CHAPTER 4

Phosphorus

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ABSTRACT

Most prairie soils originally were high in total phosphorus (P) but only contained marginal amounts of plant available P. The ability of plant roots to take up P is further aggravated by low soil moisture and/or soil temperature, both of which often are dominant during the critical four to six weeks after seeding when the plant P requirements are at their highest.

The major mechanisms of loss of P from the soil are via erosion and plant removal. Because of its very low solubility in the soil solution, losses by leaching or as soluble P in surface soils are uncommon.

A major portion (25-55%) of the soil P in surface horizons of virgin soil is in the organic form; microbial P often accounts for only approximately 10% of the organic P content. While the microbial P is present in only small amounts, it is very dynamic and plays a significant role in the soil P cycle. Most organic P compounds released by soil organisms are quickly degraded and have only a transient existence in soils. However, these transient P forms are relatively highly mobile and, under certain conditions, i.e., heavy manure applications, result in downward movement of significant amounts of P in the soil profile.

Cultivation decreases the organic P content of soil as it exposes the soil organic matter to a vigorous microbial attack. In contrast, fertilizer P, particularly when broadcast in the presence of crop residues, will increase organic P levels. A wide range of soil organisms play a role in these immobilization reactions. One of the most notable effects of intensive tillage has been a decline in soil organic matter, and hence in organic P. Conversely, conservation tillage and extended cropping systems rebuild soil organic matter as a portion of the fertilizer P is quickly incorporated into the organic pool.

Chemical fixation rates of fertilizer P in soil are dependent on soil temperature, with solution P concentrations sharply reduced as soil temperatures increase.

Approximately 20% of the fertilizer P applied in a band with the seed (cereals) is taken up by the above ground plant parts in the year of application. In contrast, uptake may be reduced twofold or more for broadcast placement. Residual fertilizer P is quickly immobilized through adsorption and precipitation reactions, and biological immobilization. A very wide array of products from P fixation have been identified in prairie soils. A large majority of such products are sufficiently soluble to meet crop requirements. Numerous field experiments have shown that most of the P applied in large applications (200 kg P_2O_5 ha^{-1} or higher) can be expected to be recovered over a period of 10 years or more. Similarly, the fertilizer P not used in the year of application will enhance the available soil P over time.

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Positive interactions between fertilizer N and P have been recorded in numerous experiments. In soils deficient in both N and P, applications of optimum quantities of N and P results in yield increases considerably larger than when either nutrient is applied alone.

Under cool, moist conditions in the spring, yield increases resulting from fertilizer P applied in a band with the seed are often higher than expected ("pop up" effect).

Phosphorus plays a major role in suppressing browning root rot infections and common root rot in spring wheat seeded on fallow soils. Limited evidence also suggest that a significant reduction in net blotch of barley can be expected from the addition of fertilizer P, particularly under cool, wet spring conditions.

The P cycle, P fertilizer management practices, and factors influencing plant available soil-P, have been extensively researched in recent years, yet the reasons for the decline in crop response to applied fertilizer P (*see Chapter 2*), the practical significance of organic P, and the large annual fluctuations in $NaHCO_3$ extractable P (*see Chapter 8*) remain speculative.

CONTENTS

INTRODUCTION

Very little commercial P fertilizer was used for crop production in Saskatchewan until 1927 when the benefits of seed-placed triple super phosphate fertilizer for wheat grown on fallow was established (Mitchell, 1932). Similar results were obtained in a series of trials conducted co-operatively between federal and provincial agencies, universities, and commercial firms during 1928-1930 (Mitchell, 1946). By 1946, four points regarding P fertilization on the prairies were clearly established: i) monoammonium phosphate (11-48-0) was a more effective P source (when seed placed) than triple super phosphates, ii) textural effects were more important than soil zone effects on P yield responses, iii) fertilizer P could hasten maturity of cereal crops; and iv) residual P became less available to plants over time through fixation processes in soil (Maas and Bentley, 1946; Mitchell, 1946).

By the mid 1950s, P was considered the first nutrient to limit crop production across the prairies. In 1980, an estimated 22.0 million hectares of agricultural land required fertilizer P at rates ranging from 10 to 50 kg ha^{-1}. Laverty et al. (1980) projected that if continuous cropping increased so that the land in fallow would drop to an average of 18% over the following decade, then an estimated 27 million hectares of cultivated land in western Canada would require supplemental P. In contrast, the review of P response patterns in Saskatchewan suggest that a significant increase in the "P suppling power" of the soil may have occurred (*Chapter 2*); the frequency of a P response of $\approx$ 250 kg ha^{-1} has declined from a high of 90% to less than 35%.

The purpose of this chapter is to highlight the large amount of soil and fertilizer P research that has been carried out in Western Canada in recent years, and to ascertain if significant changes have indeed occurred in any of the several factors influencing the P production of annual grains in particular, and some of the other crops grown.

An accounting of the very large amount of field research addressing crop response to various P fertilizers, rates, and other management practices is not provided as changes in

P response patterns have already been discussed in Chapter 2. An account of the net removal of P in grain (export) of our crops was included in Chapter 1.

SOIL-PLANT RELATIONSHIPS

The P requirement of most crops grown on the prairies is much less than that of N and similar to that of K (WCFA, 1992). Phosphorus nutrition is very important to crop production and quality because, for most crops, P content of the grain or seed represents approximately 70-80% of the total P present in the above-ground growth (Beaton, 1980). Generally, oilseed crops such as canola, flax, and sunflowers, have a much higher P requirement than the cereals wheat, oats, or barley. For example, the P concentration of the seed canola is over twice that found in the grain of cereal crops (Beaton, 1980; Grant and Bailey, 1990).

Wheat and other small grains take up P rapidly during the early stages of growth but not as rapidly as N uptake (Clarke et al., 1990). The P is stored in roots, stems, and leaves and is translocated to the grain at heading (Figs. 1 and 2). In comparison to other crops, however, wheat and other small grains are poor feeders of P. Strong and Soper (1974a, b) attributed the low utilization of fertilizer P by wheat, relative to rapeseed and buckwheat, to the small degree to which wheat roots proliferate in the reaction zone of applied P, as compared to the other crops.

Phosphorus requirements are similar for the oilseed crops, rapeseed and mustard (Ukrainetz et al., 1975; McKenzie, 1989). Both crops are quite responsive to applied P and, when grown under good fertility management, rapeseed may contain as much as 0.8 to 1.0% P which is more than twice that of wheat (0.35 to 0.45%). In addition, canola is extremely efficient in utilizing fertilizer P because it increases the solubilization of P and the concentration of P in the soil solution adjacent to the root (Grant and Bailey, 1990).

Flax, like wheat, is a slow and poor user of fertilizer P (Racz et al., 1965). Strong and Soper (1974a, b) attributed this to very poor root proliferation in the fertilizer zone.
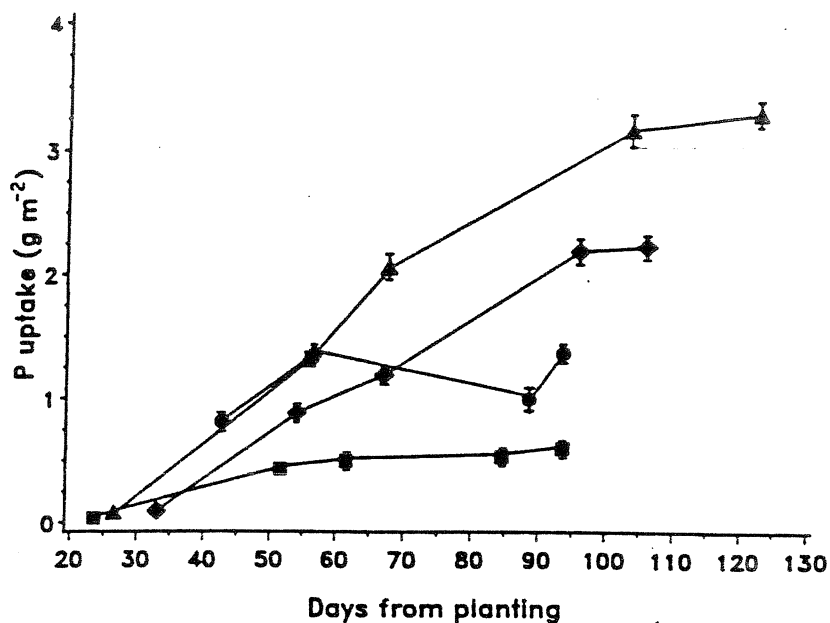
Figure 1. Uptake of P by wheat in four environments (◆ 1984,
           ■ 1985 dryland, ▲ 1985 irrigated, ● 1986); from left
           to right within each year the measurement points
           correspond to the four-leaf (not measured in 1986),
           ligule of last leaf visible, anthesis, soft dough,
           and harvest stages of maturity (Clarke et al., 1990).
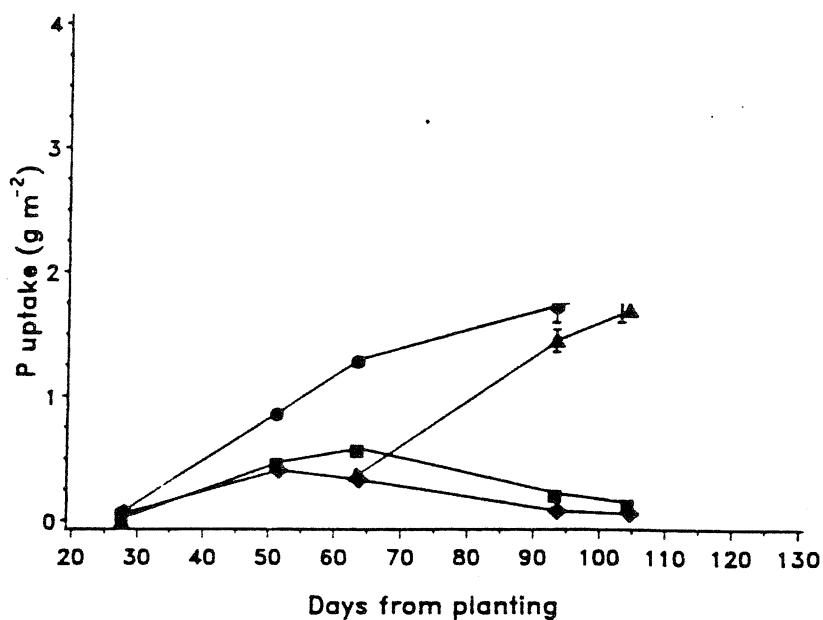

Figure 2. Average distribution of N and P among plant parts of wheat
           at the four-leaf, ligule of last leaf visible (LLV), anthesis,
           soft dough, and harvest stages of development (◆ leaf, ■ stem,
           ▲ spike, ● total plant) (Clarke et al., 1990).

Racz et al. (1965) and Stiver and Racz (1967) reported that flax tends to use native soil P in preference to fertilizer P.

Peas appear to have a higher requirement for P than fababeans; however, their response to fertilizer P is often quite variable. In western Canada, Racz (1970) obtained no yield increase to P on Black soils that were low in available P. However, Ukrainetz (1979) reported significant yield increases to P banded below the seed. Yield was depressed when P was banded with the seed, due to reduced plant emergence.

The fundamentals of the role of P in plant nutrition have been well documented in review articles (Barber, 1980; 1984; Reetz, 1986; Glass et al., 1980; Ozanne, 1980). Factors affecting P nutrition of crops, such as rhizosphere conditions, have also been reviewed (Sheppard and Racz, 1980; McKenzie, 1989; McKenzie and Roberts, 1990).

Most prairie soils are high in total P, but are inherently very low in the proportion available for crop growth. This situation is often aggravated by unfavourable environmental conditions such as low soil moisture (Warder and Ferguson, 1968), and perhaps low soil temperatures early in the growing season (Campbell et al., 1993). For example, winter wheat seeded in September-October may be able to extract more P from, and require different fertilization than, spring wheat seeded in the same soil in May (Stewart and Karamanos, 1986).

