5.0 Phosphorus Fertilizer Rates

Key Messages:

- Phosphorus fertilization rate should be selected to ensure that the crop can access the P that it requires as it is needed to optimize crop growth.
- Phosphorus fertilizer rate should be based on a suitable soil test and a prediction of crop requirement for P for the specific crop type and yield potential.
- Rates of P application can be managed for short-term sufficiency or long-term sustainability, depending on the crop rotation, land tenure, relative cost of P fertilizer, risk of P movement to water systems, and the P status of the soil.
- Rate of P application will interact with source, timing and placement.
- Crops differ in quantity of P removed, efficiency of P use, sensitivity to seed-placed P and response to P application, so P fertilizer rate will differ with crop species.
- In the long-term, rate of P application should be matched to P removal to avoid excessive accumulation or depletion of soil P over time.
- Site-specific management (e.g., varying P applications within a field based on soil variability in available P or in risk of P movement to waterbodies) may be beneficial to optimize P inputs, increase fertilizer use efficiency and reduce the potential environmental impact of P applications.

Summary

Phosphorus fertilization rate should be selected to ensure that the crop can access the P that it requires as it is needed to optimize crop growth. However, different strategies exist for phosphorus management, depending on the time scale of production that is considered in the management program. Phosphorus may be managed to optimize production for a single production year, over a rotational cycle or for long-term sustainability. The management strategy selected will be influenced by crop rotation, land tenure, relative cost of P fertilizer, risk of P movement to water systems, and the P status of the soil.

Recommendations for P fertilizer applications based on a **short-term sufficiency strategy** aim to supply just enough P to produce good yield of the current crop. Fertilization is based on applying a rate where the net returns are maximized in the year of application. Economic value of the residual benefits of P fertilizer is not considered. This strategy tends to be most suitable on land with short-term tenure, where cash flow is limited, or in years where fertilizer price is high relative to crop values. Raising or maintaining the soil test P value is not a goal in the sufficiency method and this strategy tends to keep soil test levels in the low to medium range. Phosphorus application rate is based on the critical threshold, soil test values and the probability of response to P by the crop in the current year. In the Northern Great Plains, the fertilizer P would normally be applied as starter or in band placement near the seed to improve efficiency.

A long-term sustainability strategy aims to manage the soil test P level in the soil towards a specific critical range to ensure that the background level of P in the soil is not limiting to crop production. If the soil test is below a critical level, fertilization would **build** the soil P level by

adding more P than is removed by the crop until the target soil level is reached. If the soil test P level is higher than desirable, no P or only a minimal amount of starter P would be applied, to **deplete** the soil P reserves. After that, a **balance** or **maintenance** approach would be followed, to apply the amount of P that is removed by the crop, perhaps plus some extra P to account for retention and other losses, and maintain a target level of soil P. In this approach, application rates are designed to maintain soil test values and eliminate nutrient deficiency, but not necessarily to maximize profit from fertilization of one crop in a single year. The long-term sustainability strategy assumes that P applied to the soil will not be lost from the system in appreciable amounts except through crop removal. It is suited to land that has a long tenure arrangement and where capital is available to carry the operation through the P fertility building phases. It is also attractive if the present cost of P fertilizer is lower than anticipated future cost or if low cost fertilizer sources such as livestock manure are readily available.

Soil testing plays an important part in the selection of P fertilization rate, regardless of whether a short-term sufficiency or long-term sustainability strategy is used. Therefore, an effective soil test to determine the plant-available P in the soil is essential to determine the need for fertilizer application and an estimation of the appropriate fertilizer application rate. The type of soil test used should be suited to the soil characteristics and calibrated for the area. The Olsen test is commonly used in the Northern Great Plains, because it is effective across a broad range of soils, including high pH, calcareous soils. However, the Olsen test may be less reliable on acid soils, while the Bray test is effective only in neutral to low pH, non-calcareous soils. Kelowna and modified Kelowna tests are also considered effective on many of the soils in the Northern Great Plains. Resin-based tests are also available and can provide a measurement of both plant-available P concentration in the soil and rate of replenishment of solution P at the adsorbing surface.

While soil testing is an important guide to P requirements, the response of crops to fertilizer P addition varies with environmental conditions (i.e., from one year to another) and is often not precisely related to the P concentration of the soil. Therefore, soil testing will not predict exactly how much to apply, nor will it assure that a response will be attained every year. Nevertheless, soil test P information is good for estimating the average probability of response to P application and assessing the accumulation or depletion of P from a field over a long period of time. It is fair for estimating the average relative yield response to P across similar fields and yields and for estimating the probability of response in a given field and year. However, soil tests for P are relatively poor at predicting if a specific response will occur in a specific field and a specific year.

