The Importance of Early Season Phosphorus Nutrition

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Abstract

Phosphorus (P) fertilization is a major input in crop production on the Great Plains, as many soils lack sufficient P for effective crop production. To optimize crop nutrition, P must be available to the crop in adequate amounts early in the growing season. Phosphorus is needed from the earliest stages of crop growth, because it is important in nearly all energy-requiring processes in the plant. Phosphorus stress early in the growing season will reduce crop productivity more than P restrictions later in the year.

Plants have adapted to increase their ability to access P and avoid deficiencies. When under P stress, plants will use their resources to extend their root system to improve the chance of contacting P. Some plants can modify rhizosphere pH or excrete organic acids to increase the uptake of P. Plants such as canola or wheat can increase root proliferation in high-P regions to enhance P uptake while others will form associations with vesicular arbuscular mycorrhizae. Plants differ in strategies adopted and in efficiency of P absorption. Understanding how different plants respond to P deficiencies and fertilization can help in designing P management practices most suited to each crop type.

Phosphorus placement in or near the seed-row helps supplies P to the crop early in the growing season. Other ways of managing P could include increasing seed concentrations of P, using tillage system and crop sequencing to improve mycorrhizal activity, or maintaining adequate P levels in the soil. Since plants differ in their ability to access P from the soil and fertilizer applications, different practices may be needed for different crops. We need to more accurately predict early P supply from the soil to avoid over-fertilization or crop deficiencies. By fertilizing only where P limits crop production and by improving fertilizer efficiency, we can optimize economic of crop production and avoid environmental problems.

Introduction

Phosphorus is a critical nutrient for plant growth, since it is involved in cellular energy transfer, respiration, and photosynthesis. Phosphorus is also a structural component of the nucleic acids of genes and chromosomes and of many coenzymes, phosphoproteins and phospholipids (Ozanne 1980). An adequate supply of P is essential from the earliest stages of plant growth. Early season deficiencies of P can lead to restrictions in crop growth from which the plant will not recover, even when P supply is increased to adequate levels.

In most crops, only a small amount of the phosphate is actively involved in metabolism (Bieleski 1973; Lefebre and Glass 1982). If P supply is adequate, the majority of the P is non-metabolic and stored within the vacuole as inorganic P. Concentrations of stored inorganic P tend to vary to a great extent with external P availability, while concentrations of metabolically active organic P are more stable. The length of time required for a P deficiency to affect plant growth depends on the extent of P reserves in the plant. High concentrations of stored P from the seed or from luxury uptake early in the season will produce reserves of available P that can protect the plant from short-term P deficiencies later in the plant's life cycle. Under P stress, the inorganic reserves are depleted while the metabolic phosphate levels remain essentially unaffected.

Effect of P Deficiency on Plant Development

Moderate P stress may not produce obvious deficiency symptoms. However, with more severe P deficiency, plants become dark green to purplish in colour (Hoppo et al. 1999). Phosphorus deficiency can reduce both respiration and photosynthesis but, if respiration is reduced more than photosynthesis carbohydrates will accumulate, leading to dark green leaves (Glass et al. 1980). A deficiency can also reduce protein and nucleic acid synthesis, leading to the accumulation of soluble nitrogen (N) compounds in the tissue, and ultimately resulting in cell growth being delayed and potentially stopped. As a result, symptoms of P deficiency include decreased plant height, delayed leaf emergence, reductions in tillering, secondary root development, and dry matter yield and seed production.

Plants respond to P deficiency by adaptations that maximize the likelihood of producing some viable seed (Hoppo et al. 1999). Generally, P stress decreases the number of seeds produced more than seed size. For example, in cereal crops the reduction in seed number occurred through reduced numbers of fertile spikes and reduced numbers of grains per tiller. Reducing the number of seeds formed increases nutrient supply per seed and enhances the likelihood of producing viable seed for successful reproduction.