As the P concentration in soil solution at the root surface is reduced by plant uptake, a concentration gradient is established in the surrounding soil-water films, and P ions flow toward the root. Replenishment of the soluble P depleted zone depends on the supply of P from: (i) slightly soluble P minerals; (ii) P adsorbing surfaces; and (iii) from organic P mineralization (Stewart et al., 1980). More detail on the complex cycle of P in soils is illustrated in Fig. 3 (Tiessen and Stewart, 1985).

Phosphorus is absorbed by plants as primary and secondary orthophosphate ions ($H_2PO_4^-$ and HPO_4^{2-}) which exist transiently in the soil solution and are continually being replenished from exchangeable and labile forms of soil P (Barber, 1984). The amount of
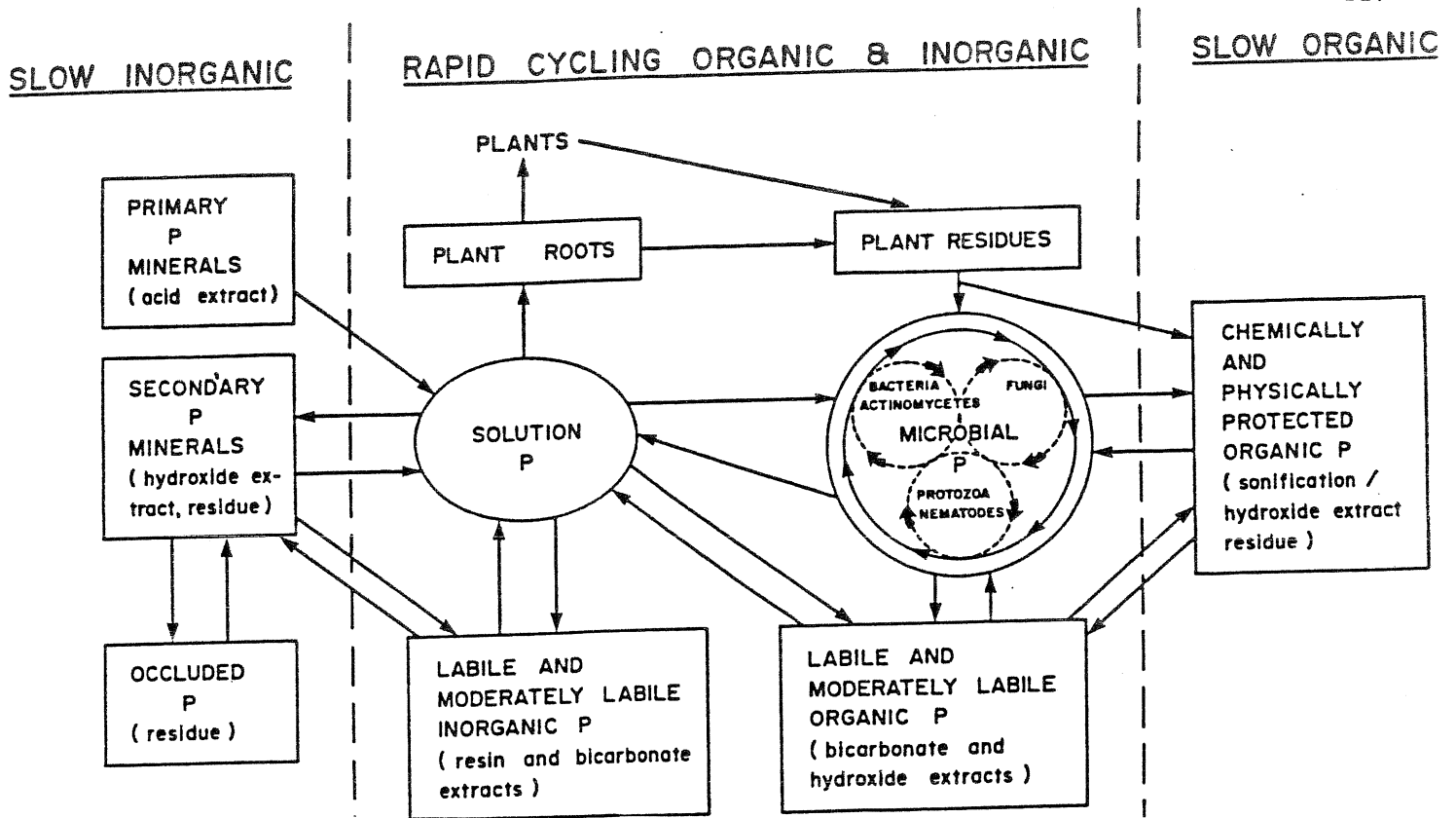
Figure 3. Conceptual phosphorus cycle: Its components and measurable fractions (from Tiessen and Stewart, 1985).

each form of P is largely dependent on soil solution pH, with $H_2PO_4^-$ as the major form at pH < 7.2 and HPO_4^{2-} dominating at solution pH above 7.2. The uptake of P is most critical at least 4-6 weeks after seeding (Campbell et al., 1993). P uptake later in the season appears to have little effect on final yield (Bole, 1966).

The major mechanisms of movement of solution P to the plant roots is through diffusion and mass flow mechanisms (Barber, 1980; 1984; Sheppard and Racz, 1980). The proportion of P supplied by these processes is dependent on the size of the root system, the degree of vesicular-arbuscular mycorrhizal infection (Kucey and Paul, 1980), the P and water absorption characteristics of the root, and the levels of labile P and solution P within the rhizosphere soil (Gould and Bole, 1980; Stewart and Karamanos, 1986). Root hair density and phosphatase activity are also important factors affecting P supply to plants (Bole, 1973; McKenzie, 1989).

Plant roots have a marked influence on the forms of P removed. For example, McKenzie (1989) found that the majority of the total-P removed by wheat and canola (averaged over 8 soils) came from inorganic P fractions, with a much smaller amount derived from organic sources. Phosphorus was not only removed from the labile fractions, but also from apparently very stable solid forms of inorganic P.

Soil microbes compete with plant roots for soluble P thereby causing acute P deficiencies, especially when stimulated by the addition of carbon-rich substrates such as crop residues. The microbial population of soil also plays an important role in the redistribution of P through simultaneous mineralization and immobilization reactions (Hedley et al., 1982; Tiessen and Stewart, 1985; McKenzie and Roberts, 1990).

The interactions between soil and rhizosphere microbes and soil P uptake is discussed in detail in Chapter 11 of this publication. An excellent treatise of the role of rhizosphere microorganisms in P uptake by plants is provided by Tinker (1980).

DISTRIBUTION OF SOIL P

Areas and Conditions of P Deficiencies

There are wide differences in the distribution of soil test P levels in the various agricultural areas of Alberta, Manitoba, and Saskatchewan. For example, in northern Alberta, soil samples from the Peace River region and the Thin Black and Black / Dark Gray soil zones all had less than 10% of soil samples (over a 12 year period) with an extractable P status in the "very low" category (< 11 kg extractable P ha^{-1}, in 0-15 cm). However, soil samples from the southern Thin Black soil zone recorded the highest percentage of fields in the "very low", and "low" categories (i.e., 12-28 kg extractable P ha^{-1}) with 28 and 44%, respectively (Leich et al., 1980). In Manitoba, approximately 33% of the soil samples submitted from the northwest region were in the "very low" P category, while only 20% of the samples from the southern Red River Valley region were in the same range (Leich et al., 1980).

Summaries of P soil-test results from Alberta show that soil samples from forage fields have a higher tendency to test "very-low" than soil samples from either stubble or fallow fields. In Alberta, approximately 25% of the soil samples from forage fields had less than 12 kg ha^{-1} available P, and up to 60% had available P levels less than 29 kg ha^{-1} ("low" and "very low" categories, respectively). Generally, only slight differences were found in the P status of fallow and stubble fields (Leitch et al., 1980). More recent data for the 1989-91 period further confirms the available P in fallow and stubble soils are similar (Table 1).

The available P status of Brown, Dark Brown, and Black soils in Saskatchewan was similar (Table 2) (Henry, 1980). The P status of Gray Black and Gray soils was also quite similar but was about 25% higher than in the Chernozemic soils. Thick Black soils appear to be the intermediate between the two extremes. Poorly drained Gleysolic soils may also have a higher P status than more arid soils of upper slope positions (Henry, 1980). Roberts et al. (1985) reported similar results to Henry's. Phosphorus

Table 1. Comparison of the P status (μg g^{-1}) of fallow and stubble fields, Alberta[1].

Soil zone	Fallow	Stubble
Brown	16	18
Dark Brown	17	19
Thin Black	18	19
Black	18	18
Dark Grey	18	18
Grey Wooded	18	19
Peace River	15	16

[1] Averages for the period, 1989-91: Acetic-fluoride extract of 1:10 (Norwest Labs, Edmonton).

Table 2. Available P status of Saskatchewan soils by soil zone (13 year average 1966-1979 (from Henry, 1980).

Depth (cm)	Average extractable NaHCO$_3$ extractable P levels					
	Brown	Dark Brown	Black	Thick Black	Gray Black	Gray
	kg ha^{-1}					
Fallow (29 685 fields)						
0-15	18	19	19	22	26	27
15-30	11	10	12	13	15	17
30-60	17	15	17	16	23	25
Stubble (36 106 fields)						
0-15	23	19	19	21	25	25
15-30	13	10	11	12	15	16
30-60	22	16	17	15	21	24

concentrations increased from upper to the lower slope position of a catena and decreased with rooting depth of cereals in the soil profile (Roberts et al., 1989). The reader is referred to Chapter 8 for further details.

Preliminary investigations carried out by Campbell (1992) on soils from four long-term crop rotations at Swift Current, Scott, Indian Head, and Melfort have shown that subsoil bicarbonate-extractable P levels increase with depth below the cereal rooting zone (up to 300 cm).

The P Cycle

The nature and distribution patterns of soil P are very complex (Fig. 3) and not all aspects of P-cycling are known. The heterogeneity of the soil system and the large number of P reaction products within the soil create a situation where quantitative analysis of individual P-species is difficult; consequently indirect approaches are often used to identify some of the compounds that control P-distribution (Stewart and Karamanos, 1986). Comprehensive reviews are available which address the soil P cycle (Stewart et al., 1980; Stewart and McKercher, 1982; Tiessen, 1982; Tiessen and Stewart, 1985; Stewart and Tiessen, 1987; Roberts and Stewart, 1987; McKenzie, 1989).

Soil P may be broadly classified as organic and inorganic, depending on the nature of the compounds in which it occurs. The transformations of organic and inorganic soil P are very closely interrelated, because inorganic P is a source of P uptake for both plants and soil organisms and organic P may replenish solution P through hydrolysis, or be stabilized by the mineral phase of the soil (McKenzie and Roberts, 1990).

Fertilizer P additions are extremely important to the maintenance of soil P dynamics and hence sustained crop production. The addition of inorganic-P fertilizer has been shown to increase organic P fractions in soil (O'Halloran et al., 1987), while cropping without P fertilizer inputs often results in a continuous drain on soil P pools.

A recent study in Alberta (Lethbridge and Breton sites) showed that the addition of P fertilizer dramatically increased labile inorganic P levels and, when combined with N fertilizer, increased labile and stable inorganic P levels and stabilized or slightly increased organic P levels under continuous cropping (McKenzie, 1989). Without supplemental N and P, both organic and inorganic P fractions (in both the labile and stable pools) were rapidly depleted by plant removal under wheat-fallow rotation (McKenzie, 1989; McKenzie et al., 1989 Stewart et al., 1980). In an earlier study, Wagar et al. (1986b) found that a change from a wheat -fallow to continuous wheat cropping produced a build-up of organic P which occurred with and without the addition of P fertilizer.