In the long-term sustainability strategy, the soil test P level is an important part of the decision to build, replace or draw down the P in the soil. The level of soil P below which a yield response to fertilizer P application is likely to occur is often referred to as the critical level or critical threshold. A long-term sustainability strategy would target a soil P level near the critical threshold, which ranges from approximately 15 ppm to over 30 ppm for Olsen soil test P on the Northern Great Plains.

With very low levels in the soil, building of soil test P may be desirable to ensure that the crop's supply of P is optimized. The P can be built up slowly over time, with small surplus applications of P fertilizer applied annually or through the crop rotation. The approach of slowly building up a low soil P status soil to a satisfactory level will usually be economically viable over the long term, since the applied P is eventually used efficiently. The rate of fertilizer required to build soil test P will depend on the amount of crop removal and the P buffering capacity of the soil. The P fertilizer in a gradual building program should be managed to optimize efficiency by seed-placing or banding near the seed-row. In a crop rotation that includes crops with high sensitivity to seed-placed fertilizer, it may not be possible to apply enough P with the seed to both optimize crop yield and replace or increase background soil P.

Alternatively, if low cost sources of P are available, it may be desirable to add a large amount of P to more quickly increase the soil test P level. This would be especially attractive if the price of P fertilizer is low relative to crop values or if low-cost forms of P, such as livestock manures, are available. Application of manure to satisfy crop N requirements will usually apply enough P for several years of crop removal and increase soil P over time. Situations occur across the Northern Great Plains where long-term annual applications of manures to satisfy N requirements have led to excess concentrations of P in the soil. With excess concentrations in the soil it may be desirable to deplete the soil reserves, to reduce P fertilizer costs, as well as environmental risks such as excess P in runoff. Once the critical level is established, maintaining soils near the critical value for the soil type and farming system is done primarily by replacing the P removed in the harvested crop.

If the short-term sufficiency strategy is selected, a soil test will indicate the likelihood of a response to P application and an estimate of the rate of P required to optimize crop yield in the year of application. The rate of fertilizer application will depend on the ability of the plant to access P from the soil, especially during the early stages of growth. If the soil supply of P is high enough to provide an adequate supply of P to the plant throughout the growing season, P application can be reduced or eliminated. If the soil is deficient in P, fertilizer applications can be used to provide P to the plant as it is required, particularly early in the growing season. Likelihood and magnitude of a response to P will tend to increase with the yield potential of the crop but will also vary with environmental conditions. The rate of P required to optimize crop yield is usually within a narrow range, from about 10 to 50 lb P_2O_5 per acre for small grains, oilseed and pulse crops. A minimum rate of P application will be required to ensure that individual plants have access to fertilizer granules or droplets in a timely fashion, based on the physical distribution of the fertilizer. Reducing the rate of application to extremely low levels limits the number of granules applied and reduces the probability of a seedling root contacting the fertilizer.

If a short-term sufficiency strategy is used for selecting P application rates, differences among crops in their responsiveness to P application must be considered. Different crops have different requirements for P and different strategies that affect their ability to use soil P and their response to fertilizer P. Phosphorus fertilization requirement and yield response of a crop depend both on the total amount of P needed by the plant and its ability to access it from the soil at the time it is required. Cereal crops tend to be moderately effective while canola is highly effective at using both fertilizer and soil P. Flax is relatively poor at using fertilizer P and is highly dependent on mycorrhizal associations to help it access P from the soil. Soybean and other pulse crops appear to be able to use soil P very effectively and therefore do not respond well to fertilizer P applications in Northern Great Plains soils.

Crops such as canola, flax and pulses are sensitive to seed-placed P and yield may be reduced if high rates of P are placed too close to the seed-row. If the rate of P needed for optimum yield is greater than can be safely placed with the seed, it may be applied away from the seed-row or to other, more tolerant crops in the rotation.

Available P differs substantially across a field, so uniform fertilizer application based on an average soil test P value for the field may result in over- and under-fertilization in different areas of the field, reducing fertilizer use efficiency. As well, P runoff may be concentrated in specific areas of the field and ignoring differences across the field would reduce the effectiveness of environmental P management practices. Use of more detailed site-specific information to vary P applications within a field based on soil variability in available P or in risk of P movement to waterbodies could help to optimize P inputs, increase fertilizer use efficiency and reduce the potential environmental impact of P applications.

