoba, Winnipeg, MB.

Grunes, D. 1959. Effect of nitrogen on the availability of soil and fertilizer phosphorus to plants. Advances in Agronomy 11:369-396.

Grunes, D. L., Viets, F. and Shih, S. 1958. Proportionate uptake of soil and fertilizer phosphorus by plants as affected by nitrogen fertilization: I. Growth chamber experiment Soil Science Society of America Journal 22(1):43-48.

Halvorson, A. and Havlin, J. L. 1992a. Response of dryland winter wheat to residual P. Proc. Proceedings of the Great Plains Soil Fertility Conference, Denver, CO.

Halvorson, A. D. and Havlin, J. L. 1992b. No-till winter wheat response to phosphorus placement and rate. Soil Sci Soc Am J 56(5):1635-1639.

Hammond, D. 1997. Effect of band geometry and chemistry on fertilizer phosphorus availability. M.Sc. Thesis. University of Manitoba, Winnipeg, MB.

Harapiak, J. and Flore, N. 1986. Nitrogen interference with P uptake from dual NP bands. Proc. Proceedings Great Plains Soil Fertility Workshop, Denver, CO.

Henry, J., Slinkard, A. and Hogg, T. 1995. The effect of phosphorus fertilizer on establishment, yield and quality of pea, lentil and faba bean. Canadian Journal of Plant Science 75(2):395-398.

Holzapfel, C. B. 2016. Safe rates of side-banded and seed-placed phosphorus in canola (Project #20140427) Pages 11. Indian Head Agricultural Research Foundation, Box 156, Indian Head, SK, S0G 2K0 Indian Head, SK.

Kaiser, D. E. and Rubin, J. C. 2013. Maximum rates of seed placed fertilizer for corn for three soils. Agronomy Journal 105(4):1211-1221.

Katanda, Y., Zvomuya, F., Flaten, D., Cicek, N. and Amarakoon, I. 2019. Effects of seed-placed hog manure-recovered struvite on canola seedling emergence. Agronomy Journal 111:1-7.

Kalra, Y. P. and Soper, R. J. 1968. Efficiency of rape, oat soybean and flax in absorbing soil and fertilizer phosphorus at seven stages of growth. Agronomy Journal 60:209-212.

Kar, G., Peak, D. and Schoenau, J. J. 2012. Spatial distribution and chemical speciation of soil phosphorus in a band application. Soil Science Society of America Journal 76(6):2297-2306.

Karamanos, R., Flore, N., Harapiak, J. and Stevenson, F. 2014. The impact of phosphorus fertilizer placement on crop production. Soils and Crops Workshop, Saskatoon, SK.

Karamanos, R., Flore, N., Harapiak, J. and Stevenson, F. 2017. The impact of phosphorus fertilizer placement on crop production. Agri Res & Tech: Open Access J 11(4):1-7.

Karamanos, R., Harapiak, J. and Flore, N. 2002. Fall and early spring seeding of canola (Brassica napus L.) using different methods of seeding and phosphorus placement. Canadian Journal of Plant Science 82(1):21-26.

Karamanos, R., Harapiak, J. and Flore, N. 2008. Long-term effect of placement of fertilizer nitrogen and phosphorus on barley yields. Canadian Journal of Plant Science 88(2):285-290.

Karamanos, R. E., Robertson, J. A., Puurveen, D. and Domier, K. W. 2013. Assessment of phosphorus status in a long-term tillage and phosphorus placement experiment. Communications in Soil Science and Plant Analysis 44(1-4):219-231.

Kitchen, N., Westfall, D. and Havlin, J. 1990. Soil sampling under no-till banded phosphorus. Soil Science Society of America Journal 54(6):1661-1665.

Lauzon, J. D. and Miller, M. H. 1997. Comparative response of corn and soybean to seed-placed phosphorus over a range of soil test phosphorus. Communications in Soil Science and Plant Analysis 28(3-5):205-215.

Leikam, D. F., Murphy, L. S., Kissel, D. E., Whitney, D. A. and Moser, H. C. 1983. Effects of nitrogen and phosphorus application method and nitrogen source on winter wheat grain yield and leaf tissue phosphorus. Soil Science Society of America Journal 47(3):530-535.

Leyshon, A. 1982. Deleterious effects on yield of drilling fertilizer into established alfalfa stands. Agronomy Journal 74(4):741-743.

Li, S., Elliott, J. A., Tiessen, K. H. D., Yarotski, J., Lobb, D. A. and Flaten, D. N. 2011. The effects of multiple beneficial management practices on hydrology and nutrient losses in a small watershed in the Canadian Prairies. Journal of Environmental Quality 40(5):1627-1642.