The main mechanisms of P loss from surface soils is by physical erosion of topsoil and the accompanying loss of P in the form of surface runoff. Generally, losses of P by leaching are uncommon, because P is a very immobile nutrient in most soils (Barrow, 1980). Further, because approximately 90% of the total P uptake is in the grain, major losses of P result from grain harvest (Chapter 1).

Organic P: Plants and soil microorganisms are responsible for the establishment and maintenance of organic P in soils. Soil organic P serves as an important source and sink of P in soil. Its importance may not only depend on its ability to supply P to crops, but also on its role as an integral component of soil organic matter. Stewart et al. (1980) suggest that a major change in soil P has occurred because the organic P levels have declined by approximately 50% since prairie soils were cultivated. Excellent reviews of the nature and processes of organic P in soils are provided by Halstead and McKercher (1975), Dalal (1977), Anderson (1980), Stewart and McKercher (1982), and Stewart and Tiessen (1987).

The organic P content in the surface horizons of cultivated Chernozemic soils in western Canada can be as high as 480 μg P g^{-1} soil and may constitute as much as 25 to 55% of the total P content of the soil (McKercher, 1966; Dormaar 1968; McKercher and Anderson, 1968; Halstead and McKercher, 1975; McKercher and Tinsley, 1982). This

represents a large amount of potentially plant-available P some of which may be released as the organic matter is degraded.

Organic P content is largely dependent on the conditions of soil formation such as weathering intensity. For example, it has been shown that the concentration of organic P, in both the surface and subsurface horizons of Saskatchewan soils, increases from the upper to lower slope positions and from the Brown to Black soils (Roberts et al., 1985).

Most of the naturally-occurring forms of soil organic P are esters (i.e., C-O-P bond) of orthophosphoric acid. These compounds have been identified in five classes of compounds: inositol phosphates, phospholipids, nucleic acids, nucleotides, and sugar phosphates. Derivatives of phosphonic acid, containing a C-P bond, have also been detected in soil (Anderson, 1980). The stability of these compounds to enzymatic hydrolysis varies widely. Phosphorus present as nucleic acids and phospholipids may be readily hydrolyzable and hence are presumably readily available to plants, whereas P present as inositol phosphate is not (Halstead and McKercher, 1975; Dalal, 1977; McKercher and Tollefson, 1978).

To date, only about 50 to 70% of the organic P in soil has been identified (Stewart and McKercher, 1982). Approximately 10-60% of the total organic P has been identified as inositol phosphate (McKercher, 1968), $\approx$ 10% as microbial P, 1-2% as phospholipids (Kowalenko and McKercher, 1971a) and < 1% as nucleic acids (Stewart et al., 1980). The form of the remaining organic P is largely unknown (McKercher and Anderson, 1968).

In absolute terms, phospholipid levels between 0.2 and 1.4 μg g^{-1} were measured in the surface horizons of 20 mineral soils in Saskatchewan (Kowalenko and McKercher, 1971b). However, these values constituted less than 5% of the total organic P. As much as 14% of the organic P in the B horizon of a Chernozemic soil in Alberta occurred as phospholipids. Dormaar (1970) measured the phospholipid contents of 10 Chernozemic soils in southern Alberta and observed a range from 13 to 0.089 μg g^{-1} of total lipid phosphate. In an incubation experiment, Tollefson and McKercher (1983) established that

the degradation of phospholipid (phosphatidyl choline) results in increased $NaHCO_3$-extractable soil inorganic P.

Most organic P compounds released by soil organisms are quickly degraded and only have a transient existence in soil. Others may be stabilized within the soil and accumulate to detectable levels. Generally, the extent to which organic P compounds accumulate in soil is governed by the balance of the rates of production, decomposition and retention (Anderson, 1980).

Organic P compounds can be retained in soil through adsorption to soil constituents. McKercher and Anderson (1989) examined the retention of organic P species in two Saskatchewan soils and established that the sorption capacity for organic-P compounds increases with the number of phosphate esters on the parent molecule. The following retention sequence was established:

Inositol >> Inositol > KH_2PO_4 > Inositol > x -Glycerol > Glucose
Hexa-P   Tri-P   Mono-P   -P   -1-P
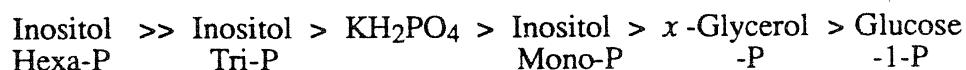
These results may account for reports of inositol phosphate compounds being found in soil, but no quantitative measurements of glucose or glycerol - phosphates in soil are available.

Stable organic P fractions may accumulate in soil as both chemically resistant and aggregate protected forms (Stewart and Karamanos, 1986). The long-term changes of organic P in prairie soils have been well documented (Haas et al., 1961; Tiessen et al., 1983), but few attempts have been made to measure the dynamics and short-term processes which cause long-term changes in soil P (Chauhan et al., 1979).

Generally, cultivation decreases the organic P content of soil by increasing and exposing the organic matter to a more vigorous microbial attack (Hedley et al., 1982; McKenzie, 1989). In addition, P fertilization tends to increase organic P levels in soils until an equilibrium is established where input and decomposition balance (Anderson, 1980).

Organic P in chemically or physically protected forms, may be slowly mineralized as a by-product of overall soil organic matter mineralization or by specific enzyme action, in response to the need to replenish solution P (Stewart and Karamanos, 1986). Phosphatase enzymes play a major role in the mineralization of organic P in soil (Gould and Bole, 1980; McKenzie, 1989). They are a broad group of enzymes which catalyze the hydrolysis of both esters and anhydrides of phosphoric acid. A wide range of soil microbes and plants are capable of mineralizing organic P through dephosphorylation reactions (Barrow, 1980; Tinker, 1980).

Significant changes in the accumulation of organic P over the growing season have been noted on two unfertilized Dark Brown Chernozemic soils of southern Alberta (Dormaar, 1972). In this study, the organic P content decreased with crop growth and development and increased again with the onset of dormancy (Table 3).

Table 3. Measurements of total organic P content of two unfertilized soils (0-15 cm) under alfalfa over the growing season (Dormaar, 1972).

Year	Organic P in soil						
	April	May	June	July	August	September	October
				$\mu g \ g^{-1}$			
Coaldale - 1							
1963	88	51	43	43	56	72	73
1964	242	153	146	134	116	122	138
1965	213						
Coaldale - 2							
1963	102	73	56	36	20	46	82
1964	226	158	130	110	100	120	146
1965	206						

The seasonal fluctuation was explained by the fact that a large percentage of the total organic P in Chernozems occurs in a humic fraction that is plentiful in the winter and at a minimum in the summer (Dormaar, 1968). It was also suggested that additions of fertilizer P would build-up organic P levels over time as free phosphate ions bound to Ca ions in this fraction. Crop maturity and the dates of harvest also affected soil organic P levels (Dormaar, 1972). Similar results were noted by Halm et al. (1973) in Saskatchewan. Total organic P in a native grass Sceptre clay soil had minimal values in August and maximum values in November, wheras data obtained for total inorganic soil phosphate did not change. In contrast, McKenzie and his co-workers (1989c) at Lethbridge, Alberta, observed a major decline in organic P levels over the winter which he attributed to mineralization and degradation of organic soil P fractions. Inorganic P levels, however, also vary widely between fall and spring. In a 24 year study at Swift Current, Saskatchewan, Campbell and Zentner (1993) have presented convincing evidence that $NaHCO_3$ extractable P may be substantially higher, lower or equivalent in fall vs. spring soil samples (Fig. 4). This confirms his earlier observation that seasonal variability of $NaHCO_3$ extractable soil-P levels can be expected to be high. This matter is discussed further under the heading "Residual fertilizer P".

One of the most notable effects of cultivation on prairie soils has been a decrease in the total organic P (Haas et al., 1961; Hedley et al., 1982; Tiessen, 1982; Tiessen et al., 1982, 1983; Sharpley and Smith, 1985; Stewart et al., 1989). This means that changes in crop management that affect soil organic matter accumulation, such as changing from a wheat - fallow to continuous cropping system, would positively affect the ratio of soil organic P : inorganic P and hence plant available P. Some studies have attributed the lack of crop response to fertilizer P application, and lack of seasonal variation in available P to organic P mineralization (Stewart and McKercher, 1982; Stewart and Sharpley, 1985). In contrast, Campbell et al. (1984) found no change in available P during fallow periods in a
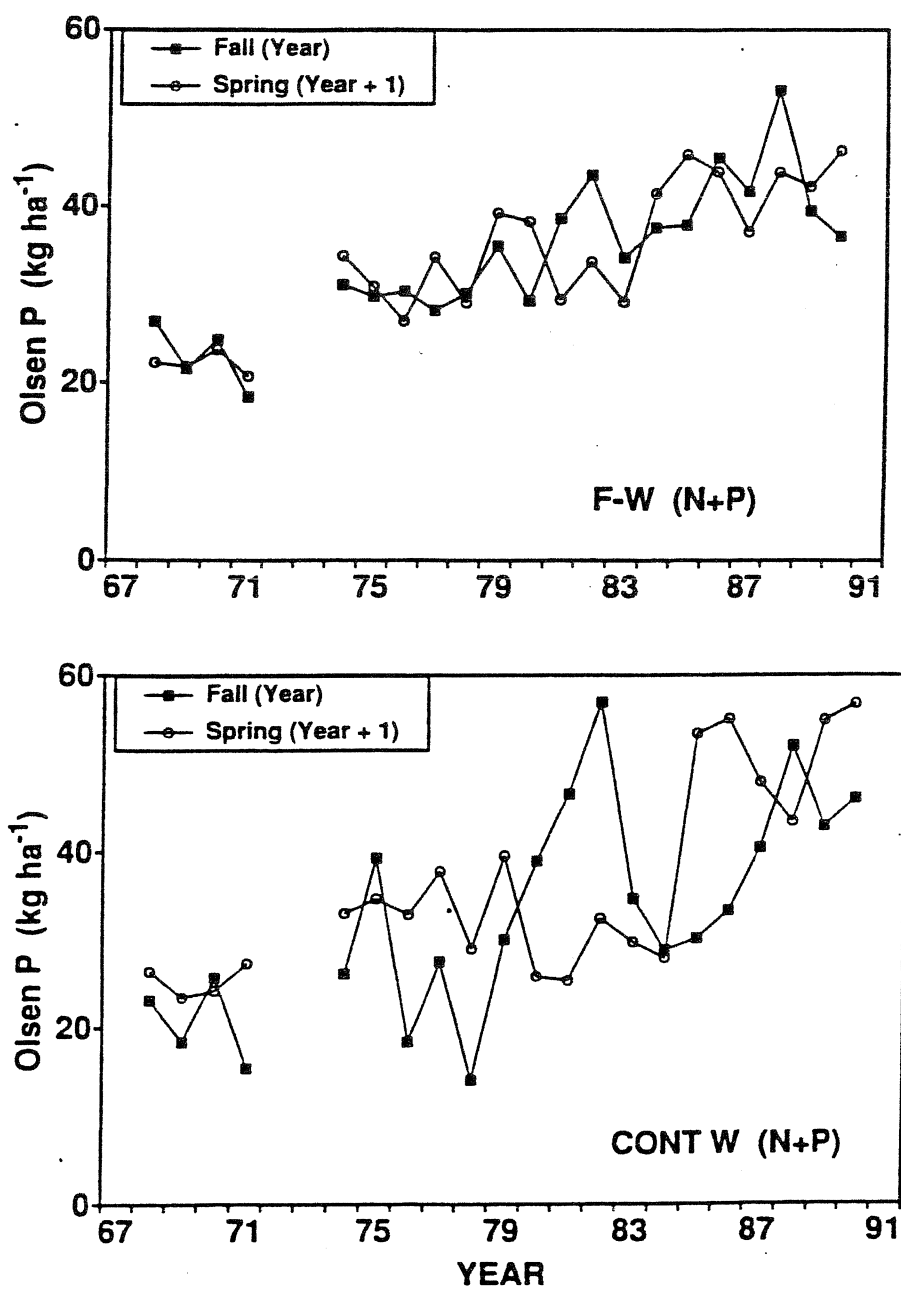
Figure 4. Fall and spring NaHCO3 extractable P in a fallow-wheat, and continous wheat rotation for a 24 year period (Zentner et al., 1993).