Fertilizer applications may be adjusted based on grid sampling to identify high and low-testing zones in the field. Optical sensors linked to variable rate applicators are being tested to measure soil P and adjust fertilizer rate on the go. Available P tends to be highly correlated to topography, being greater in depressional areas and less on knolls, so sampling may be based on topographical zones to identify high and low-testing areas. Application of high rates of P to correct deficiencies on upper slope positions may be used to remediate eroded knolls and make the P levels more uniform across the field. Manure is particularly beneficial for correction of P deficiency on eroded knolls because the organic matter it provides can also improve soil structure and water-holding capacity. The benefits from large applications of P would persist for many years.

In a long-term sustainability system, where P removal is balanced by P inputs, variable P inputs could be based on a yield map. Phosphorus removal is highly driven by crop yield. In soils with a long-term history of uniform P application, P may have accumulated in low-yielding areas and may be depleted in high-yielding areas. Using variable P application rates based on crop yields would correct the rate for crop removal, if lower yields were not caused by P deficiencies.

Detailed Information

5.1 Strategies for Managing Rates of P Fertilization

The nutrients that a crop needs to grow must come from somewhere and in managed agricultural systems, the crop will normally access P from fertilizer additions and from the soil. If more P is removed by the crop than is added, P is mobilized from the soil reserves and they will decline over time. If more P is added than removed, the P in the soil will build over time. Phosphorus may also be lost from the system by erosion or movement in runoff, or to a lesser extent, leaching, and this removal must also be considered in the management program. Also, retention or release of nutrients into or out of less available pools may be considered. Phosphorus fertilization rate should be selected to ensure that the crop can access the P that it requires as it is needed to optimize crop growth. However, strategies for managing rates of P fertilization depend on the time scale of production that is considered in the management program. Phosphorus may be managed to optimize production for a single production year, over a rotational cycle or for long-term sustainability. The management strategy selected will be influenced by crop rotation, land tenure, cost of P fertilizer, risk of P movement to water systems, and the P status of the soil.

Recommendations for P fertilizer applications based on a **short-term sufficiency strategy** aim to supply just enough P to produce good yield of the current crop. Fertilization is based on applying a rate which maximizes the net returns in the year of application. Economic value of the residual P fertilizer is not considered. This strategy tends to be most suitable on land with short-term tenure, where cash flow is limited, or in years where fertilizer price is high relative to crop values (Kastens et al. 2000). Altering the soil test value is not a goal in the sufficiency method and this strategy tends to keep soil test P concentrations in the low to medium range and, in many cases, leads to declines in soil test P concentrations. Phosphorus application rate is based on the critical threshold, soil test values and the probability of response to P by the crop in the current year. In the Northern Great Plains, the fertilizer P for annual crops would normally be applied as starter or in band placement to maximize efficiency.

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

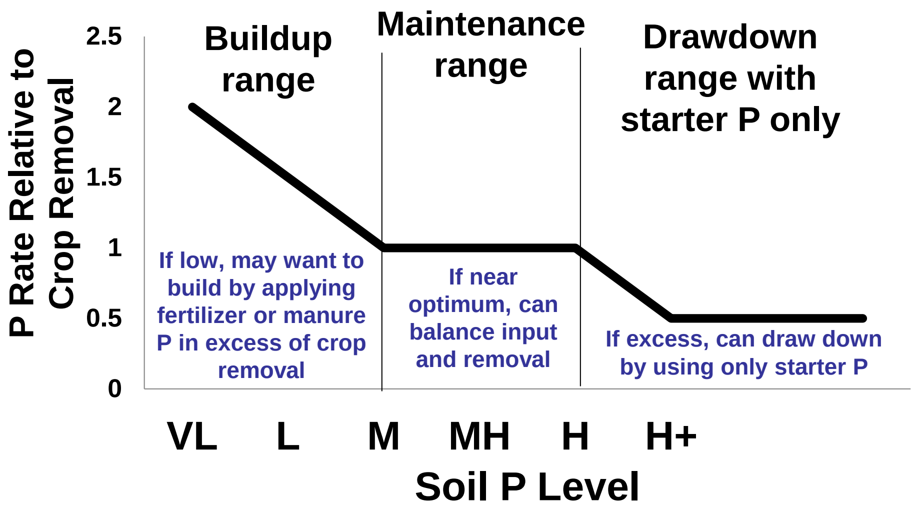


Figure 1. The long-term sustainability strategy for P management relies on building, maintaining or depleting soil P, based on soil test P concentration.