Assessment of P Deficiencies

The visual symptoms of plant P deficiency are generally neither definitive nor pronounced enough in the field to be very diagnostic. These symptoms can be mistaken for symptoms of other stresses unless P-fertilized and non-treated areas within the field are compared. Plant analysis for assessing plant nutrient status assumes consistent relationships between tissue nutrient concentrations and the adequacy of nutrients for plant growth. Phosphorus status is usually determined from the total tissue P concentration on a dry weight basis. Other procedures measure inorganic P present in expressed sap or in an extract from the fresh or dried tissue. Interpretive criteria (empirically established) must be specific for the crop, plant part sampled, stage of growth and nutrient fraction determined. Critical nutrient concentrations for optimum crop growth can be affected by factors such as cultivar, growing conditions and concentrations of other nutrients in the tissue.

The P concentration in tissue of annual plants generally declines with advancing plant age/stage of growth (Racz et al. 1965, Bélanger and Richards 1999), as do critical nutrient concentrations (Bélanger and Richards 1999). Thus, highest tissue P concentrations are required at early growth stages. The decline in P concentrations with time is greatest for plants initially highest in P, resulting in a narrowing in the range of plant P concentrations as the season progresses; by late stages of growth, tissue P concentrations in P-stressed cereal plants may be only slightly lower than those in non-stressed plants (Elliott et al. 1997a,b,c). Phosphorus concentrations decline with time in annual plants because as the plant matures an increasing proportion of its dry weight is composed of low-P structural and storage tissues. For spring wheat in Manitoba, Tomasiewicz (2000) found that critical leaf P concentrations for maximum grain yield declined most sharply early in the season, to the beginning of stem extension, and then tended to level off. Between ten and thirty days after emergence (i.e. beginning of tillering and beginning of stem extension) the critical P concentration in the youngest expanded blade declined from 0.43% to 0.30%. Under the slower early season growing conditions of South Australia, Elliott et al. (1997b,c) reported that critical P concentrations were constant until the 3_leaf stage, after which they declined steeply. Relatively early-season (e.g. tillering stage) plant analysis for P was recommended in both studies, confirming the importance of early-season P nutrition. Other studies have shown the advantage of early tissue testing to diagnose P status of annual grain crops (McLachlan 1982), while Mallarino (1996) indicated that tests based on the P concentration of young plants and ear leaves have similar capacities for identifying severe P deficiencies in corn.

Phosphorus Supply during Early Plant Growth Is Critical

A large number of studies in many plant species have shown that early season P supply is critical for optimum crop yield. In the 1920's, a series of studies by Gericke (1924, 1925) and Brenchley (1929) demonstrated that P restrictions during the first 4 to 6 weeks of growth led to large reductions in tillering and head formation in wheat and barley, while deficiencies after 6 weeks had limited effects on final crop yield. Withholding P during early plant growth will limit crop production and cause a restriction in crop growth from which the plant may not recover. Phosphorus limitation later in the season has a much smaller impact on crop production than do limitations early in growth.

Table 1: Average tiller and secondary root development of wheat as influenced by the absence of P during various intervals (adapted from Boatwright and Viets, 1966)

Weeks without P in a 10-week growing period	Tillers/6 plants at week 10	Secondary roots/6 plants at week 10
0 Control	27.7	120
First 2 weeks	22.3	76.2
Last 2 weeks	23	123.6
First 2 weeks	10.3	21.6
Last 2 weeks	24	106.2
First 2 weeks	9.4	19.8
Last 2 weeks	24	66

Table 2: Influence of P supply in nutrient medium on the dry matter accumulation of spring wheat and intermediate wheatgrass. Results are presented as a percentage of the check (1 to 5 weeks). Adapted from Boatwright and Viets, 1966)

P supply period (weeks of growth)	Spring wheat	Intermediate wheatgrass
	-------------------------Dry matter,	% of check--------------------------
1 to 5	100	100
1 to 4	80	66
1 to 3	50	25
3 to 5	80	59
4 to 5	30	19

In spring wheat and intermediate wheat grass, maximum tiller production was obtained when P was supplied in the nutrient culture for the first five weeks of growth (Boatwright and Viets 1966) (Table 1). Longer periods of available P did not increase number of tillers produced, and tillers did not develop until P had been supplied for one week or more. If P was withheld for three or more weeks, final tiller production was reduced. Available P is required early in plant growth for maximum root development and secondary root development followed the same pattern as tiller development.