Brown soil. Perhaps the naturally large variability in labile P compared to changes caused by mineralization on occasion mask each other.

Stewart (1978) conducted a series of experiments to determine the contributions of soil organic P to prairie wheat crops. He noted that large decreases in P content of all organic P fractions had occurred as the result of wheat production compared to little change in inorganic P levels. However, it has also been shown that some of the applied fertilizer P can be reincorporated into the organic P pool (Sadler and Stewart, 1975; Wagar et al., 1986b). The transformation of fertilizer P into organic P forms can play an important role in the recovery efficiency and the long-term availability of applied P (McKenzie and Roberts, 1990).

REACTIONS OF PHOSPHATE FERTILIZERS IN SOIL

Not all of the fertilizer P applied to soil is absorbed by plants in the year of application. Excess P will react with soil constituents and will be 'fixed' or retained by the soil. This information is important in understanding the quantity of added phosphate that will remain in a labile form and also in predicting the magnitude and duration of residual effects of applied P on plant availability. Much of this information has been discussed in comprehensive reviews (Larsen, 1967; Olsen and Flowerday, 1971; Sadler and Stewart, 1974; Barrow, 1980; Sample et al., 1980; Soper and Racz, 1980).

Fertilizer P Dissolution and Immobilization

In general, three zones may be recognized near a P-fertilizer granule: (i) a central zone which contains the residue of the P fertilizer; (ii) an outer layer in which P fertilizer solution has passed and has dissolved soil minerals thereby resulting in the formation of Ca-, Fe-, and Al-P precipitates; and (iii) an outer zone of low P concentration where P is adsorbed on the surface of soil minerals such as clays (Barrow, 1980).

When fertilizer P is applied to soil, water is drawn into a P fertilizer zone by vapor or capillary transport, the resultant fertilizer solution moves into the surrounding soil through capillary flow (Bole, 1966; Sample et al., 1980). While this process is occuring, precipitation reactions occur immediately in close proximity to the P-source and are responsible for most of the P being retained in the vicinity of application (Soper and Racz, 1980). For example, the precipitation of dicalcium phosphate at the application site of monocalcium phosphate monohydrate accounts for 20 to 34 % of the total P applied (Hinman et al., 1962).

The soil matrix has relatively little influence on the chemistry of the *in situ* reactions, serving mainly as a source of water and as a sink for the fertilizer solution (Bouldin et al., 1980). Adsorption reactions are believed to be most important at the periphery of the soil-fertilizer reaction zone where P concentrations are much lower (Barrow, 1980; Soper and Racz, 1980).

Although variable, the initial movement of P away from fertilizer application sites seldom exceeds a distance of 5 cm (Barrow, 1980). For example, Bell and Black (1970a) identified traces of insoluble P compounds in soils at distances of 3 to 5 cm from applications of MAP (monoammonium phosphate). However, they did not speculate as to how much of the total P retained at these sites was accounted for by these products (Sample et al., 1980).

The rate and distance P moves from a fertilizer source increases with prill size (Bole, 1966). In time, applied P tends to become more evenly dispersed. This is partly due to slow diffusion of P away from the original site, and partly to the destruction of the fertilizer band by cultivation (Barrow, 1980).

When the concentrated fertilizer solution leaves the application site and moves into the surrounding soil, some soil minerals in the first increments of soil contacted by the solution may undergo dissolution, placing relatively large quantities of reactive cations (e.g., Al, Fe, Ca) in soil solution. These cations may initiate a second series of

precipitation and immobilization reactions, the nature of which depends on the kinds and amounts of cations and anions supplied by both the fertilizer and the soil, as well as soil pH and soil moisture (Sample et al., 1980; Soper and Racz, 1980).

Phosphorus Fixation

The process of P fixation in soil is a continuous sequence of precipitation and adsorption reactions which follows two distinct patterns: an initial rapid reaction period followed by a much slower process (Barrow, 1980; Soper and Racz, 1980). It is very difficult to distinguish between phosphate adsorption and chemical precipitation processes, because the end products are similar. Basically, as fertilizer P moves through the soil matrix, becoming more dilute from precipitation and adsorption reactions, a point should be reached at which adsorption dominates and separate-phase precipitation is negligible (Sample et al., 1980). The formation of initial products from the reaction between soil and water soluble phosphate fertilizer is largely complete in less than 4 to 8 weeks (Racz and Soper, 1967). Laboratory studies have shown that the greatest reduction of water-soluble P in the soil-fertilizer reaction zone occurs in the first two weeks after application (Beaton et al., 1965). The initial products are meta-stable and with time will change into more stable and less soluble P compounds (MacKenzie and Campbell, 1962). The amount of time taken to form stable compounds is important because the initial and meta-stable reaction products may persist for sufficient time to act as good sources of P for plants.

Dicalcium phosphate dihydrate (DCPD or $CaHPO_4 \cdot 2H_2O$), has been identified as an initial reaction product of western Canadian soils with pH values between 6.0 and 8.5 for all of the major orthophosphate fertilizers (Hinman et al., 1962; Beaton and Read, 1963; Racz and Soper, 1967; Bell and Black 1970b; Strong and Racz, 1970). In most soils, DCPD is gradually changed to OCP (octacalcium phosphate) and eventually HA (hydroxyapatite) as the result of P-fixation (Sadler and Stewart, 1974; Sample et al., 1980).

In prairie soils, hydroxyapatite (HA or $Ca_{10}(PO_4)_6(OH)_2$) is generally the dominant stable calcium phosphate mineral from P fixation (Beaton et al., 1963a; Racz and Soper, 1967; Bell and Black, 1970b; Sadler, 1973; Tiessen, 1982). This sparingly soluble mineral makes up the majority of the inorganic P fraction in Chernozemic and Luvisolic soils (Stewart and Karamanos, 1986).

On highly calcareous soils, soluble P often becomes immobilized with $CaCO_3$ compounds. A fraction of the solution P may be adsorbed on the surface of $CaCO_3$ minerals or react with soluble $CaCO_3$ to form a precipitate which is then adsorbed on mineral surfaces (Barrow, 1980). Bell and Black (1970b) found that the change of initial P reaction products to more stable compounds was more rapid in the presence of $CaCO_3$. The importance of soil carbonates to P fixation in calcareous soils was clearly established in a review by Wild (1950).

On soils with elevated Mg levels, dimagnesium phosphate trihydrate (DMPT) has been identified as an initial reaction product of ammonium and K phosphate fertilizers (Racz and Soper, 1967; Strong and Racz, 1970). In a similar experiment, Strong and Racz (1970) treated four soils of varying Ca and Mg status with phosphate fertilizers and incubated them for periods of up to 15 months. DCPD was formed in all soils, but gradually changed to OCP, except for one soil where DCPD persisted for 15 months. On soils with a Ca:Mg ratio of < 0.64, , several insoluble Mg-P complexes were formed instead of DCPD (Soper and Racz, 1980).

The nature, amount, and rate at which P precipitation reactions occur is dependent on the nature of the soil. Some major soil factors which influence P retention in soils include: oxide content, type and amount of clay, $CaCO_3$ content, soil pH, soil CEC, soil temperature, and type and amount of organic matter. Generally, Al and Fe oxides and hydrous oxides play a dominant role in the reaction of P in acid soils, but are not important for P-retention in neutral to calcareous soils (Soper and Racz, 1980). There have been numerous investigations of the reactions of soil and fertilizer P with aluminosilicate clay

minerals (MacKenzie and Campbell, 1962). Generally, the rate of P fixation by these minerals is directly related to temperature and P concentration, and inversely related to pH (Soper and Racz, 1980). A tremendous array of products result from the process of P fixation in prairie soils (Table 4).

Soil organic matter may also increase the ability of soils to adsorb P. Rennie and McKercher (1959) report a positive relationship between soil organic matter content and P adsorption. This relationship is likely the reflection of the association of organic matter with cations such as Fe, Al, and Ca which are capable of fixing solution P (Wild, 1950; Weir and Soper, 1963; Dormaar, 1972; Soper and Racz, 1980).

In alkaline and calcareous soils, an increase in soil pH will increase the rate at which the initial reaction products of P fixation change into the more stable compounds. For example, Bell and Black (1970b) noted that the change in DCPD to OCP was more rapid in soils having pH values above 7.9 than above 6.9.

The P-fixation process is very dependent on soil temperature (Sheppard and Racz, 1984). Early studies have shown that P concentrations in the soil solution is inversely related to temperature. Beaton et al (1965) showed that for each 15°C increase in soil temperature, a 33% reduction in the concentration of water soluble soil P occurred (Table 5). Sheppard and Racz (1980) reported that at soil temperatures above 20°C much higher percentages of DCPD were hydrolyzed to OCP over two and four month reaction periods.

The concentration of phosphate in soil solution is a characteristic often overlooked as a factor influencing fixation rates in P retention studies. The distribution of P between solution and surface phases is often described as a curve such that each successive increase in the concentration of solution P results in a smaller increase in the amount of P adsorbed. However, a linear relationship exists between P concentration in the adsorbed phase and the amount of P fixed into ultra-stable forms (Barrow, 1980).

Residual Fertilizer P

Excellent reviews of residual P in western Canadian soils are provided by Sadler and Stewart (1974), Roberts and Stewart (1987), and McKenzie and Roberts (1990). These manuscripts provide a comprehensive and complete treatise of the residual P research that has been conducted in western Canada. The reviews indicate that up to 75% of P fertilizer not used by the first crop after P application remains in forms available for subsequent crops. The purpose of this section is to highlight some of the major early findings and some of the more recent residual P work conducted since these reviews were written.

The performance of fertilizer P on most prairie soils cannot be assessed based on the yield of the first or second crop. Compounds such as those listed in Table 4, can persist for as long as 5 to 10 years depending on the rate of initial application, form of fertilizer P applied, crop removal characteristics, soil pH, soil $CaCO_3$ content, and the buffering capacity of the soil for P (Barrow, 1980; Soper and Racz, 1980). Thus, under dryland conditions such as the Canadian prairies, residual P can be thought of as a sparingly soluble fertilizer which can increase available P status of soil and induce a residual crop response (Spratt and Read, 1980).

Even though previously applied P may be less effective than recently applied P, it nevertheless has value (Roberts, 1992). This value is difficult to quantitatively measure, because a great number of processes and constituents influence its status in soil (Barrow, 1980; Roberts and Stewart, 1987).

How long fertilizer P can remain effective for future crops has yet to be determined. The expected period of utilization will ultimately depend on soil conditions, the type and frequency of crop grown, and the initial application rate of fertilizer P. For example, Spratt and McCurdy (1966) using "A" values and a curvilinear decline of $NaHCO_3$ - extractable P to a 15 μg g^{-1} base level as a criterion for sufficiency, predicted that initial applications of 229, 460, and 816 kg P_2O_5 ha^{-1}, on a Black Chernozemic clay loam, could sustain wheat

Table 4. A summary of some of the compounds which have been identified from the reaction of phosphate fertilizers with soils or soil constituents in the prairie provinces.