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

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

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

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

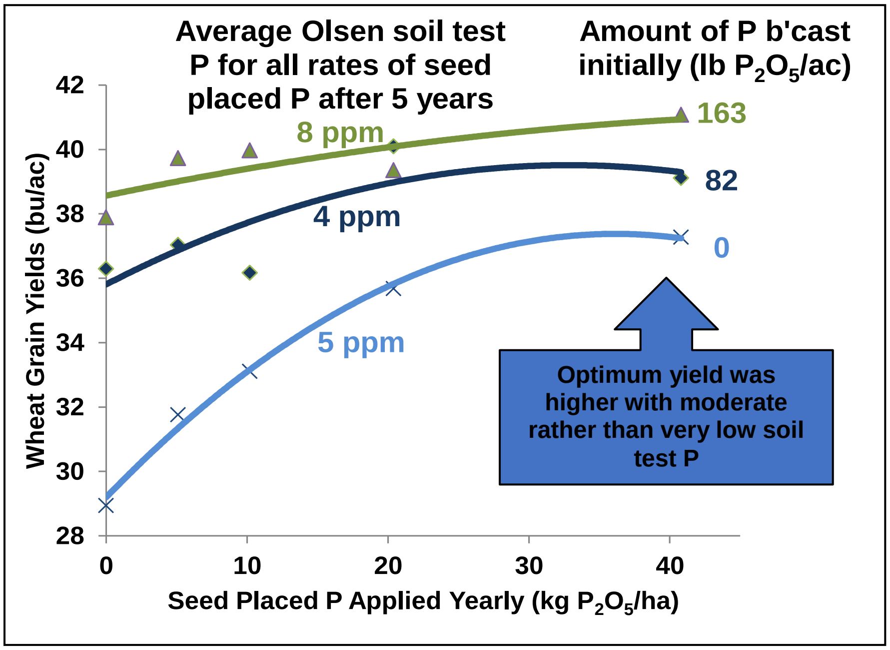


Figure 2. Yield is a function of both background P fertility in soil and annually applied fertilizer P (Wagar et al. 1986a).

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

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

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

Soil testing plays an important part in the selection of P fertilization rate, regardless of whether a short-term sufficiency or long-term sustainability strategy is used. An effective soil test measuring the plant-available P in the soil is essential to determine the need for fertilizer application and estimate the optimum rate of fertilizer application. Different soil testing methods are available using solutions that selectively extract a portion of soil P that provides an index of the plant-available P (Table 2).

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

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

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

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

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

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

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

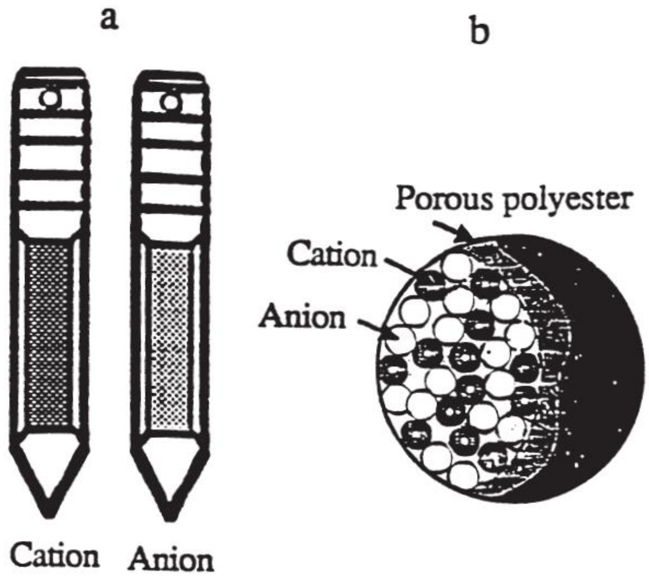


Figure 3. Diagram of PRS™ membrane probes (a) and UNIBEST resin capsules (b) (Qian and Schoenau 2002)