Malhi, S., Nyborg, M., Penney, D., Kryzanowski, L., Robertson, J. and Walker, D. 1993. Yield response of barley and rapeseed to P fertilizer: Influence of soil test P level and method of placement. Communications in Soil Science and Plant Analysis 24(1-2):1-10.

Malhi, S. S., Gill, K. S. and Heier, K. 2001a. Effectiveness of banding versus broadcasting of establishment-time and annual phosphorus applications on yield, protein, and phosphorus uptake of bromegrass. Journal of Plant Nutrition 24(9):1435-1444.

Malhi, S. S. and Heier, K. 1998. How to get the most of P fertilizer in alfalfa stands. Pages 5 Saskatchewan Soil and Crops Workshop. University of Saskatchewan, Saskatoon, SK.

Malhi, S. S., Zentner, R. P. and Heier, K. 2001b. Banding increases effectiveness of fertilizer P for alfalfa production. Nutrient Cycling in Agroecosystems 59(1):1-11.

May, W. E., Fernandez, M. R., Holzapfel, C. B. and Lafond, G. P. 2008. Influence of phosphorus, nitrogen, and potassium chloride placement and rate on durum wheat yield and quality. Agronomy Journal 100(4):1173-1179.

McKenzie, R. and Middleton, A. 2013. Phosphorus fertilizer application in crop production. Alberta Agdex 542-3. Available: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex920 [April 25, 2019].

McKenzie, R. H., Kryzanowski, L., Cannon, K., Solberg, E., Penney, D., Coy, G., Heaney, D., Harapiak, J. and Flore, N. 1995. Field evaluation of laboratory tests for soil phosphorus Pages 505. Alberta Agricultural Research Institute, Edmonton, AB.

Miller, M., Mamaril, C. and Blair, G. 1970. Ammonium effects on phosphorus absorption through pH changes and phosphorus precipitation at the soil-root interface. Agronomy Journal 62(4):524-527.

Miller, M. H. and Ohlrogge, A. J. 1958. Principles of nutrient uptake from fertilizer bands. I. Effect of placement of nitrogen fertilizer on the uptake of band-placed phosphorus at different soil phosphorus levels. Agron J 50:95-97.

Mooleki, S., Malhi, S., Lemke, R., Schoenau, J., Lafond, G., Brandt, S., Hultgreen, G., Wang, H. and May, W. 2010. Effect of form, placement and rate of N fertilizer, and placement of P fertilizer on wheat in Saskatchewan. Canadian Journal of Plant Science 90(3):319-337.

Nkebiwe, P. M., Weinmann, M., Bar-Tal, A. and Müller, T. 2016. Fertilizer placement to improve crop nutrient acquisition and yield: A review and meta-analysis. Field Crops Research 196:389-401.

Nuttall, W. F. and Button, R. G. 1990. The effect of deep banding N and P fertilizer on the yield of canola (Brassica napus L.) and spring wheat (Triticum aestivum L.). Canadian Journal of Soil Science 70(4):629-639.

Nyborg, M. and Hennig, A. M. F. 1969. Field experiments with different placements of fertilizers for barley, flax and rapeseed. Canadian Journal of Soil Science 49:79-88.

Qian, P. and Schoenau, J. 2010. Effects of conventional and contolled release phosphorus fertilizer on crop emergence and growth response under controlled environment conditions. Journal of Plant Nutrition 33(9):1253-1263.

Qian, P., Schoenau, J. J., King, T. and Fatteicher, C. 2005. Preliminary study on impact of seed-row placed P fertilizer on emergence and yield of 10 crops under controlled environment conditions. Pages 6 Saskatchewan Soils and Crops Workshop. University of Saskatchewan, Saskatoon, SK.

Qian, P., Urton, R., Schoenau, J., King, T., Fatteicher, C. and Grant, C. 2012. Effect of seed-placed ammonium sulfate and monoammonium phosphate on germination, emergence and early plant biomass production of Brassicae oilseed crops. Pages 53-62 *in* U. G. Akpan, ed. Oilseeds. InTech, Rijeka, Croatia

Rader, L., White, L. and Whittaker, C. 1943. The salt index-A measure of the effect of fertilizers on the concentration of the soil solution. Soil Sci 55(4):201-218.

Randall, G. and Hoeft, R. 1988. Placement methods for improved efficiency of P and K fertilizers: A review. Journal of Production Agriculture 1(1):70-79.

Randall, G. and Vetsch, J. 2004. Don't overlook effect of variables on P use in corn-soybean rotations. Fluid Journal (Early spring):1-3.

Randall, G. and Vetsch, J. 2008. Optimum placement of phosphorus for corn/soybean rotations in a strip-tillage system. Journal of Soil and Water Conservation 63(5):152A-153A.