Compound	Reference[†]
$CaHPO_4$ (Monetite)	1
$CaHPO_4 \cdot 2H_2O$ (Brushite)	1, 2, 3, 5
$CaHPO_4 \cdot 2H_2O$ (Dicalcium phosphate dihydrate)	2, 3, 6, 7, 8
$Ca_8H_2(PO_4)_6 \cdot 5H_2O$ (Octocalcium phosphate)	3, 5
$Ca_{10}(PO_4)_6(OH)_2$ (Hydroxyapatite)	1
$Ca_3Mg_3(PO_4)_4$	5
$MgHPO_4 \cdot 3H_2O$ (Dimagnesium phosphate trihydrate)	3, 5, 8
$Mg_3(PO_4)_2 \cdot 4H_2O$	3
$Mg_3(PO_4)_2 \cdot 22H_2O$	3, 5
$MgNH_4PO_4$	8
$MgNH_4PO_4 \cdot 6H_2O$	8
$Ca_2P_2O_7 \cdot 4H_2O$	4
$Ca(NH_4)_2P_2O_7 \cdot H_2O$	4
$Ca_3(NH_4)_2(P_2O_7)_2 \cdot 6H_2O$	4
$Ca_5(NH_4)_2(P_2O_7)_3 \cdot 6H_2O$	4
$Ca(NH_4)_2(HPO_4)_2 \cdot H_2O$	8
$CaK_2P_2O_7$	4
$Ca_3K_2(P_2O_7)_2 \cdot 2H_2O$	4
$Ca_3K_2(P_2O_7)_3 \cdot 6H_2O$	4
$Ca_3KH_3(P_2O_7)_2 \cdot 3H_2O$	4

[†] Numbers represent the following references: 1. Beaton et al. (1963a); 2. Hinman et al. (1962); 3. Racz and Soper (1967); 4. Savant and Racz (1973); 5. Strong and Racz (1970); 6. Beaton and Read (1963); 7. Bell and Black (1970[b]); 8. Bell and Black (1970[c]).

production for 5, 10, and 20 years, respectively. If the P was present in less available forms (both organic and inorganic were considered) these time periods could be expected to extend much longer (McKenzie and Roberts, 1990).

Residual P may have merit because hydroxyapatite (HA) formation is slow enough that fractions of sparingly soluble P compounds, DCPD and OCP, can persist for long periods under normal cropping conditions of western Canada and be available for plant uptake (Dawley, 1965; Read et al., 1973, 1977; Ridley and Tayakepisuthe, 1974; Sadler and Stewart, 1975; 1977; Wagar et al., 1986a,b). Similar results were noted in Montana and North Dakota (Alessi and Power, 1980; Halvorson and Black, 1985a,b).

Some of the first experiments to demonstrate the residual effects of P were conducted in southwestern Saskatchewan on native range and later for wheat and other crops over an eight-year period (Read, 1969; Read et al., 1973). This work, plus the detailed laboratory work of Sadler and Stewart (1974; 1975; 1977), confirm that most applied P will eventually be recovered by crops on the Canadian prairies. Spratt and Read (1980) suggest that the beneficial effects from one application of 916 kg P_2O_5 ha^{-1} could last for over 25 years in southwestern Saskatchewan.

Residual P pools may also be established from regular applications of small amounts of P fertilizer over an extended period (Spratt and McCurdy, 1966; McKenzie and Roberts, 1990; Ukrainetz, 1990). The establishment of a strong residual P pool in topsoil can also be achieved through the application of large batch applications of P fertilizer (e.g., 200 to 1000 kg P_2O_5 ha^{-1}). Such a practice would raise the overall solution phosphate level and theoretically sustain crop production in future years (Rennie and McKercher, 1959; Sadler and Stewart, 1975; Stewart and Karamanos, 1986). The practicality of this would be dependent on economical considerations.

Spratt and Read (1980) suggest that the establishment of large soil P reserves is an agronomically sound practice because of advantages in off season fertilizer prices, time saved at seeding, and the opportunity to hedge against inflation. Jose (1981) concluded,

from field studies of large batch applications of fertilizer P at two locations in Saskatchewan and two in Manitoba, that "batch applications can be economic. Roberts and Stewart (1987) reported that a large single broadcast P application can be as economically viable as annual seed-placed P applications over a five year period.

Field experiments conducted on Ca dominated soils of Alberta, Manitoba, and Saskatchewan clearly show that large batch applications of 200 to 281 kg P_2O_5 ha^{-1} can remain effective for periods of 8 to 10 years. The long-term benefits of an initial application of 207 kg P_2O_5 ha^{-1} for seven consecutive winter wheat crops was demonstrated by Halvorson and Black (1982).

The effect of large initial additions of P on available soil P was clearly shown by Spratt (1978). At P_2O_5 rates of 112, 225, 460, and 919 kg ha^{-1}, there was a substantial improvement in the level of available P in soil. The large applications of P initially increased available soil P to high levels, followed by a rapid decline within the first year, and then available P decreased by about 5 to 8 μg g^{-1} per year (Fig. 5). Several other researchers have demonstrated residual effects of P by measuring labile inorganic P with time (Ridley and Hedlin, 1962; Read et al., 1973; Olsen et al., 1978; Campbell et al., 1984). These results confirm earlier findings (Spratt and McCurdy, 1966; Spratt and McIver, 1978) who reported that the continuous use of MAP at 67 kg ha^{-1} or more created high levels of available soil P (up to 23 μg g^{-1}), which complemented recently applied MAP to give yield increases much higher than previously attained. In a similar study, Ridley and Hedlin (1962) noted that the application of 96 kg P_2O_5 ha^{-1} every 4 years increased the NaHCO$_3$-P status of a Red River clay soil from 18 to 35 μg g^{-1} after 36 years of cropping. Ukrainetz (1990) measured various P fractions of an acidic Scott loam soil and found substantial increases in NaHCO$_3$ extractable P levels in the top 30 cm of soil after 57 years of continual P fertilizer application.

Read et al. (1977) evaluated the residual effects of P applied at 0, 229, 450, and 916 kg P_2O_5 ha^{-1} in Manitoba (wheat-flax rotation) and Saskatchewan (wheat-fallow

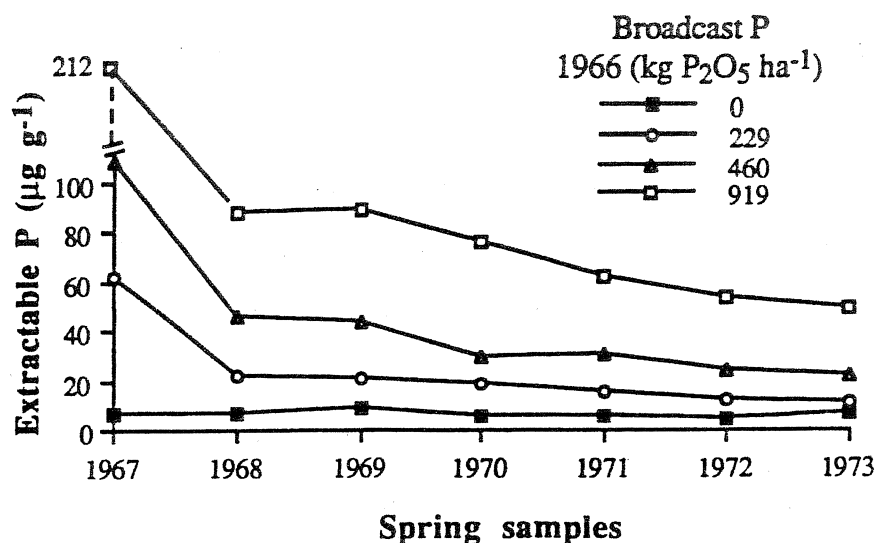Figure 5. The effect of single broadcast applications of P fertilizer in 1966 on the NaHCO3 extractable P levels in the soils while being cropped alternately with wheat and flax on two Manitoba soils from 1967 to 1973 (adapted from Spratt, 1978).
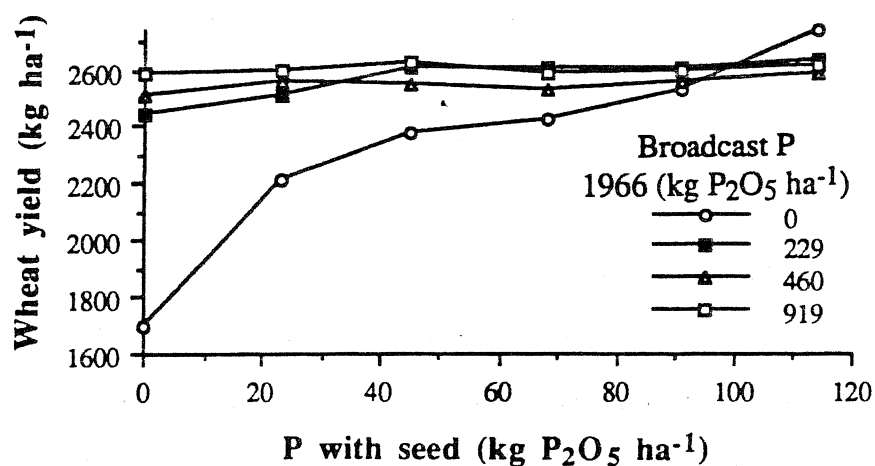

Figure 6. Average yield response of wheat to residual and annual P applications. Combination of eight years data (1967-74) on two soil types (adapted from Spratt, 1978).

rotation) over an 8 year period. The effect of small annual applications of fertilizer P was included by superimposing seed-placed treatments on plots receiving the single application. Over 8 years, residual effects were observed at all sites, although differences between rates were significant at only one of the four locations. In addition, all applications of P were found to increase the amount of available P in the soil. In most cases, superimposing seed-placed treatments on the single P application did not significantly increase grain yield. They concluded that minimal to no response could be expected from annual application of seed placed phosphate when soil $NaHCO_3$ extractable P levels were above 10 μg g^{-1} (20 kg ha^{-1}). This level is slightly less than the 15 μg g^{-1} level set by the Manitoba and Saskatchewan provincial soil test labs as the amount of $NaHCO_3$ extractable P necessary for wheat production without additional P fertilizer (Roberts and Stewart, 1987). However, recent reports indicate that even on soils high in P, seed-placed P can enhance early growth and development and increase yield of prairie crops (Roberts, 1992; Zentner et al., 1993), particularly under cool, wet soil conditions.

Residual P may also be leached so that a gradual increase in available P may occur at depths down to 120 cm (Read, 1982). The higher amounts of P taken up by crops feeding in soil enriched with phosphate fertilizer is believed to be cycled back into the soil through decomposing roots, etc. The net result is a form of deep P placement.

Biocycling of P by plant roots is another pathway by which residual P can be redistributed (Ukrainetz, 1990). Research at Swift Current has shown a gradual downward movement of P in soils receiving applications of between 230 and 920 kg P_2O_5 ha^{-1}. A significant increase in the amount of $NaHCO_3$-extractable P was found at all sampling depths from 15 to 120 cm. This transport from surface to lower soil depths was explained as due to cycling of P taken up by crops back into the entire rooting media through decomposition of plant roots (Read and Campbell, 1981).

Wagar et al. (1986b) also showed that 5 years following application of batch P, a considerable portion of the applied P had moved into the subsurface (30-60 cm) horizons

(Table 6). Organic P was the main contributor to the increase. Unlike previous conclusions (Read and Campbell, 1981; Read, 1982), Roberts and Stewart (1987) suggested that the downward movement of P was from leaching of low molecular weight fulvic acid materials enriched with P as described by Schoenau and Bettany (1987). The results of a recent study found that organic-P compounds had relatively high mobility in prairie soils and could be responsible for a considerable portion of soil P redistribution and loss from prairie soils (Frossard et al., 1989). Recent unpublished data of Campbell at Swift Current (1992), showing that below the rooting zone of wheat, there is a buildup of $NaHCO_3$-P which is deeper as one moves from the Brown to Black and Gray Luvisolic soils may support this theory of leaching.