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

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

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

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

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

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

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

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

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

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

[c] Formerly used by Enviro-Test Labs

[d] Formerly used by Norwest Labs

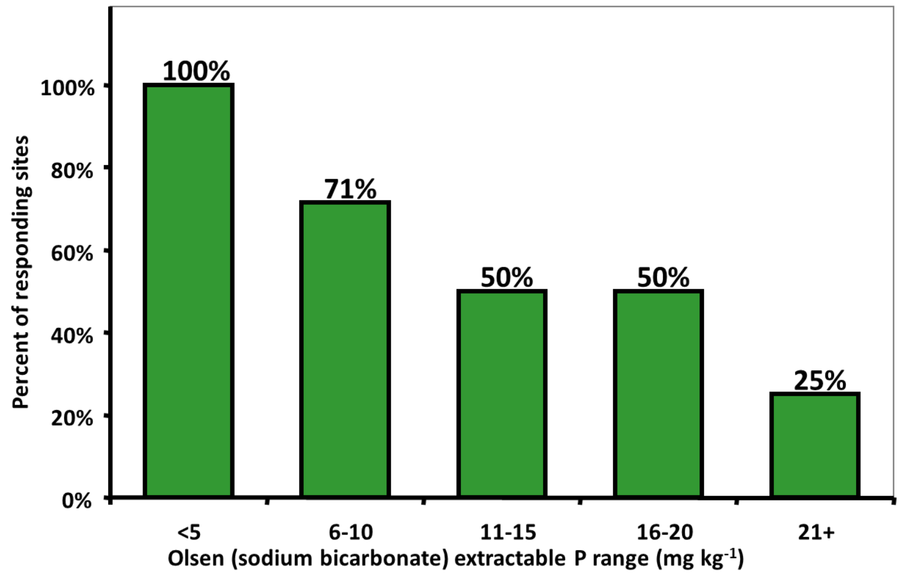


Figure 4. Percentage of sites responding to phosphorus application at various Olsen-P soil test ranges (Karamanos et al. 2010). Of the 47 sites, 5 sites tested less than 5 ppm, 14 sites tested between 6 and 10 ppm, 20 sites tested between 11 and 15 ppm, 4 sites tested between 16 and 20 ppm and 4 sites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