Final dry matter yields of spring wheat and intermediate wheatgrass were as high when P was provided for only five weeks as when it was applied for longer periods (Table 2). Supplying P for the first three to four weeks of growth led to reduced to dry matter yields. In addition, withholding P for the first two to three weeks led to dry matter yields. Although both crops absorbed only small quantities of P during the first two weeks of growth (15 percent of maximum for wheat and 5 percent for intermediate wheat grass) this early accumulation of P was extremely important for maximum dry matter and grain yields at maturity.

Under field conditions, an adequate supply of P during early season growth is critical in obtaining maximum yield. In corn, P was needed until the six-leaf stage to promote maximum grain yield in studies conducted by Barry and Miller (1989). But, effects of early season P stress may be less persistent under field conditions than under controlled environment conditions. Tomasiewicz (2000) monitored shoot dry matter accumulation through the growing season for spring wheat in Manitoba, as affected by fertilizer P applied at planting in the seed-row and/or broadcast/incorporated just prior to planting (Figure 1). At all P-deficient sites, relative dry matter yields crop were reduced by P restrictions for only the first two to five weeks from crop emergence. The slopes of the lines joining data points in Figure 1 correspond to relative shoot growth rates in the various treatments, with the slope for the high-P set to zero (i.e. at 100% Relative Yield at all times). At maturity, P deficiency reduced yield by about 12 to 25% when compared to the yield of the high-P treatment as compared to a 25-50% loss in dry matter yield due to P stress apparent earlier in the season. Other factors, such as moisture supply, may restrict yield later in the growing season so that the yield potential promoted by optimal early season P supply is not attained. However, early season P deficiency can set a limit to the maximum potential yield (Barry and Miller 1989).

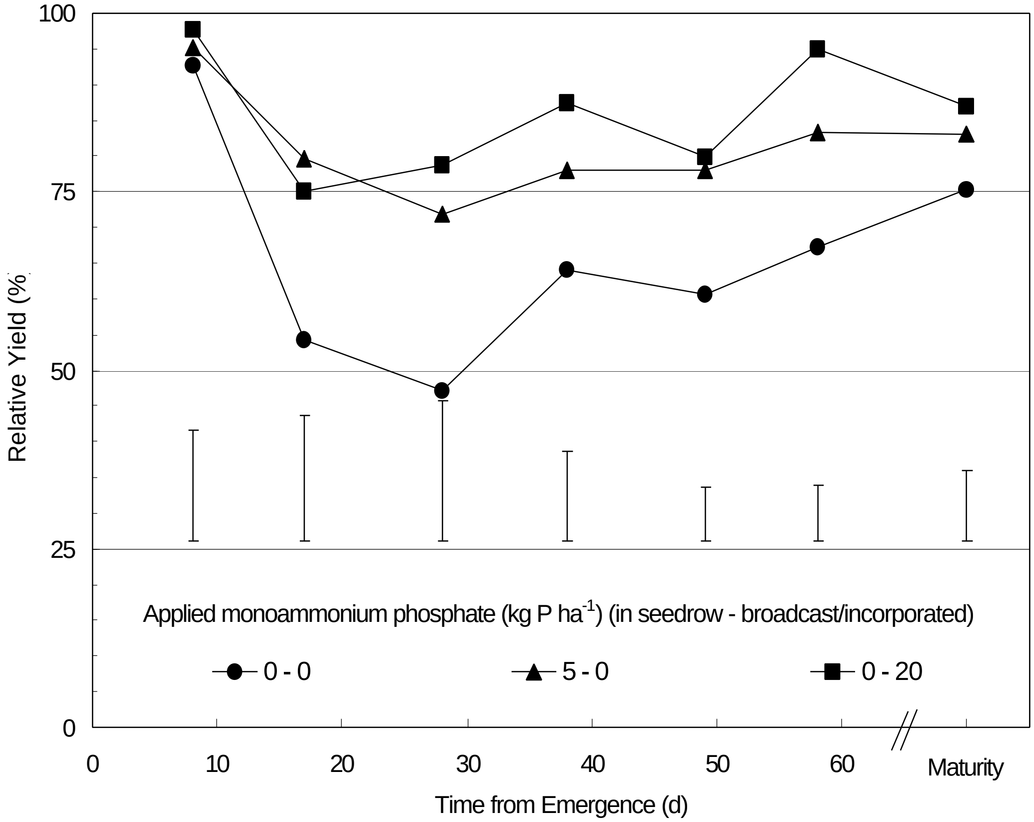

Figure 1. Effect of P fertilizer treatments on spring wheat shoot dry matter yield through the growing season at a very low-P site in Manitoba. Yield is expressed as a percentage of the yield of the high-P treatment (20-50); i.e. relative yield. Error bars indicate LSD (P<0.05) among treatments.

