Agronomic Thresholds for Soil Phosphorus in Alberta: A Review

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Alberta Soil Phosphorus Limits Project

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EXECUTIVE SUMMARY

This review was carried out at the request of the Soil Phosphorus Limits Steering Committee to identify agronomic thresholds of soil phosphorus for Alberta. This review is part of a study to identify limits for soil phosphorus limits of agricultural land in Alberta.

Phosphorus (P) is a key element in crop production and environmental sustainability. While good agronomic management requires use of phosphorus to optimize crop growth, excessive phosphorus may degrade water quality. A major difficulty in managing soil phosphorus is knowing what levels of soil phosphorus are optimum for crop growth and what levels present an unacceptable risk to water quality. A key tool for managing crops for optimum production is soil testing; however, to achieve a balance between optimum crop production and environmental sustainability, a better understanding of how soil tests are interpreted is needed. Increased care in applying phosphorus from commercial fertilizer and manure sources will be required to achieve the desired balance between optimum crop productivity and sustainable water quality.

The Soil Phosphorus Limits Steering Committee requested the study address three areas: review the basis for soil test phosphorus recommendations in Alberta, to review the agronomic thresholds for phosphorus that apply to different crops and soil types in Alberta, and to review the implications for the application of non-commercial nutrient sources. The Soil Phosphorus Limits Steering Committee agreed that “basis for soil test phosphorus recommendations in Alberta” was to be interpreted to mean the basis for phosphorus fertilizer recommendations in Alberta. In this report, an agronomic threshold of soil phosphorus is defined as the soil phosphorus level, as determined by soil test phosphorus analysis, beyond which there is no practical economic or crop yield response to added phosphorus from either commercial (inorganic) fertilizer or organic fertilizer sources.

The review examined more than 200 references from the literature and provided an analysis of Alberta soil phosphorus data for four crops over several soil types.

Basis for phosphorus fertilizer recommendations in Alberta

1. Conventional soil tests for phosphorus are used to determine the amount of supplemental phosphorus required to prevent loss of crop value from phosphorus deficiency.
2. Several philosophies can be used to interpret soil test results to make fertilizer recommendations. In Alberta, the philosophy is to recommend application of only those nutrients lacking in the soil.
3. There is no standard method for determining soil test phosphorus levels.
4. The two versions of the modified Kelowna extraction are most commonly used for determining soil test phosphorus levels in Alberta. One version should be chosen as the standard test.
5. Because the processes governing crop uptake of phosphorus from the soil are different from those governing phosphorus enrichment of water, care must be taken when using soil test phosphorus data for assessing environmental risk, a purpose for which it was not intended.

Agronomic thresholds for soil phosphorus in Alberta

1. A moderate buildup of soil phosphorus levels is beneficial for good crop production; however, soil phosphorus must be managed carefully to prevent degradation of water quality.
2. Based on data from field trials across the major soil groups of Alberta, an agronomic threshold of 60 mg kg^{-1} in the top 0.15 m of soil, based on a modified Kelowna extraction, would provide the most flexibility for crop production should a single threshold for all crops and soils in Alberta be required.
3. Agronomic thresholds reported in other areas are less than 60 mg kg^{-1}.
4. Agronomic thresholds are identified by selecting an acceptable amount of yield reduction below maximum levels. Because the relationship between yield response and soil test phosphorus levels is not linear, determining how to set the yield threshold can have a large effect on the soil test phosphorus value for the threshold.
5. The relationship between soil test phosphorus and crop yield may need to be re-examined to identify the impact of lower soil test phosphorus levels on crop production if environmental limits have similar or lower values than the agronomic thresholds.

Implications for application of phosphorus from organic sources

1. Long-term application of phosphorus in commercial fertilizer or manure has resulted in accumulation of phosphorus in agricultural soils.
2. There is no evidence to indicate that soil test phosphorus results from manured soils should be interpreted differently than test results from non-manured soils.
3. In the early years of manure application, phosphorus forms in manure change rapidly from more mobile to more stable forms in the soil. The amount of mobile phosphorus forms that are stabilized decreases with time, suggesting that risk to water quality by phosphorus from manured lands is probably lower in the early years of manure application and increases with long-term, repeated applications in excess of crop uptake.
4. More research is needed to understand how to manage crops to achieve environmental and economic sustainability when manure is used as a nutrient source.

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INTRODUCTION

Background

A recent provincial water quality study showed that agriculture was adversely impacting water quality in Alberta (CAESA 1998). The livestock industry is undergoing considerable expansion in Alberta. To maintain a marketing advantage by promoting high quality Alberta meat produced in a healthy environment, the livestock industry needs to be environmentally sustainable. As livestock production increases, the need to maintain public and consumer confidence that the industry is environmentally responsible becomes more acute. By 1999, the industry and the public requested that a process be initiated to develop regulations for the industry.