Read, D. W. L., Spratt, E. D., Bailey, L. D. and Wader, F. G. 1977. Residual effects of phosphorus fertilizer: I. For wheat grown on four chernozemic soil types in Saskatchewan and Manitoba. Canadian Journal of Soil Science 57:255-262.

Read, D. W. L., Spratt, E. D., Bailey, L. D., Warder, F. G. and Ferguson, W. S. 1973. Residual value of phosphatic fertilizer on Chernozemic soils. Canadian Journal of Soil Science 53:389-398.

Rehm, G. W. and Lamb, J. A. 2009. Corn response to fluid fertilizers placed near the seed at planting. Soil Science Society of America Journal 73(4):1427-1434.

Rennie, D. and Mitchell, J. 1954. The effect of nitrogen additions on fertilizer phosphate availability. Canadian Journal of Agricultural Science 34(4):353-363.

Rennie, D. and Soper, R. 1958. The effect of nitrogen additions on fertilizer phosphorus availability. II. Journal of Soil Science 9(1):155-167.

Roberts, T. and Harapiak, J. 1997. Fertilizer management in direct seeding systems. Better Crops with Plant Food 81 (2):18-20.

Sadler, J. and Bailey, L. 1981. Effect of placements and rates of band-applied phosphorus on growth and uptake of soil and fertilizer phosphorus by flax. Canadian Journal of Soil Science 61(2):303-310.

Sadler, J. M. 1980. Effect of placement location for phosphorus banded away from the seed on growth and uptake of soil and fertilizer phosphorus by flax. Canadian Journal of Soil Science 60:251-262.

Schoenau, J. J., Qian, P. and King, T. 2005. Crop tolerance and response to seed-row phosphorus fertilizer. Agricultural Development Fund, Saskatoon, SK.

Sheard, R. W., Bradshaw, G. J. and Massey, D. L. 1971. Phosphorus placement for the establishment of alfalfa and bromegrass. Agronomy Journal 63:922-927.

Sheppard, S. C. and Racz, G. J. 1984a. Effects of soil temperature on phosphorus extractability. I. Extractions and plant uptake of soil and fertilizer phosphorus. Canadian Journal of Soil Science 64(2):241-254.

Simons, R. G., Grant, C. A. and Bailey, L. D. 1995. Effect of fertilizer placement on yield of established alfalfa stands. Canadian Journal of Plant Science 75(4):883-887.

Soper, R. J. and Kalra, Y. P. 1969. Effect of mode of application and source of fertilizer on phosphorus utilization by buckwheat, rape, oats and flax. Canadian Journal of Soil Science 49:319-326.

Strong, W. M. and Soper, R. J. 1974a. Phosphorus utilization by flax, wheat, rape, and buckwheat from a band or pellet-like application. I. Reaction zone proliferation. Agronomy Journal 66:597-601.

Swiader, J. M. and Shoemaker, W. H. 1998. In-furrow starter fertilization enhances growth and maturity in early sweet corn. HortScience 33(6):1007-1010.

Urton, R., King, T., Schoenau, J. and Grant, C. 2013. Response of canola to seed-placed liquid ammonium thiosulfate and ammonium polyphosphate. Pages 5 Saskatchewan Soils and Crops Workshop. University of Saskatchewan, Saskatoon, SK.

Urton, R., Qian, P., King, T., Schoenau, J. and Grant, C. 2012. Tolerance of Brassicae crop species to seed-placed N, P and S specialty fertilizer. Pages 5 Saskatchewan Soils and Crops Workshop. University of Saskatchewan, Saskatoon, SK.

Wagar, B., Stewart, J. and Henry, J. 1986. Comparison of single large broadcast and small annual seed-placed phosphorus treatments on yield and phosphorus and zinc contents of wheat on Chernozemic soils. Canadian Journal of Soil Science 66(2):237-248.

Weiseth, B. 2015. Impact of fertilizer placement on phosphorus in crop, soil, and run-off water in a brown Chernozem in south-central Saskatchewan. M.Sc. Thesis, University of Saskatchewan.

Wheatland Conservation Area, I. 2017. Seed-placed versus side-banded phosphorus fertilizer effects on faba bean establishment and yield. Pages 1-10. Wheatland Conservation Area, Swift Current.

Wheatland Conservation Area, I. 2018. Demonstrating 4r phosphorus principles in canola Pages 1 pp. Wheatland Conservation Area, Inc., Swift Current.

Wiens, J. T. 2017. Agronomic and environmental effects of phosphorus fertilizer application methods M. Sc. Thesis, University of Saskatchewan, Saskatoon, SK. 123 pp.