A number of reasons have been proposed as to why early season P is so critical for later plant growth and development. Some process in the plant apparently leads to an irreversible response that impairs later growth, even when the plant subsequently receives adequate nutrients. Early season P deficiency may reduce yield by restricting carbon (C) nutrition of the plant. In field-grown corn, P deficiency slows the rate of leaf appearance and leaf size, particularly in the lower leaves (Barry and Miller 1989, Pellerin et al 2000). With less leaf growth and solar radiation interception caused by P deficiency, C nutrition of the plant may fall and so reduce subsequent nodal root emergence, which would have an additional impact on P uptake capacity.

Yield response of corn to seed-placed P is related to the P concentration at the four- to five-leaf stage, or possibly earlier. It has been suggested that a mechanism relating seedling P nutrition to kernel number in corn might be due to the effects of P on early ear size (Barry and Miller 1989). A P deficiency during ear formation, which occurs by the six- or seven-leaf stage, could decrease ear size, leading to fewer initiated kernels per ear. A similar mechanism may occur in other species, since reductions in seed number with P deficiency occur in a variety of crops (Elliott et al. 1997a, Hippo et al. 1999).

Requirement for P Supply during Grain Fill/Flowering

Although P supply during early development has a dominant effect on crop yield potential, there may also be a requirement for an external supply of P later in crop growth. Boatwright and Haas (1961) suggested that spring wheat normally attains maximum uptake of P by heading, and P accumulation in the grain is largely due to redistribution from the leaf and stem tissue. However, in studies of hard red spring wheat under irrigation, only 45 percent of the total above-ground P had been accumulated by flowering (Miller et al. 1994). As the plant developed, P was removed from the leaves and stems and moved to the grain, until at maturity, the distribution of P among the leaves, stems, heads, and grain was approximately 3, 8, 9 and 80 percent. Adequate P had been absorbed by winter wheat at the first node stage to ensure maximum P concentration levels in the mature grain, but a small supply of P was required through the ripening stage to allow carbohydrate translocation mechanisms to function for maximum mature grain yield. Phosphorus in the head of wheat may be supplied from both post-anthesis soil uptake and internal redistribution of nutrients accumulated during early growth (Mohamed and Marshall 1979).

Differences Among Plants in P Uptake Strategies and Effectiveness

The importance of P for plant survival has supported the development of plant adaptations to improve the access of the crop to P supplies. Concentration of P in the soil solution is usually low since phosphate ions are rapidly adsorbed on soil surfaces as well as precipitated as calcium (Ca), magnesium (Mg), and iron (Fe) and aluminum (Al) phosphates. Most phosphate moves to the plant by diffusion rather than mass flow, and as P movement through the soil to the root is restricted, diffusion is generally considered to be the rate-limiting factor in P absorption by plants (Barber 1977). It is estimated that, on average, phosphate could only diffuse approximately 0.5 mm, so that only phosphate within 0.5 mm of a plant root is positionally available for absorption.

Uptake of P by the plant is proportional to the root density, so enlargement of the root surface area increases the ability of the plant to access and absorb P from the soil. Therefore, many plants respond to low soil P concentrations by enlarging the root system and developing highly branched roots with abundant root hairs to enhance their ability to explore new soil reserves of P and efficiently extract P from the soil when areas of high P are encountered (Barber 1977, 1980). Many plants will form associations with mycorrhizal hyphae, which also increase the ability of the crop to access and absorb P (Miller et al. 1995).