Phosphorus (P) is a key element in environmental sustainability. While phosphorus is an essential element for crop nutrition, it is also the limiting nutrient in accelerated eutrophication of water bodies. The potential for soil phosphorus loading to degrade water quality was reviewed by Howard et al. (2006). According to Sims (2000), crop production increases with soil phosphorus levels to an optimum, beyond which there is no appreciable gain in yield; however, once soil phosphorus levels exceed the optimum for crop production, the risk to water quality increases (Fig. 1). A major difficulty in managing for economic and environmental sustainability is to know the levels of soil phosphorus that are optimum for crop growth and the levels that present an unacceptable risk to water quality.

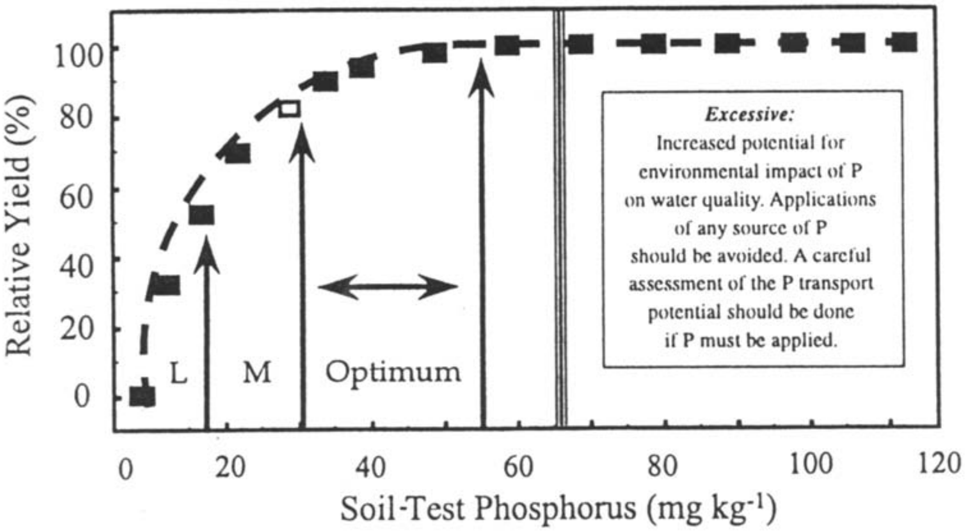


Fig. 1. Generalized representation of the relationship between soil test phosphorus, crop response, and the potential for an impact on water quality (Sims 2000).

Livestock manure is a major source of phosphorus. If manure is applied on land, it can potentially reduce the amount of commercial fertilizer required for crop production. If commercial fertilizer or manure is applied in strict accordance with agronomic recommendations based on soil test phosphorus values and crop demand, soil phosphorus levels are expected to increase minimally and the risk to water quality will likely remain acceptable (Sims 2000). However, in many cases there is insufficient land within an economically feasible distance to apply manure at rates that would meet but not exceed recommended agronomic rates for phosphorus. Acquiring additional land or transporting manure to more distant land can be costly. Thus, in the past, manure was applied in excess of crop phosphorus requirements on some fields. As a result, phosphorus has accumulated in these soils.

The Livestock Regulatory Stakeholder Advisory Committee requested that a study be undertaken to identify environmentally safe phosphorus loading limits for soils in the agricultural area of Alberta. These limits could be used as guidelines for phosphorus application from all sources, including livestock manure, commercial fertilizer, food processing waste, and municipal waste. The study is currently in progress and is being led by the Soil Phosphorus Limits Steering Committee, which is composed of industry and government members.

One of the guiding principles for the Steering Committee was to ensure that phosphorus loading rates would not impede optimal crop production. Several studies have reported that crops no longer respond to soil phosphorus levels beyond a threshold (Pierzynski and Logan 1993; Qian et al. 1994; Ashworth and Mrazek 1995; McKenzie et al. 1995; Johnston and Poulton 1997). It was expected that agronomic threshold levels would be less than environmental risk levels except in a limited number of very sensitive areas.

This review was carried out at the request of the Soil Phosphorus Limits Steering Committee to identify the agronomic threshold levels of soil phosphorus for Alberta so that these levels could be incorporated into the study to develop soil phosphorus limits for agricultural land in Alberta.

Objectives

The objectives of this report were to review

- the basis for phosphorus fertilizer recommendations in Alberta ,
- the agronomic thresholds for phosphorus that apply to different crops and soil types in Alberta,
- the implications for the application of organic phosphorus sources.