At Brandon, Manitoba, wheat and flax, when rotated over 8 years, used P quite efficiently from large applications of P fertilizer. Approximately 20% of the applied P was recovered in 8 years from a 229 kg P_2O_5 ha^{-1} applied in 1966, while 22.5% was recovered from 22 kg P_2O_5 ha^{-1} applied with the seed annually. The recoveries of the 460 and 919 kg P_2O_5 ha^{-1} broadcast applications were 15 and 9% respectively, but the benefits of the residual P were not exhausted after 8 years of cropping (Spratt, 1978). Over the 8 years of cropping, annual applications of 46 kg P_2O_5 ha^{-1} gave about the same yields as when 229 kg P_2O_5 ha^{-1} was applied once (Figure 6). Similar results were obtained by Ridley and Tayakepisuthe (1974). A single broadcast application MAP at 0, 115, 229, and 458 kg P_2O_5 ha^{-1} in 1966 provided notable yield benefits for barley in the year of application and as residual P for wheat as the third crop after initial application (Fig. 7). Additional barley yield benefits were also noted for seed-placed P combined with high broadcast P rates. Similar results were also reported at Brandon by Bailey et al. (1977). Broadcast applications of 0, 229, 458, and 916 kg P_2O_5 ha^{-1} were made on two Chernozemic soils in 1965 (Fig. 8). The soils were cropped for eight years in a continuous wheat-flax rotation. In each year, crops grown on the residual P yielded more (Fig. 8) and had higher P content than unfertilized crops. At the end of the 8 year experiment, the two crops used

Table 5. Influence of temperature and P source on soluble P in 1:15, soil:water extracts of soil-fertilizer reaction zones (Beaton et al., 1965).

Source of P	Fertilizer P in 1:15 soil : water extracts (%)			Phosphorus source means[†]
	Temperature			
	5	20	35	
(15 mg P 200 g^{-1} soil)	———————— (°C) ————————			
MKP	52.4	35.2	23.5	37.0
MAP	40.7	26.0	17.0	27.9a
DAP	39.8	24.4	18.3	27.5a
MCP	24.3	16.2	9.5	16.7
DCPD	3.3	4.4	3.4	3.7
Temperature means[†]	32.1	21.2	14.4	

[†] Any two means with the same letters are not significantly different (1% probability).

Table 6. Recovery of fertilizer P five years following the application of 366 kg P$_2$O$_5$ ha^{-1} on a Sutherland clay soil (from Wagar et al., 1986b; Roberts and Stewart, 1987).

Source		Phosphorus recovered in excess of control	Recovery of P fertilizer[†]
		(mg P ha^{-1})	%
Soil	0-15 cm	56.5	60.2
	15-30 cm	19.0	20.2
	30-60 cm	15.0	16.0
Grain		12.5	13.3
Total		103.0	109.7

[†] Fertilizer P applied as triple super phosphate (0-45-0).

Annual seed-placed P†
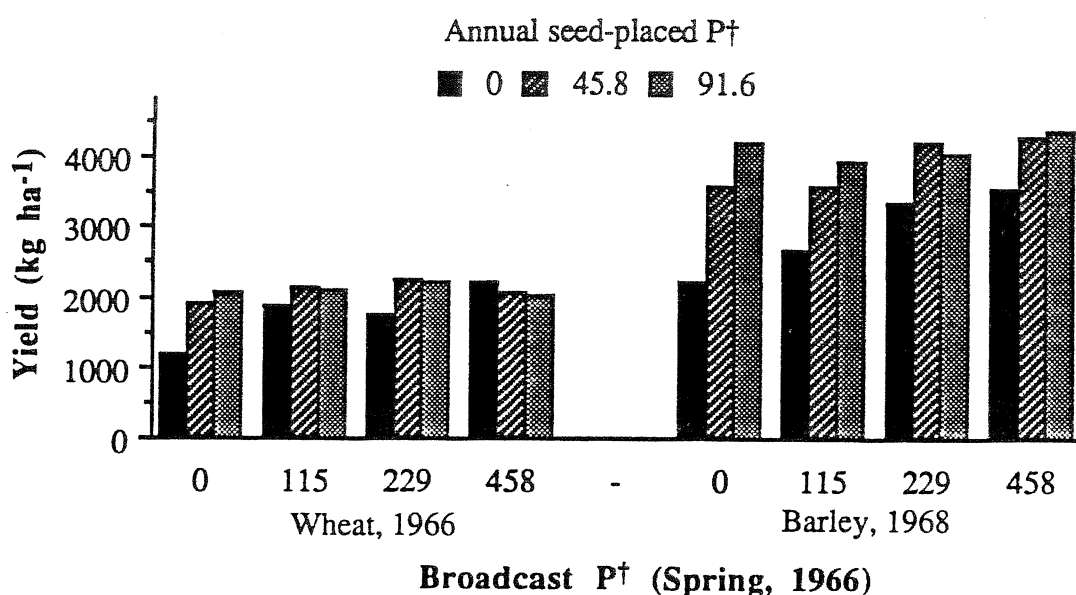
■ 0 ▨ 45.8 ▦ 91.6

Broadcast P† (Spring, 1966)

Figure 7. Yield response of wheat and barley to broadcast P with and without additional P applied with the seed on an Altona FSL. † P was seed placed as monoammonium phosphate; broadcast P was monocalcium phosphate in kg P_2O_5 ha^{-1} (Ridley and Tayakepisuthe, 1974).
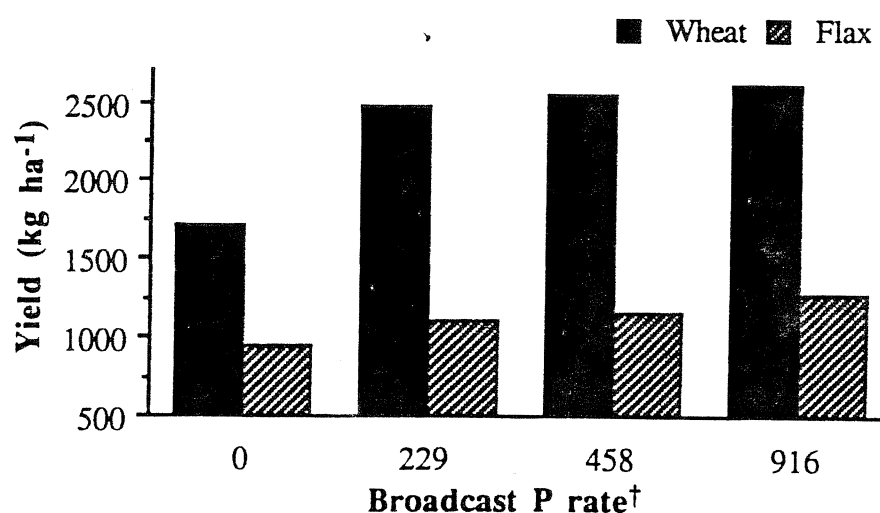

Broadcast P rate†

Figure 8. Eight year average yield responses of wheat and flax to a single application of broadcast P fertilizer on a continuous wheat-flax rotation averaged over four sites on two Chernozemic soil types. † P broadcast as superphosphate, rates in kg P_2O_5 ha^{-1} (Bailey et al., 1977).

approximately 30, 22, and 14% of the 229, 458, and 916 kg P_2O_5 ha^{-1} applied. The most efficient P rate in terms of crop production over the eight year period was the 229 kg P_2O_5 ha^{-1} treatment (Bailey et al., 1977). In these experiments, wheat was able to utilize twice as much P as flax, showing recovery ratios (wheat:flax) ranging from 1.9 to 2.3.

Wagar et al. (1986a) compared the residual effects of P fertilizer versus repeated annual seed-placed applications on wheat over a 6 year period . The results showed that single broadcast P applications can produce yields comparable to annual seed-placed P applications without requiring additional P inputs. Broadcast P applications of 46, 92, 183, and 366 kg P_2O_5 ha^{-1} increased the average yield by 9, 24, 33, and 35% respectively (Fig. 9). Yearly seed-placed P treatments of 5.7, 11.5, 22.9, and 45.8 kg P_2O_5 ha^{-1} applied over the first 5 years of the study increased the average wheat yield by 10, 15, 24, and 29% (Fig. 10). However, they noted that "luxury consumption" of P occurred at the higher rates of broadcast P.

Recent research in Alberta (Mayko et al., 1987; McKenzie et al., 1989b) suggest that the ability to predict crop response to added P fertilizer may be of greater concern than the actual method of placement and that the contributions of residual P fertilizer applied in previous years must be seriously considered in formulating phosphate fertilizer recommendations

CROP PRODUCTION

In recent years, research has often been frustrated by lack of significant yield response to added P on most commercially farmed soils. This diminished frequency of yield response has been partially a result of the accumulation of P fertilizer residues and may be a reflection of the large variability of crop response to fertilizer P (Roberts, 1992). Several other factors may contribute to the decreasing crop response to fertilizer P including: changes in crop varieties, differences in early growing season climate, changes in root colonization by vesicular arbuscular mycorrihzae (VAM), and an increased

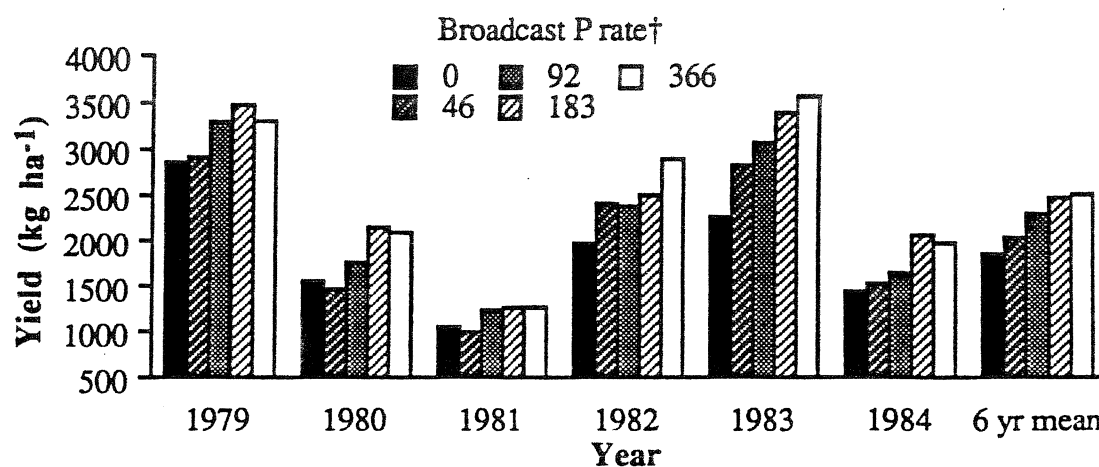Figure 9. Average wheat yield response from plots receiving a single broadcast application of triple super phosphate fertilizer at various rates. † Phosphorus fertilizer in kg P_2O_5 ha^{-1} (Wagar et al., 1986a).
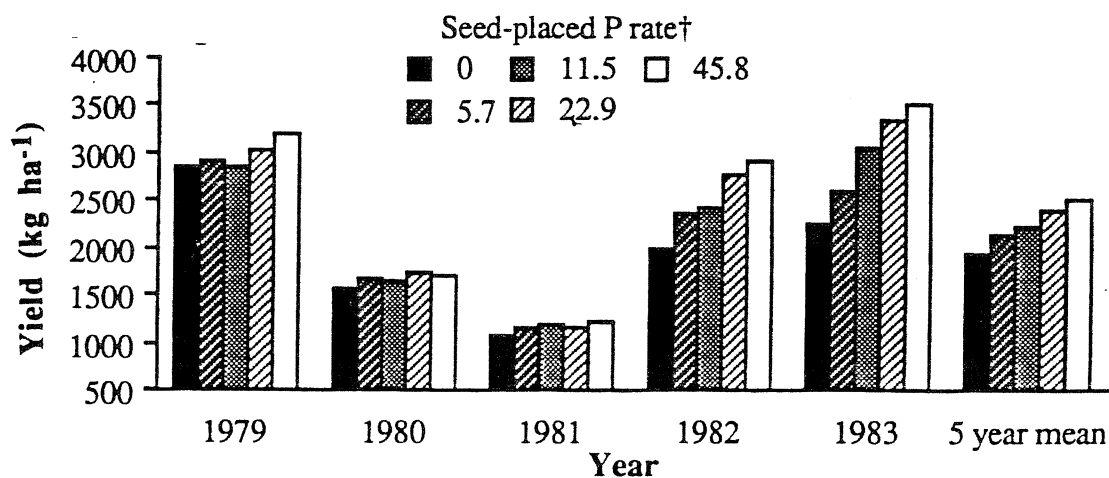

Figure 10. Average wheat yield response from plots receiving an annual seed placed application of monoammonium phosphate at various rates. † Phosphorus fertilizer in kg P_2O_5 ha^{-1} (Wagar et al., 1986a).

contribution of organic P components to available P. Reviews of the general agronomic effectiveness of phosphate fertilizers are provided by Engelstad and Terman (1980) and Roberts (1992).