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

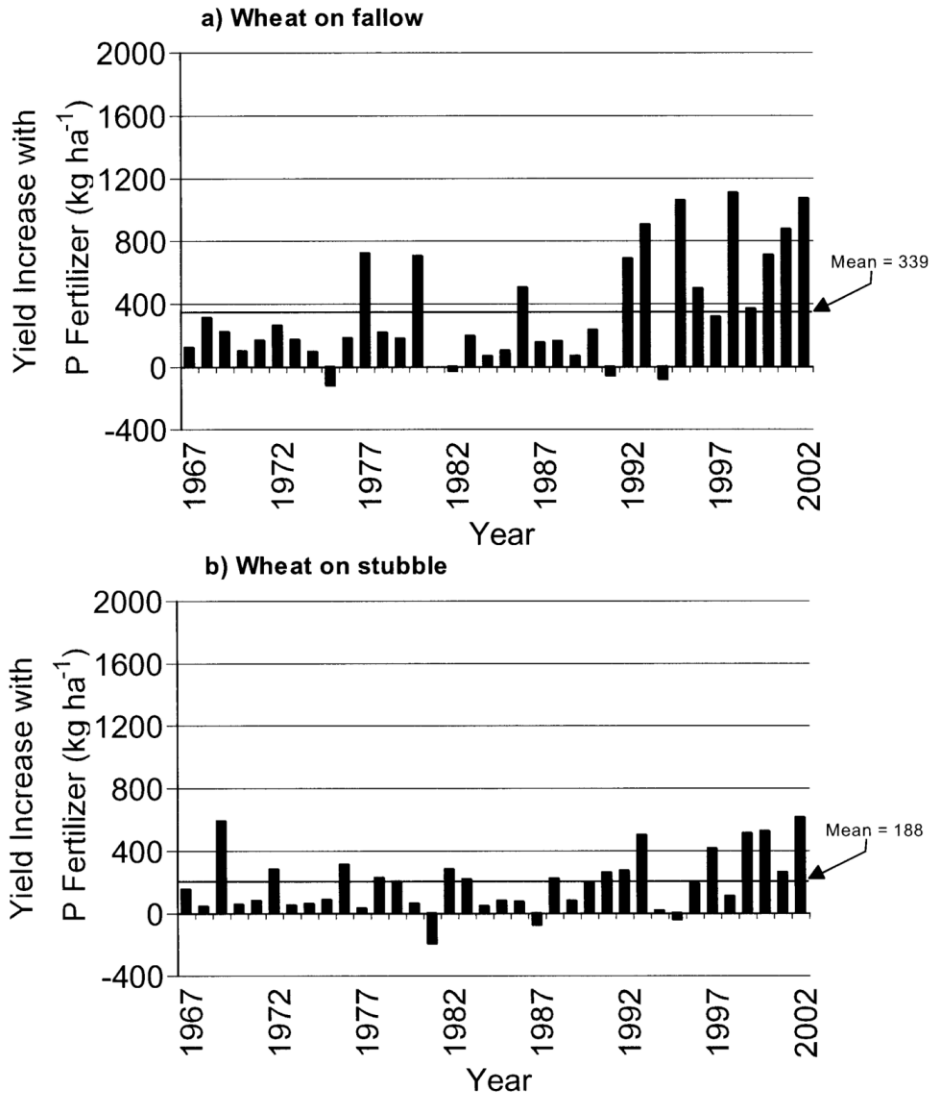


Figure 5. Spring wheat response to annual applications of seed-placed P fertilizer at a rate of 20 lb P_2O_5/acre on stubble and fallow in a fallow-wheat-wheat rotation at Swift Current, SK from 1967 to 1998 (Campbell et al. 2005).

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

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

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

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

In a long-term sustainability strategy, the soil test level is an important part of the decision to build, replace or draw down the P in the soil. The level of soil P below which a yield response to fertilizer P application is likely to occur is often referred to as the critical level or critical threshold. Phosphorus fertilizer applications are used very inefficiently in the year of application when soil test P concentration is much above the critical value (Syers et al. 2008). A long-term sustainability strategy would aim to target a soil P level near the critical threshold, that may range from approximately 15 ppm (Malhi et al. 1993) to over 30 ppm (McKenzie et al. 2003b; McKenzie et al. 2001b) in the Northern Great Plains.

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

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

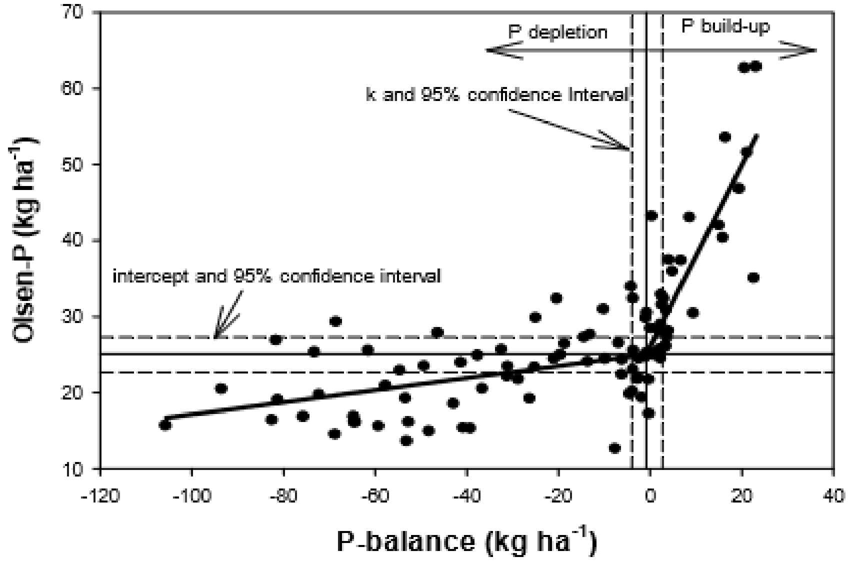
Table 5. Phosphorus uptake and removal (lbs per unit of yield) for a range of crops[a].

Crop	Unit for Yield	Uptake Min	Uptake Max	Uptake Prairies	Removal Min	Removal Max	Removal Prairies
		---- lb P_2O_5 ----					
Spring wheat	Bushel	0.73	0.88	0.68	0.53	0.65	0.51
Barley	Bushel	0.50	0.61	0.33	0.38	0.46	0.29
Oats	Bushel	0.36	0.45	0.27	0.26	0.28	0.23
Canola	Bushel	1.31	1.63	0.87	0.94	1.14	0.68
Faba Beans	Bushel	1.78	2.19	-	1.10	1.34	-
Flax	Bushel	0.75	0.92	0.71	0.58	0.71	0.64
Lentil	Bushel	0.76	0.92	-	0.60	0.66	-
Peas	Bushel	0.76	0.92	0.53	0.62	0.76	0.44
Corn	Bushel	0.57	0.69	0.46	0.39	0.48	0.39
Sunflowers	CWT	1.15	1.40	1.90	0.70	0.90	1.20
Soybeans	Bushel	1.10	1.32	1.37	0.80	1.00	1.17
Dry Beans	CWT	-	-	1.39	1.40	1.40	1.12
Potatoes	CWT	0.15	0.18	0.18	0.08	0.10	0.16