For the purpose of this review, an agronomic threshold for soil phosphorus is defined as the soil phosphorus level, determined by soil test phosphorus analysis, beyond which there is no practical economic or crop yield response to added phosphorus from either commercial (inorganic) fertilizer or organic fertilizer sources.

Methods

The information to address each objective of this report was initially obtained from an exhaustive review of the current literature. More than 200 sources were reviewed. Emphasis was placed on obtaining recent information from the Northern Great Plains of Canada and the United States.

The literature review on agronomic thresholds revealed two reports (McKenzie et al. 1995; McKenzie et al. 2001) that interpreted wheat, barley, canola, and pea yield response to soil phosphorus for Alberta. McKenzie et al. (2001) provided their original raw data on pea yield response to soil phosphorus in Alberta.

This information was highly relevant but did not precisely define any agronomic thresholds; therefore, an analysis was developed to define agronomic thresholds from the data. The analysis calculated the yield increase for each 10 mg kg^{-1} increase in soil test phosphorus. A yield increase of 1% or less for a 10 mg kg^{-1} increase in soil test phosphorus was considered to be the zero return point because the yield increase was insignificant compared to the cost of raising the soil phosphorus level by 10 mg kg^{-1}. This zero return point was used as the agronomic threshold, which was then compared to agronomic thresholds reported in the literature.

Phosphorus Terminology

Phosphorus concentrations can be expressed in several ways, and no standard for the terms of expression has been adopted. Phosphorus is usually expressed as concentration of elemental phosphorus in soil and water, and as P_2O_5 in commercial fertilizers. It can also be expressed as orthophosphate (PO_4^{-3}). Phosphorus concentrations in soil are often expressed as mg kg^{-1} of soil, which is the same as parts per million (ppm). Phosphorus content in water, because of the sensitivity of water to low concentrations, is often reported as μg L^{-1}, which is the same as parts per billion (ppb). In this report, phosphorus in soil will be expressed as mg kg^{-1} of elemental phosphorus. The relationships between some of the units are presented in Table 1.

Table 1. Conversion factors for some common phosphorus (P) reporting terms.

μg L^{-1}	=	ppb
mg L^{-1}	=	ppm
mg kg^{-1}	=	ppm
ppb	=	1000 × ppm
P_2O_5	=	P × 2.2914
P	=	P_2O_5 × 0.4364

Note: the equality between mg L^{-1} and ppm, and between μg L^{-1} and ppb assumes a solution in water where the specific gravity is near 1.0.

There are several methods for testing soil for plant-available phosphorus, each yielding a slightly different available phosphorus value. For consistency, all soil test phosphorus levels will be expressed in terms of the Norwest Labs' modified Kelowna method unless otherwise stated. Conversion formulas used in this report are based on relationships developed by McKenzie et al.

(1995).

Phosphorus Forms Referred to in this Report

Phosphorus exists in a variety of inorganic (P_i) and organic (P_o) forms in the soil. Table 2 presents the abbreviations used to refer to phosphorus forms in this report. The same abbreviations are commonly used in the literature.

Table 2. Terminology and abbreviations used for the various forms of phosphorus (P).

P_t	= Total P	= All forms of P
P_i	= Inorganic P	= Mineral forms of P
P_o	= Organic P	= Organic forms of P
P_d	= Dissolved P	= All forms of P dissolved in water
BAP	= Biologically available P	= P used by algal populations
STP	= Soil test P	= Correlated to plant-available P
PO_4^{-3}	= Orthophosphate	= One form of solution P or P_d
P_p	= Particulate P	= P sorbed to soil particles

The forms vary in their solubility in water and availability to plants, and have been described in detail by Stewart and Sharpley (1987). The solution pool contains P_i and P_o in forms used directly by crops and microorganisms. Labile phosphorus refers to readily available forms that can move into solution quickly as the phosphorus concentration in the solution pool is depleted by plants or microorganisms. Moderately labile forms include inorganic phosphorus that is associated with iron (Fe) or aluminum (Al), or moderately available organic forms, both of which are capable of contributing to the solution phosphorus pool. Slowly available forms include P_i associated with calcium (Ca) and magnesium (Mg), or primary mineral phosphorus. The least available forms include P_o in particulate forms, which are occluded (unavailable), and P_i forms that are insoluble.

Chemical analyses to determine the proportion of the various forms of phosphorus in soils have been reported by Hedley et al. (1982), Tiessen and Moir (1993), and Qian and Schoenau (2000a). All analysis methods generally use an extractant to change the targeted phosphorus form(s) to orthophosphate PO_4^{-3}. The concentration of the orthophosphate can then be measured and related to the amount of the targeted phosphorus form in the soil. Since the forms of phosphorus are often referred to by the type of extraction procedure used to detect them, Table 3 presents the extractant used to isolate the particular form.