The root:shoot ratio of crops tends to increase with early season P deficiency (Brenchley 1929, Schjorring and Jensen 1984). Growth reduction is generally greater in the shoot than in the root, allowing the plant to maintain root growth and encounter and extract P from the soil. Growth of tops and roots closely paralleled the distribution of P between the plant parts. Where P supply was low, the proportion of P held in plant roots was higher than where the P supply was moderate. At higher P status, there was also a relative increase in root P as compared to shoot P. This may imply P retention by the root to meet its requirements at low concentration, P export to the shoot at sufficient concentrations, and P retention by the root at high concentration to avoid P toxicity in the shoot (Schjorrring and Jensen 1984).

While increased rooting is an important factor in improved P access under conditions of a limited P supply, there are other plant responses to restricted P supply that can increase the accumulation of P in the plant (Glass et al. 1980). Some plants release phosphatases into the growth medium to break down organic phosphates, increasing the supply of available P. Plants such as canola can acidify the rhizosphere through secretion of organic acids to increase P availability. Some plants may also respond to P deficiency by increasing their ability to accumulate the P that they contact. In corn, a decrease in P level in the plant appears to signal the roots to absorb P more rapidly. Plants which have experienced P stress show a great increase in rate of P uptake when they come in contact with P as compared to plants that have not experienced P stress. The higher rate of uptake leads to higher P concentration in the tissue of plants that were initially P-stressed plants as compared to plants that were grown with a consistently adequate P supply (Boatwright and Viets 1966).

Phosphorus-deficient plants may lose the ability to regulate P uptake, leading to unrestricted uptake of P when P supply in the nutrient solution is re-established (Green et al 1973). Normal plants may have a regulatory mechanism that limits excessive P uptake or accumulation, with the mechanism being ineffective in P-deficient plants. Therefore, P-deficient plants may accumulate toxic amounts of P on exposure to levels of solution P that, when continuously available, are non-toxic. A high ratio of organic to inorganic P in the plant seems to signal a transport system to increase the influx rate. The restoration of an external inorganic P supply appears to be regulated by inorganic P concentration in the plant, which could help to protect plants against P toxicity.

Soil Temperature and P Supply

Annual crops on the prairies are often planted into cold soils. With cold temperatures, P supply during the early stages of crop growth to may be reduced because of slower diffusion of P in soil and lower soil P solubility. Cold soil temperatures at seeding may enhance the need for P application near the seed-row.

The simplest effect of soil temperature is on P solubility, with less P being soluble at lower temperatures (Sheppard and Racz 1984a). However, the effect of temperature is not necessarily the same among different soils (Sheppard and Racz 1984b). On soils where root growth was least affected by low temperature, plant uptake of P was most affected by temperature. Clearly, solubility of soil P was affected regardless of the effect on root growth.

Temperature also affects the rate of reaction of fertilizer P with soil (Sheppard and Racz 1984a). Fertilizer P reacts and transforms rapidly when first applied to soil, but continues to transform for months afterward. The transformation is generally to less-soluble forms, with lower temperatures slowing the process. Obviously, this effect of temperature can be important in early season, and is opposite to the effect on the solubility of native soil P. The result is that with cold soil, native soil P will be less available to the plant and fertilizer P will remain more available. This increases the relative value of fertilizer P for cold soils.

Banding of fertilizer P is common practice, because the plant uses P in the band more effectively than broadcast P. Temperature can affect plant use of banded P by influencing root proliferation in the fertilizer band compared to adjacent unfertilized soil (Sheppard and Racz 1985). At warm soil temperatures, wheat showed little root proliferation in the band, but at 10°C (50°F), root mass was up to 3.6-fold greater in the P band than in the adjacent soil volume. However, at soil temperatures above 20°C (68°F), banded P became more toxic and decreased growth. As a result, plants are able to exploit the differences between the availability of soil and fertilizer P brought about by cold soil temperatures.

Implications for P Management

For optimum crop yield, P supply must be adequate during the first few weeks of growth. Where the supply of plant-available P in the soil is high, the soil may supply sufficient P to the plant to optimize economic crop yield (Nyborg et al. 1999). A wide number of soil testing methods are used in an attempt to predict the adequacy of soil-supplied P for optimum plant growth (Follett et al. 1981). However, specific plant factors as well as environmental factors such as soil temperature, moisture, and compaction, will all influence the ability of the plant to absorb sufficient P to support optimum growth. Nutrient management practices must be designed to supply required nutrients to the plant, taking into account the balance between crop demand and supply from the soil.