Common Phosphate Fertilizers

Two types of P fertilizers are currently used in crop production on the prairies. These include calcium orthophosphates, and ammonium phosphates (Table 7). In western Canada, the ammonium phosphates predominate. The most popular ammonium phosphate fertilizers include: monoammonium phosphate, diammonium phosphate, and ammonium phosphate sulphate. Virtually all of the fertilizer P used in western Canada is in the form of monoammonium phosphate (MAP) (Beaton, 1980). The most common calcium orthophosphate fertilizer is triple superphosphate (TSP) (primarily used in eastern Canada). Polyphosphate fertilizers were introduced into western Canada in the late 1970s. These compounds are based on pyro - (P_2O_7) and meta-phosphates which are thought to be fixed at a slower rate in soils than orthophosphate fertilizers. However, when polyphophates are added to soil, they hydrolyze to orthophosphate and are subsequently immobilized by soil constituents (Bailey et al., 1980). Excellent overviews of the manufacture of P-fertilizers are provided by Nielsen and Janke (1980) and by the Potash and Phosphate Institute (1992).

A pronounced increase in plant uptake of fertilizer P occurs when ammonium is blended or combined with a P source (Rennie and Mitchell, 1954; Rennie and Soper, 1958). Ammonium phosphate fertilizers are effective P sources on alkaline soils because a temporary increase in P availability may result from local acidification in the fertilizer band as the NH_4-N is nitrified. The net effect of this process on P-deficient soils is a higher early growth response and higher crop yields than when Ca-phosphates of similar P solubility are used. In contrast, compounds such as urea- and diammonium-phosphates temporarily increase the pH of the soil adjacent to the fertilizer and may inhibit the

Table 7. Analysis, solubility, and chemical composition of some common P fertilizers (from Engelstad and Terman, 1980).

Fertilizer material	Analysis[†]	P solubility in water	Composition
		(%)	
Ordinary superphosphate	0-21-0	85	$Ca(H_2PO_4)_2 \cdot H_2O \cdot CaSO_4 \cdot 2H_2O$
Triple superphosphate	0-45-0	87	$Ca(H_2PO_4)_2 \cdot H_2O$
Monoammonium phosphate	11-55-0	100	$NH_4H_2PO_4$
Diammonium phosphate	18-46-0	100	$(NH_4)_2HPO_4$
Ammonium phosphate sulfate	16-20-0-14	>90	$NH_4H_2PO_4$, $(NH_4)_2SO_4$

† Fertilizer analysis based on percentage $N-P_2O_5-K_2O$.

Table 8. Estimation of the P uptake by wheat from fertilizer and soil using ^{32}P. (The P fertilizer was applied as solution (Spinks and Barber, 1947)).

Days after seeding	Stage of wheat growth	P from soil[†]	P from fertilizer[†]	P fertilizer use efficiency
		%	%	%
53	Before shot blade	21.1	78.9	12.9
72	Heading	14.0	86.0	21.3
93	Early dough	9.6	90.4	23.7
106	Ripe	6.5	93.5	22.3

† Fraction of P in total plant material.

nitrification process. If this occurs, temporary accumulations of NO_2 and NH_3 may occur, which are both toxic to plant growth (Engelstad and Terman, 1980).

In Saskatchewan, the application of fertilizer P is recommended on P soils containing less than 10 to 15 kg ha^{-1} of $NaHCO_3$-extractable P (Stewart and Karamanos, 1986). It should be noted that $NaHCO_3$-extractable soil P varies considerably spatially, and that proper measurement of the available P status of a field will often require intensive soil sampling (O'Halloran et al., 1985; Liang et al., 1991).

Further detail regarding soil test criteria for P-responses is provided in Chapter 8. In addition, reviews of the methodology for soil test P determinations and interpretations are available (McKenzie; 1989; McKenzie et al., 1989a; McKenzie and Roberts, 1990).

Best Management Practices for Fertilizer P

The effectiveness of P fertilization is determined by the properties of the P source (such as the accompanying cation and prill size), and of the soil being fertilized and by the reactions which occur between the P fertilizer and various soil constituents (Barrow, 1980; Sheppard and Racz, 1980). As well, weather conditions play a significant role.

Placement: Fertilizer P placement is one of the main factors affecting fertilizer use efficiency (Bailey et al., 1980; Harapiak, 1980; Murphy and Dibb, 1986). A brief summary of some of the principles and practices of P fertilizer placement follows.

Since soluble P reacts quickly with soil components, and can therefore become immobile quite rapidly, placement to minimize P fixation and maximize access to plant root systems is desireable (Engelstad and Terman, 1980). The method of placement of fertilizer P is one of the most important factors governing the efficiency or recovery of supplemental P in the year of application. (Barrow, 1980; Beaton, 1980; Sheppard and Racz, 1980). Generally, fertilizer P is most efficiently utilized in the year of application when placed with the seed or in a band near the seed (Bole, 1966; McKenzie and Roberts, 1990; Rennie, 1990). This method of placement reduces surface contact between the soil and fertilizer

and, consequently, reduces the amount of P fertilizer required to obtain a crop response. Seed-placed phosphate is most likely to be beneficial under conditions of low soil P and optimal moisture (Harapiak and Penney, 1984). The efficiency of banded fertilizer P is largely dependent on its distance from the seed row (Rennie, 1990).

"Starter" P (seed-placed or banded) is especially effective for crops growing in cool (<15-18°C) wet soils in the spring. It is much less effective at increased soil temperature (Wallingford, 1986; Sheppard and Racz, 1985). Supplemental P provided in these cool, wet conditions often results in a "pop-up" effect for fertilized crops (Engelstad and Terman, 1980; Zentner et al., 1992, 1993). When soil temperatures are low, root growth is severely retarded and the germinating seed literally starves for phosphate—unless a small quantity (e.g., 15 kg P_2O_5 ha^{-1}) has been placed in the seed row (Rennie, 1990).

Plant roots often proliferate in zones of elevated P concentration (e.g., fertilizer P bands). However, the ability of plants to develop roots in zones of high P concentration may differ among various crops (Strong and Soper, 1973). Root systems of crops that recover a large proportion of applied P have been found to proliferate more extensively within the fertilizer reaction zone than the roots of crops that recover only small amounts of applied P (Strong and Soper, 1974a, b).

Broadcast applications of P (at similar rates) are much less efficient for soluble P sources than banded or seed-placed P because the majority of applied P is immobilized by soil constituents (Bailey et al., 1980). For low solubility P products (e.g., rock phosphate), broadcast application is the most effective application method because it encourages a high dissolution rate in surface soil (Engelstad and Terman, 1980).

Seed-placed P application has, in certain cropping situations, become too restrictive and often impractical, particularly as farm size and fertilizer rates increase. In addition, the germination and early emergence of oilseed crops are often seriously impaired by placing over 25 kg P_2O_5 ha^{-1} in the seed row. High-yielding oilseed crops often have a much

higher P requirement than seed-placed rates can furnish without seedling injury (Beaton, 1980; Harapiak and Beaton, 1986; McKenzie and Roberts, 1990).

Seed-placed P may not be as effective as once thought (Harapiak and Flore, 1984). Alternatives to seed-placed P are deep banding and broadcast applications. However, "pop-up" responses to phosphate fertilizer have never been recorded where fertilizer P has been deep-banded or broadcast (Rennie, 1990).

Most crops generally respond well to P fertilizer banded a short distance either below or below and to the side of the seed (Bailey et al., 1980). Broadcasting P is a rapid, convenient alternative method of application that is best suited for soils testing medium to high in P. Broadcast P which is not used in the year of application will still be available in most prairie soils for succeeding crops (as previously discussed). In addition, a large single application of P prior to crop initiation could be particularly important in supplying the future P requirements under zero or minimal tillage (McKenzie and Roberts, 1990).

Phosphorus Fertilizer Use Efficiency (FUE): Traditionally, fertilizer P was considered a relatively inefficient nutrient, because only a relatively small fraction is used by crops in the year of application. The following is a summary of the FUE of annual P applications based on a single crop. (A true measure of FUE would also include the benefits of residual fertilizer P, as previously discussed).

One of the first FUE measurements was at Floral, Saskatchewan, where only 10 to 25 % of a ^{32}P labelled phosphatic fertilizer (applied as a solution to the seed row) was recovered by the crop over the growing season in the year of application (Spinks and Barber, 1946). Subsequent experiments with wheat and radioactive P (applied in a similar manner) clearly showed that the FUE for P was approximately 22% in the first year (Spinks and Barber, 1946; Barber et al., 1947). In a series of greenhouse experiments, Spinks and Barber (1948) showed that in the early stages of plant growth, a large fraction of the P taken up by a fertilized plant came from the fertilizer source. As growth continued,

the uptake of soil-P became increasingly more important until, at maturity, a much greater percentage of the P in the plant was coming from the soil (Table 8).

Later greenhouse and field studies with ^{32}P clearly established that, in terms of FUE, monoammonium phosphate was a more effective P source than Ca-phosphate sources and that increasing the rates of P fertilizer increased P uptake by wheat, but decreased the percentage of P utilized for grain production by wheat (Dion et al., 1949a, b). In a later review, Stewart and Karamanos (1986) confirmed that approximately 20% of the applied fertilizer P is used by prairie crops in the year of application.

Bole (1966) compared the efficiency of ^{32}P uptake by wheat for seed-placed versus broadcast P fertilizers. Fertilizer P placed with the seed was much more effective than broadcast applications for a silty loam soil of low P status. Approximately 21% of fertilizer P was recovered in wheat grain when seed-placed compared to only 9.4% recovery for broadcast fertilizer P. However, on a clay soil with higher soil-P levels, seed-placed and broadcast P additions were equally effective. Summaries of 'A' values and percent P utilization values for all field experiments clearly showed that the availability of fertilizer P is affected by placement in the order: drill > discer = to > broadcast (Table 9). Read et al. (1977) later compared the efficiencies of seed-placed and broadcast applications of P over several years so as to evaluate the contribution of residual P. Their results were later confirmed by Wagar et al. (1986a), who showed that in Chernozemic soils, both seed-placed and broadcast P are viable methods of P addition. Small quantities of seed-placed P provided immediate benefits to crops on low P soils by providing supplemental P in an immediately available form at the plant root. Zentner et al. (1993) have recently shown yield benefits from seed-placed P on relatively high P soils.

Nutrient Interactions

The P nutrition of crops is often improved by increases in the supply of other nutrients (Sheppard and Racz, 1980; Harapiak and Penney, 1984). An example from

Table 9. Summary of fertilizer P availability data from 1963, 1964, and 1965 ^{32}P field experiments (Bole 1966).

Placement	'A' value		P utilization	
	1963-65	1963-65	1963-65	1963-65
	—— (kg P ha^{-1}) ——		—— (%) ——	
Drill	61	43	16.9	16.1
Broadcast	165	156	8.5	8.3
Discer	--	80	--	8.7

Table 10. Positive interaction between N and P fertilizer when applied to barley grown on an N and P deficient Black stubble soil[†] in Alberta (Johnson and Hennig, 1976).