Assumptions used in this Report

Nutrient concentrations in soil are often expressed in terms of kg ha^{-1} for a given depth within the soil profile. To allow comparisons, these units were converted from kg ha^{-1} to mg kg^{-1} in this report. This conversion requires that the depth and bulk density of the soil of interest be known or have assumed values. For the conversions in this report, soil depth was assumed to be 0.15 m, a common soil depth for nutrient analysis, and soil bulk density was assumed to be 1.2 Mg m^{-3}.

Table 3. Extractants for the various forms of phosphorus (P) based on Qian and Schoenau (2000a).

P form	Extractant
Soluble P	Distilled water
Labile (readily available) P_i	Resin
Labile (readily available) P_i and P_o	$NaHCO_3$
Moderately labile P	NaOH
Slowly available P	1 *M* HCl
Occluded P_o (unavailable)	Conc. HCl
Residual (resistant) P	H_2SO_4 and H_2O_2

For example, converting 100 mg kg^{-1} of phosphorus to a nutrient content in the top 0.15 m of the soil would require the following steps:

1. Soil bulk density is assumed to be 1.2 Mg m^{-3}
2. 100 ppm = 100 mg kg^{-1}
3. (100 mg kg^{-1} × 10^{-6} kg mg^{-1} × 1.2 Mg m^{-3} × 10^{-3} kg g^{-1} × 10^{6} cm^{3} m^{-3} × 10^{4} m^{2} ha^{-1} × 0.15 m depth) = 180 kg ha^{-1}

BASIS FOR FERTILIZER PHOSPHORUS RECOMMENDATIONS IN ALBERTA

Soil test phosphorus (STP) results ultimately form the basis for crop response and fertilizer recommendations. Agricultural soil analysis techniques have been primarily used to identify total phosphorus (P_t) or plant-available phosphorus, which is correlated with STP. Crop fertility status and fertilizer requirements are based on STP; therefore, the test is widely used in the industry for routine soil analysis. Organic phosphorus (P_o) forms are important when assessing soil phosphorus transformations, which can be applied to fertility, especially when considering manure. Other phosphorus fractions, including biologically available phosphorus (BAP), dissolved phosphorus (P_d), and particulate phosphorus (P_p), have become important factors when assessing the environmental impacts of soil phosphorus contributions; however, they have not generally been part of routine soil analysis.

Soil test phosphorus methods are based on using chemicals to dissolve enough phosphorus from the soil to estimate the amount of phosphorus the soil is capable of supplying to the crop. The main purpose of a soil phosphorus test is to determine an index of the amount of supplemental phosphorus required to prevent loss of crop value because of phosphorus deficiency (Fixen and Grove 1990). Plant uptake results in a decrease in solution phosphorus, which is replenished by dissolution of mineral phosphorus or release of adsorbed phosphorus. Soil conditions, especially pH and phosphorus sorption capacity, influence this process. The STP analysis uses chemical extractants to create solutions that dissolve phosphorus in amounts consistent enough to be correlated with crop phosphorus use. The amount of dissolved phosphorus can change for different soils and different pH levels.

Soil Tests for Plant-available Phosphorus

Analysis of soil to detect phosphorus levels follows the general method of dissolving some or all of the soil phosphorus in an extractant, then determining the concentration of phosphorus in the extractant. A typical extraction procedure involves the shaking of a known weight of soil (e.g., 5 g) with a known volume of extractant (e.g., 50 mL) for a fixed period of time (e.g., 30 min) at room temperature. The mixture is then filtered, and the filtrate is analyzed for extractable phosphorus (PO_4^{-3}) content. Measurement of plant-available phosphorus in filtered extractant is determined using an inductively coupled plasma (ICP) spectrophotometer, or colorimetrically using phosphomolybdic blue complex reduced with ascorbic acid (Watanabe and Olsen 1965). The ICP probe will respond to other forms of phosphorus as well as PO_4^{-3}, and can give some slightly higher results for some extracts (Miller and Kotubny-Amacher, in press).

The purpose of the test and the type of soils being tested determine the type of extraction and the method of soil sampling. For STP, soil tests are based on a cored or augered sample to 0.15 m depth. The results of the analysis are then correlated to crop growth or nutrient uptake. In cases where a particular soil phosphorus test does not correlate to crop response, either by research or field experience, it can eventually be replaced by a test in which the users have more confidence. For example, the Miller-Axley test, which has been used in the Alberta provincial laboratory for several years, has recently been reported as underestimating soil phosphorus availability (McKenzie et al. 1998). Most STP analyses in Alberta are now performed using modifications of the Kelowna test.