[a] Low and high values are estimates from the Canadian Fertilizer Institute (CFI 2001) and values for Canadian Prairie crops are from Heard and Hay (2006). Values for lentils and faba bean are from https://saskpulse.com/files/general/160401_Phosphorus_management_for_pulses2.pdf, accessed March 25, 2019). It is important to note that these values are strongly affected by crop yield potential, genetics and environment. Much of the data contributing to this table was collected using older cultivars and management practices. Efforts are currently underway to update uptake and removal values using more current information.

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

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



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

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

Ideally, the P fertilizer in a gradual building program should be managed to optimize efficiency by seed-placing or banding near the seed-row. However, in a crop rotation that includes crops with high sensitivity to seed-placed fertilizer, it may not be possible to apply enough P with the seed to both optimize crop yield and replace or increase background soil P (Table 6). In that case, other options such as banding P away from the seed-row or increasing rate of P application in less sensitive crops should be considered.

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

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

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

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

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

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

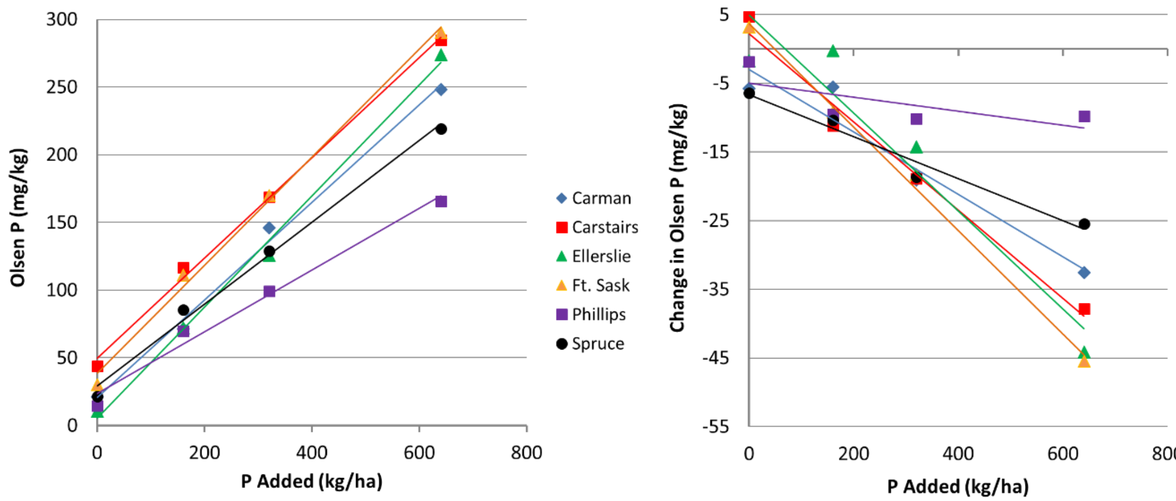


Figure 7. Response of Olsen-P concentration in the surface 6 inches (15 cm) of soil to cumulative rates of fertilizer P applied to a durum-flax rotation at 6 sites over an 8-year period. Left graph shows Olsen P in the surface soil at the end of 8 years of P fertilization, while the right graph shows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

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

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

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

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

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

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

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

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

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

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

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

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

5.5 Differences in P Response among Crops

If a short-term sufficiency strategy is used for selecting P application rates, differences among various crops in their responsiveness to P application must be considered. Different crops have different requirements for P and different strategies that affect their ability to use soil P and their response to fertilizer P. As discussed in Chapter 2, plants may increase root development and root proliferation, exude organic acids or phosphatases, or form associations with mycorrhizal fungi to improve access to P. The ability of the crop to use the various strategies for P access will influence its ability to utilize the P it needs, both from the soil or from the fertilizer application. Therefore, P fertilization requirement and yield response to P fertilizer of a crop will depend both on the total amount of P needed by the plant and its ability to access it from the soil at the time it is required.

5.5.1 Small Grain Cereal Crops

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

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

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

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

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

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

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

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

5.5.2 Canola (Rapeseed)

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

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

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

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

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

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

5.5.3 Flax

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

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

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

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

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

5.5.4 Pulse Crops and Soybeans

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

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

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

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

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

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

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

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

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

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

5.5.5 Small area crops

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

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

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

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

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

5.5.5 Forage crops

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

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

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

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

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

§Standard error of the mean.