Phosphorus Concentration in Seed

Enhanced P concentration in the seed may be used to improve early season P supply and increase subsequent plant growth. Many plants can subsist on the P contained in the seed for about two weeks. Under greenhouse conditions, wheat grown from seed of the same size but with increasing P concentrations (1.4 to 3.7 g P/kg) produced higher dry matter yields up to 35 days after seeding (Bollard and Baker 1988). In the field, the increases in wheat dry matter yield persisted until 67 days after seeding. Similarly, with wheat seeds that varied in P concentration by 40 percent, higher P concentration seedlings emerged more rapidly than low P seedlings (De Marco 1990). The high P seedlings had greater early growth, higher leaf numbers, and higher leaf area. Increasing P status of the seed increased root length, but the effect of P was greater on shoot than root growth. Increasing seed weight had similar effects to increasing seed P concentration, with the effects of seed weight and P status on leaf area appearing to be additive.

Early establishment of a greater leaf area can increase later growth rates, as under most conditions it is the area of leaf which determines the growth rate and the total dry matter yield (Milthorpe and Moorby 1974). Similarly, greater root length from seedlings will allow the seedlings to explore a greater soil volume and access a greater supply of both nutrients and water (Goss et al. 1992). So enhanced root and shoot growth due to P content of the seed could produce a long-term effect on yield potential of the crop.

Fertilizer Management

If P supplied from the soil and seed reserves is inadequate to support optimum crop yield, fertilizer applications can supply P to the plant. Phosphorus supply during the first two to six weeks of growth tends to have a large impact on final crop yield in most crops; therefore, it is important that P fertilizer applications are managed in a way that ensures early season access of the fertilizer by the growing crop.

The practical importance of applying P fertilizer early in the season has been known for many years. Research in Saskatchewan by Dion et al. (1949a,b) determined that applications of P to wheat at seeding gave the best response in growth, although the uptake of fertilizer P could be increased by applying P two to four weeks after seeding. They reported that the beneficial action of fertilizer P was due to the plant being able to make a more vigorous early start, and that late growth was completed largely from P absorbed from the soil. Another study in Saskatchewan showed that application of P at later stages of growth may lead to higher uptake of the fertilizer P, but was less effective at increasing wheat yields than when the P fertilizer was applied at seeding time (Mitchell 1957).

Table 3. Cumulative uptake of fertilizer and soil phosphorus by wheat at various stages of growth with a comparison of two phosphate fertilizers[z] (Mitchell 1957)

	4 weeks		7 weeks (heading)		9 weeks (soft dough)		13 weeks (mature)		Grain Yield
Fertilizer Source	Total P	Fertilizer P	Total P	Fertilizer P	Total P	Fertilizer P	Total P	Fertilizer P	
	---------------------------------------mg---------------------------------------								--g---
Monoammonium phosphate[x]	27.0	12.5	177.2	75.5	195.0	77.0	281.0	101.0	78.0
Dicalcium phosphate plus calcium nitrate	19.7	1.9	126.1	15.1	182.0	19.0	241.0	22.0	63.3
Unfertilized	18.8	--	95.0	--	146.0	--	188.0	--	49.0

[z] Data from field trials at Birch Hills, SK 1948. Figures are averages of four replicates of a 1.8 m row.

[x] Application rate for fertilizers was 12 kg P ha^{-1}

Table 4. The amount of soil- and fertilizer phosphorus absorbed (mg per pot) at different stages of growth (Kalra and Soper 1968)

Crop		Days after seeding						
		20	35	42	51	60-64[z]	73-81[y]	90-101[x]
Rape	Soil P	1.69	4.99	6.35	8.64	10.87	12.00	13.24
	Fertilizer P[w]	2.36	5.26	7.02	7.91	9.31	8.36	9.16
Oats	Soil P	0.82	2.99	5.57	7.30	8.96	12.70	13.73
	Fertilizer P	0.71	4.30	4.77	5.07	6.91	6.92	7.13
Soybeans	Soil P	1.87	4.11	8.10	13.24	19.49	21.52	24.16
	Fertilizer P	0.39	2.29	3.82	5.30	6.59	7.84	7.82
Flax	Soil P	0.37	4.13	6.02	8.50	10.12	9.87	11.14
	Fertilizer P	0.16	2.29	3.15	3.01	5.01	4.66	4.78

[Z] Flax - 64 days, other crops - 60 days. [Y] Soybeans - 73 days, other crops, 81 days. [X] Soybeans and oats - 90 days, other crops - 101 days.