N	Nutrient P$_2$O$_5$	Yield	Yield increase
	(kg ha^{-1})	(kg ha^{-1})	(%)
0	0	2029	--
46	0	2189	7.9
0	21	2600	28.1
46	21	3027	49.2

† The soil was N and P deficient.

Alberta of a positive interaction between N and P is given in Table 10 (Johnson and Henning, 1976). The treatment with both N and P resulted in the most profitable barley production. Similar results from Saskatchewan were observed by Ukrainetz et al. (1975) for rapeseed grown on a Waseca loam soil.

Balanced N and P fertilization is also important for maximum economic yields and hardiness of winter wheat (Grant et al., 1984; Grant, 1986). Studies indicate that high levels of fall-applied N may cause winter wheat plants to lose their hardiness earlier , leaving them more susceptible to winterkill in the later winter months. At high rates of N fertilizer, seed-placed P may decrease winterkill by encouraging spring regrowth of roots damaged during the winter and lead to dramatic yield increases in winter wheat (Table 11). Although yield increases were obtained from separate applications of N and P, the highest wheat yields were obtained from a balanced application of N and P (Grant et al., 1984; Grant, 1986).

When applying high rates of fertilizer P (as discussed earlier in this chapter), the potential interaction with other nutrients must be considered. Research has shown that maximum crop response to residual fertilizer P can only be expected if sufficient fertilizer N was supplied or enough available N was present in the soil (Roberts and Stewart, 1987).

Significant interactions between applied P and micronutrients have also been found. For example, Spratt and Smid (1978) found that seven years after application, high rates of P increased available soil P and P concentration in flax tissue, but it decreased the concentrations of zinc (Zn) and copper (Cu) to near critical levels. Similarly, in the residual P studies of Wagar et al. (1986a), the authors observed that high P rates significantly reduced Zn levels in the wheat plant tissue. Further investigations on the same residual plots confirmed the existence of a P-induced Zn deficiency which was corrected by Zn fertilizer (Singh et al., 1986). In Manitoba, Bailey et al. (1980) noted that large single broadcast applications of P tended to accentuate Zn deficiency in some crops. Grant and Bailey (1989) observed an interaction between P and Zn for flax in growth chamber

Table 11. Yield response[†] and winter survival of Norstar winter wheat to various rates of broadcast N and seed-placed P[‡] under zero-tilled conditions (Grant et al., 1984; Grant, 1986).

Treatment		1979-80		1980-81	
N	P_2O_5	Survival	Yield	Survival	Yield
— (kg ha^{-1}) —		(%)	(kg ha^{-1})	(%)	(kg ha^{-1})
0	0	56.7	1260	74.5	960
61	0	49.7	2080	69.9	2753
120	0	50.6	2353	59.7	3160
0	20	70.6	2047	75.0	1120
61	20	56.5	2547	76.6	2793
120	20	48.8	2820	69.5	3613
0	51	55.5	2347	70.8	1347
61	51	67.3	2567	78.6	3080
120	51	50.3	2840	74.1	4280

[†] Results are averaged over 2 years.
[‡] N broadcast as 34-0-0, P seed placed as 11-48-0.

Table 12. Reduction in the severity of common root rot in Manitou spring wheat grown on fallow (two year average, 1970-71, two sites) (Verma et al., 1975).

P rate	Rating of disease intensity		
	June 22 - 28	July 20 - 26	August 30 - 31
(kg P_2O_5 ha^{-1})			
0	14	41	51
13	15	27	39
43	9	30	40
52	12	25	37
62	10	24	36

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experiments. They noted that when applications of P fertilizer increased P levels in flax tissue to levels above 0.46%, both the yield and Zn tissue levels in flax decreased. Conversely, Zn fertilization increased Zn and decreased P levels in the flax tissue.

Disease Control

It is generally accepted that balanced plant nutrition is an important factor in the tolerance of crops to diseases. Often excess N levels in both plant and soil can increase the incidence of plant diseases (Piening, 1967; 1982). Maintenance of optimal P levels in soils is also important in disease resistance in crops (Griffith, 1986). However, the role of fertilizer P in disease tolerance of prairie crops is variable. Depending on the experimental conditions, supplemental P may alleviate some plant diseases, have no effect, or even enhance the development of plant disease (Piening et al., 1980).

In view of the influence P has on root development, it is not surprising that P has been shown to have a positive effect on reducing certain root rot diseases (Piening et al., 1980; Piening, 1982; Verma et al., 1975). Surveys conducted by Vanterpool (1935; 1940a, b) in Saskatchewan clearly showed that areas within fields where wheat suffered most from browning root rot, caused by *Pythium* infection, were always deficient in P. Supplemental P subsequently reduced the number of infected plants by enhancing the root development so that fertilized plants were able to outgrow the disease. Subsequent studies were much less conclusive and showed less benefit from P fertilizer (i.e., MAP and TSP) on common root rot even though yield increases from P were obtained (Russell and Sallans, 1940).

More recently, seed-placed P has been shown to substantially reduce common root rot in mid-season for spring wheat grown on fallow soils (Table 12) (Verma et al., 1975; Piening et al., 1980). However, Piening et al. (1980) found no effect of seed-placed P on common root rot of Neepawa wheat. Further, Pittman and Horricks (1972) found that additional P had no visual effect on common root rot of barley although they did isolate

fewer pathogens (*Fusarium* spp. and *Heminithosporium sativum*) from the crowns of barley growing on soils which received P. In contrast, Piening et al. (1967; 1969) report a higher incidence of root rot infection in non-fertilized than for P fertilized barley. Yield losses from common root rot averaged across four barley cultivars was 15% with no supplemental P, to 9.5% when 112 kg ha^{-1} of superphosphate fertilizer was applied.

Leaf diseases are also affected by P addition (Piening et al., 1980). A healthy, well nourished plant is more likely to tolerate diseases than a malnourished plant because well nourished plants produce new roots more readily to replace those destroyed by soil-borne pathogens (Piening, 1989). A significant reduction in net blotch of barley resulted from the addition of P individually, or P plus K, to three Alberta soils inherently deficient in both nutrients (Peining, 1967).

Increased disease resistance of P-fertilized crops may be related to low temperatures early in the growing season. Beaton (1980) noted that the critical level of P in crops such as barley was much higher at low temperatures than under ideal conditions. Phosphorus hastens plant maturity so the plant may produce its full yield potential before the disease has progressed to damaging proportions.

Supplemental P may also promote thicker cuticles and cell walls making it more difficult for rust-causing fungi (eg., *Puccinia graminis*) to penetrate cell walls. This may also limit fungal growth once inside the host plant (Piening, 1989).

Crop Quality

In western Canada, P fertilization has been shown to have an inconsistent influence on crop quality. For example, high rates of applied P may increase oil percentage of canola (Bailey and Grant, 1990) (Fig. 11). However, other reports have shown slightly reduced oil content from P fertilization (Henry and Schappert, 1971; Ukrainetz, 1979).
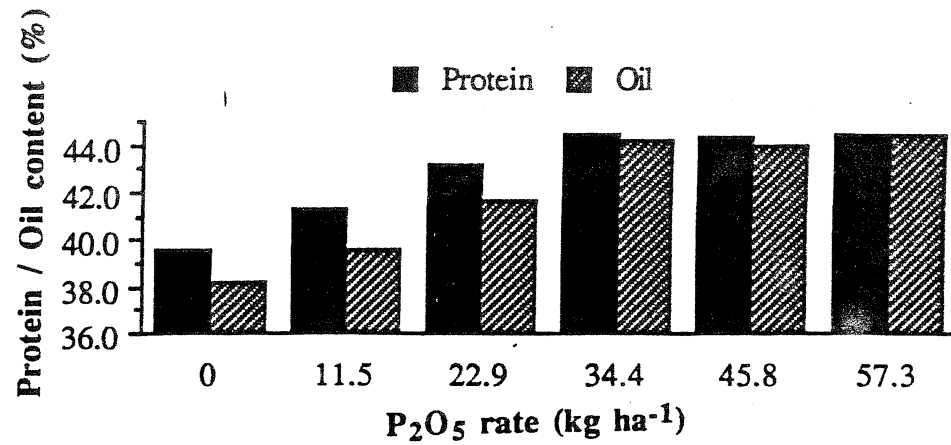
Figure 11. Percentage protein and oil content of canola as affected by various rates of P fertilization. Results averaged over 5 year, two soil types, and five P fertilizer placement methods (from Bailey and Grant, 1990).
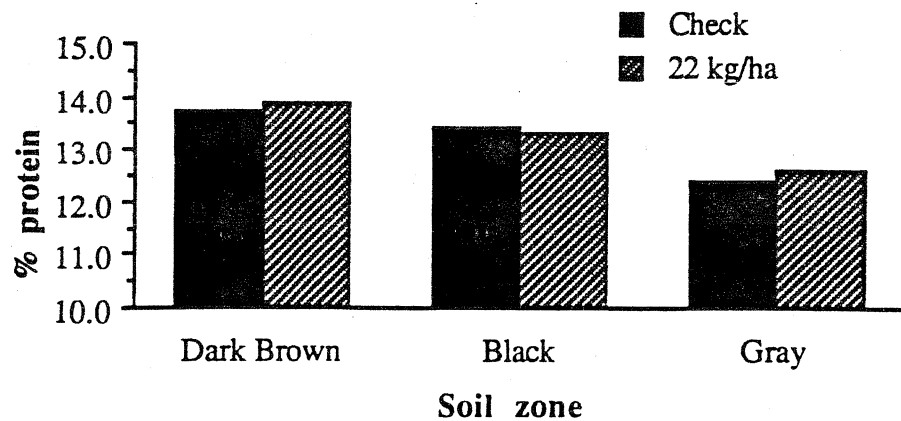

Figure 12. The effect of phosphorus fertilization on the protein content of stubble seeded wheat. Averaged over 121 trails conducted across the Dark Brown, Black, and Gray soil zones (Halstead, 1971).

Phosphorus fertilization may improve crop quality in short season areas by hastening crop maturity and development (Grant and Bailey, 1990). A brief review of the general relationship between P and crop quality is provided by (Munson, 1986).

After examination of data from 30 radiophosphorus field experiments with wheat , Rennie (1956) concluded that P concentrations in grain was significantly reduced by N application, increased by N deficiency and relatively unaffected by P fertilization. Protein concentration of grain was unaffected by N and P fertilization and varied greatly as the result of soil and climatic conditions. In a later study, Halstead (1971) summarized almost 30 years of data from field trials conducted by the Department of Soil Science at the University of Saskatchewan involving P response of cereals. He concluded that the P concentration of grain was significantly reduced by increased N and relatively unaffected by fertilizer P. The results also suggested that the protein concentration of wheat was unaffected by fertilizer P (Fig. 12). The relative effect of P on protein will likely be dependent on the yield response obtained; a high dry matter increase will deplete (reduce) grain protein, especially if available N is inadequate.

CONCLUSIONS

The challenge remains for us to better understand the nature and availability of the reserves of soil organic P in prairie soils and to improve our knowledge of the significance and economic importance of changes in these reserves induced by agronomic practices (Stewart et al., 1980).

Further research to assess the role of P in the plant response to disease producing pathogens and in winter survival of fall-seeded crops is needed with well defined test parameters (Piening et al., 1980).

Greater understanding of the spatial variability of soil P is also needed to improve our understanding of soil P and fertilizer P use efficiency.

A closer examination of organic P changes in the rhizosphere is necessary to develop a better understanding of organic P contribution to plant nutrition. Use of new techniques to measure root development and extraction of plant nutrients is also an important area. Much more information is need on root rhizosphere dynamics (Stewart et al., 1989).

Maintenance of soil P levels with fertilizer P will result in a more dynamic soil P cycle and, through improved soil quality, will lead to much more sustainable future crop production.

Predicting yield response to fertilizer P is much less precise than for fertilizer N primarily because available soil P is frequently positionally unavailable to the crop roots.

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