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

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

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

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

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

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

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

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

5.6 Site Specific Management

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

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

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

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

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

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

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

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

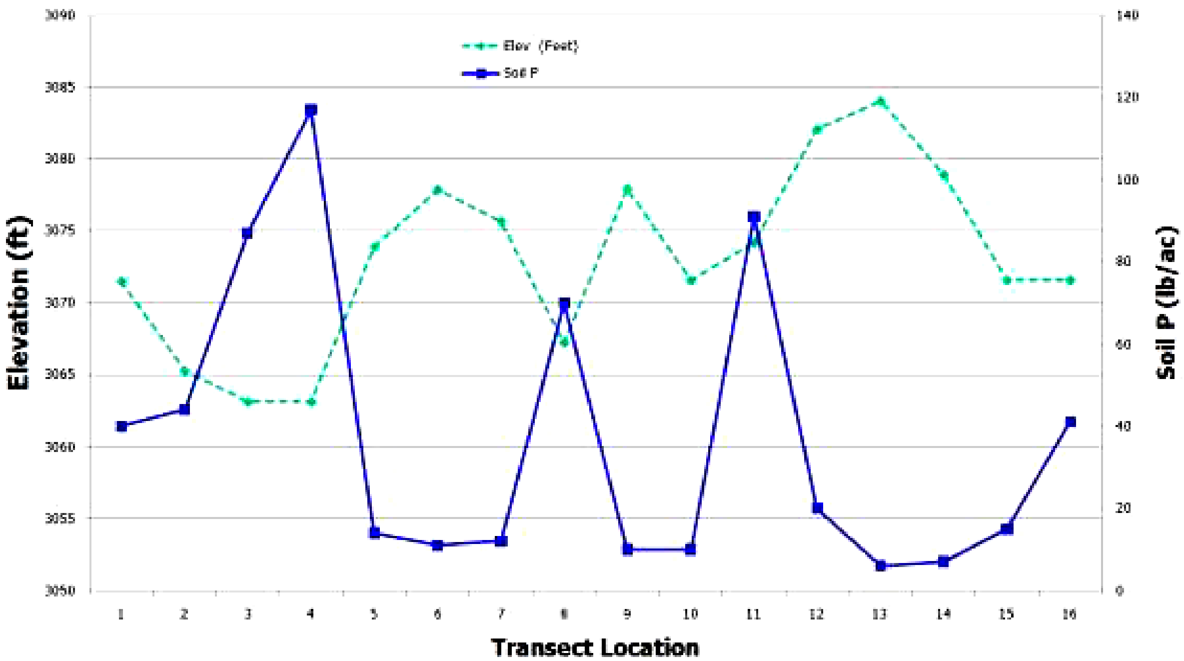


Figure 8. Changes in soil test phosphorus concentration in the 0-15 cm depth and elevation along an 800 m transect in Alberta (Pauly 2010).

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

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

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

In a long-term sustainability strategy, where P balances are managed to build, maintain or deplete soil P reserves, variable P inputs could be based on a yield map. Phosphorus removal is highly driven by crop yield. In soils with a long-term history of uniform P application, P may have accumulated in low-yielding areas and been depleted in high-yielding areas. Using variable P application rates based on crop yields would correct the rate for crop removal. This approach would assume that lower yields were not caused by P deficiencies.

Gaps in Knowledge

More information is required on:

- soil test P calibration data for probability and magnitude of P response for new crop varieties/hybrids, as well as new crops grown under field conditions for the Northern Great Plains
- the appropriate target "background" soil test P concentration for long term agronomically, economically and environmentally sustainable P management in the soils and cropping systems of the Northern Great Plains.
- changes in soil P concentrations with P surpluses or deficits on different soil types with more modern diversified and extended rotations.
- the impact of in-soil banding as compared to broadcast applications of large amounts of P fertilizer on eroded and/or carbonated knolls.
- the long-term benefits of variable rate P application, from agronomic, economic and environmental perspectives.
- crop demand and removal for P by improved cultivars with high yield potential.

Consideration should be given to collecting information from field experiments in a web-based database similar to the Better Fertiliser Decisions for Cropping Systems (BFDC) National Database from Australia (Watmuff et al. 2013) to improve decision support systems and fertilizer recommendations.

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