[w] Fertilizer rate of 20 mg P in 2 kg soil

Relative uptake of P from soil and fertilizer sources will differ with crop type and growth stage. Rate of uptake of soil P increases in the first four to six weeks of wheat growth and as the root area expands, an increasing proportion of the P in the plant comes from the soil, rather than from fertilizer applications (Mitchell 1957) (Table 3). Fertilizer P can be taken up at least until the heading stage but that P can still be taken up from the soil after heading (Spinks and Barber 1948). The total amount of P and the amount of fertilizer P taken up by wheat plants increased with increasing rates of P fertilization, with the percentage of the total P coming from the fertilizer increasing with increasing fertilizer rate (Spinks and Barber 1948).

In greenhouse studies, rapeseed and flax used about equal amounts of soil P, but rapeseed was much more effective than flax in extracting fertilizer P (Kalra and Soper 1968) (Table 4). For both crops, absorption of soil P continued to a later date than the uptake of fertilizer P. This is likely because as the root system expands, soil P becomes more accessible to roots and available fertilizer P decreases due to plant absorption and conversion to less available forms.

Phosphorus is relatively immobile in the soil and so remains near the site of fertilizer placement. In the Canadian prairies, soil pH is generally high (greater than 7.0), with the exchange saturated by calcium and magnesium. Phosphorus will react with the calcium and magnesium present in these high pH soils to form sparingly soluble calcium and magnesium phosphate compounds (Sample et al. 1980). These calcium and magnesium phosphates are less available to the plant than the fertilizer and become increasingly less available over time. In acid soils, similar reactions occur with iron and aluminum oxides. Band placement of P reduces contact with the soil and should result in less fixation than broadcast application (Tisdale et al. 1993). In P-deficient soils with a high P fixation capacity, the optimal method of supply P for early crop growth is generally by banding the fertilizer near to or with the seed, during the seeding operation (i.e. use of “starter P”).

While banding may maintain P in a plant-available form for a longer period of time, it can also improve the ability of plants to utilize fertilizer P. As roots cannot take nutrients up from dry soil, placing the band in a position where the soil does not dry out early in the season avoids having the fertilizer "stranded" on the surface of the soil where the roots cannot use it. However, banding the fertilizer restricts the volume of soil in the reaction zone, reducing the amount of the potential rooting volume that is supplied with P (Barber 1977). Maximum nutrient efficiency requires a compromise between reducing the volume of soil fertilized in order to minimize fixation and providing a large enough fertilized volume to encourage root-fertilizer contact (Barber 1977, Randall and Hoeft 1988). Soper and Kalra (1969) observed that oats and flax absorbed more P from a fertilizer if the carrier was mixed with a portion of the soil rather than applied as a concentrated source and speculated that this may be due to an increased quantity of roots being active in the enlarged reaction zone. However, many plants are able to proliferate their roots when they contact a concentrated source of P, such as a fertilizer band (Strong and Soper 1974a,b) and increase P absorption per unit root area when under P stress (Jungk and Barber 1974). This allows the plant to effectively extract the P from the band, utilizing the P efficiently. In contrast to the observations for oats and flax, Soper and Kalra (1969) observed that buckwheat and rape did not require an enlarged fertilizer reaction zone for efficient uptake of fertilizer P, possibly due to root proliferation in the high P region. It is therefore important to recognize that differences occur among crops in their response to fertilizer placement.

Since P will not move through the soil, it must be placed in a position where the plant roots can contact it early in the season. Placing the P in a band in or near the seed-row allows the highest possible concentration of roots to contact and utilize the band soon after emergence. Therefore, fertilizer P is most efficiently used when seed-placed or placed in a band close to the seed. For example, sweet corn yields were increased with seed-row or side-banded P fertilizer (Swaider and Shoemaker 1998) while Mitchell (1957) observed that if fertilizer P was banded near the seed, wheat plants utilized a higher proportion of the fertilizer than if the seed and fertilizer were separated. In studies conducted in Ontario, corn yield on soils low in P were increased to a greater extent when P fertilizer was seed-placed rather than banded below and to the side of the seed-row (Lauzon and Miller 1997). Similarly, alfalfa and bromegrass seedlings showed greater increases in early season growth and P concentration when bands were located directly below the seed-row rather than displaced to the side (Sheard et al. 1971). In barley, Hoppo et al. (1999) reported that shoot yield and P concentration in the youngest emerged leaf blades and whole shoots during early tillering were increased more by banding P near the seed-row than by broadcasting the same P rate. Placement of P near the seed is particularly important for crops such as flax, which have poorly developed root systems early in the growing season (Sadler 1980). However, in many crops, including corn (Richards et al. 1985, Swaider and Shoemaker 1998), soybean (Randall and Hoeft 1988), flax and canola (Nyborg and Hennig 1969), seedling damage may occur if P is placed in the seed-row at rates required for optimum yield. Damage is more apt to occur when P sources such as monoammonium or diammonium phosphate are used, as the ammonium contributes to seedling toxicity (Randall and Hoeft 1988). Where damage from seed-placed P is likely to occur, banding the fertilizer below the seed-row may be the best choice.

Placement near the seed-row is most important in soils with low P where plant demand for P can outstrip its ability to take up P from the soil. Barber (1958) noted that the greatest benefit of starter P occurred where soil concentrations were very low. Similarly Scharf (1999) indicated corn only showed a yield response to the P component of a starter fertilizer blend when soils were deficient in P. Reduced tillage may also increase response to P near the seed-row, as the soil under reduced tillage is slightly slower to warm up in the spring and bulk densities in the soil surface may be increased to some extent (Grant and Lafond 1993). Conversely, encouragement of mycorrhizal activity under no-till may enhance P uptake by certain crops (O’Halloran et al. 1986, Miller 2000). In soils where the soil P levels are not extremely low (e.g. soils with a history of P fertilization), P fertilizer may be effectively applied in a deep-band, dual-banded with the N, particularly under warm soil conditions.

While precision placement of P is one strategy to optimize early season uptake of P, an alternate approach, particularly for crops which are sensitive to P fertilizers or show a limited ability to absorb P from annual applications of fertilizer, may be to develop and maintain high concentrations of P in the soil. Sadler (1980) reported that dry matter yield of flax was as high or higher when grown in a soil which contained high levels of available P than in soils deficient in P which received banded MAP at planting. Similarly, in field studies in Australia even with application of 103 kg P ha^{-1}, grain yield of barley on new land, which contained low levels of bicarbonate extractable P (2 mg P kg^{-1}), was substantially lower than on an adjacent site where regular P fertilization for a number of years had resulted in a higher level of extractable soil P (13 mg P kg^{-1}) (Hoppo et al. (1999). In Manitoba and Saskatchewan, a single broadcast application of 200 or 400 kg P ha^{-1} increased crop yields and maintained bicarbonate-extractable P at levels above that where a response to application of additional P would be expected, even after eight years of cropping (Bailey et al. 1977, Read et al. 1973, 1977). In Montana, wheat grain yields increased with residual P levels for up to 11 crops grown over 16 years (Halvorson and Black 1985). Tillage system and crop sequencing may influence the availability of residual P. Use of a P-solubilizing microorganism such as *Penicillium bilaii* may enhance the ability of plants to utilize P from the soil (Kucey 1988, Kucey and Leggett 1989). There is a need to improve assessment of the availability of P to crops early in the season on soils with high residual P levels, whether from previous fertilization or manure applications, in order to determine the likelihood of a response to applications of additional fertilizer P.

Summary

Crops require an adequate P supply during the early stages of growth to optimize crop yield. Plants have evolved strategies to enhance their ability to access and utilize available P for the production of viable seed. It is important to recognize P deficiency and to manage cropping systems to ensure adequate levels of available P are provided to the crop during the early stages of crop growth. This requires recognition of the potential effects of management practices on soil physical and biological characteristics that can influence the early season availability of P to crops. Band placement of P fertilizer in or near the seed-row and maintenance of soil levels of P through long-term fertilizer management are among the management practices that can be adopted to optimize P nutrition.

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