Bray and Kurtz (1945) and Olsen et al. (1954) used weak extractants, which correlated well with plant uptake. The Bray and Kurtz (1945) extraction method, referred to as Bray-1, initially used 0.03N NH_4F and 0.025N HCl for determining “adsorbed-P”. Fluoride was included in the extractant because it had a high capability to displace adsorbed phosphorus. Surface adsorbed phosphorus has a greater influence on phosphorus availability because its surface area is exposed to the chemical reactions; therefore, it more readily replaces the phosphorus in soil solution as solution phosphorus is removed by plant uptake (Thomas and Peaslee 1973). Since adsorbed and acid-soluble forms of phosphorus co-exist in soils, Bray and Kurtz (1945) proposed a stronger extractant using 0.1 *N* HCl instead of 0.025 *N* HCl for determining both forms of phosphorus.

Relationships between crop response and the Bray-extractable phosphorus were not consistent across several soil types. Free carbonates in soils neutralize the acid in the extractant resulting in precipitation of dissolved phosphorus (Syers et al. 1987). Soils at pH values greater than 7.2 frequently contain enough free carbonates to at least partially neutralize the HCl in the Bray extractant (van Lierop 1988). Numerous extraction methods have been developed, all with advantages and limitations depending upon the soil type for which they have targeted. Their suitability relies on long-term correlation studies that have established relationships between the extraction method, the soil, and crop response. Therefore, some extraction methods are favored more in some parts of the world than in others. Soil pH, mineralogy, and organic matter content are major factors in accuracy. The tests are differentiated by the extractant used. A summary of the more common tests is presented in Table 4.

In Alberta, the Miller-Axley and the Bray methods were the main extractions for available phosphorus, but both were unsuitable for the highly calcareous, high pH, soils of southern Alberta because the free carbonates neutralized the weak acid in the extractant (McKenzie and Kryzanowski 1990). During the 1970s and 1980s, a second extraction using the Olsen ($NaHCO_3$) test was performed in Alberta and British Columbia provincial soil laboratories to determine the available phosphorus in high pH soils (van Lierop 1988; McKenzie and Kryzanowski 1990). The Miller-Axley test was developed in the 1970s before large amounts of commercial fertilizer phosphorus were added to soils. At that time, the chief sources of phosphorus were from soil minerals and organic sources (McKenzie et al. 1998).

The Kelowna extraction was proposed by van Lierop (1988) as a single test that would apply to a wide range of soil conditions. It could replace the Bray and Olsen tests. The extractant used acetic acid in place of the weak HCl used in the Bray and H_2SO_4 used in the Miller-Axley extractants. While the Kelowna extraction performs similar to the Olsen test at high soil pH levels, it does not require charcoal filtration and does not evolve CO_2 (Qian et al. 1994).

In the Canadian prairies, modifications of the Kelowna test were tested against crop response in greenhouse trials (Ashworth and Mrazek 1989; McKenzie et al. 1989; Qian et al. 1994) and field trials (Ashworth and Mrazek 1989, 1995). The testing validated the Kelowna and modifications of the Kelowna for a variety of soil types. Addition of ammonium acetate to the modified Kelowna extractant resulted in an improved prediction of available potassium compared to the Kelowna (Qian et al. 1994). The Kelowna and its modifications are considered accurate for Canadian prairie soils (Havlin et al. 1999).

Table 4. Summary of phosphorus (P) analysis methods (modified from Sibbesen and Sharpley 1997, and Howard et al. 2006).

Analysis method	Extractant	Comments
Olsen	0.5 *M* $NaHCO_3$ @ pH 8.5	-best suited for neutral and calcareous soils (Qian et al. 1994) -process of maintaining pH level, driving off CO_2, and filtering extractant through activated charcoal makes the procedure awkward (Qian et al. 1994)
Mehlich-3	0.2 *M* CH_3COOH 0.25 *M* NH_4NO_3 0.015 *M* NH_4F 0.013 *M* HNO_3 0.001 *M* EDTA[z]	-common method for assessing crop-available P in the United States
Bray-1	0.03 *N* NH_4F 0.025 *N* HCl @ pH 3.5	-designed for neutral – acidic soils -not suited for calcareous soils
Bray (strong)	0.03 *N* NH_4F 0.1 *N* HCl @ pH 1.0	
Miller-Axley	0.03 *N* NH_4F 0.03 *N* H_2SO_4	-not suited for calcareous soils
Modified Kelowna[y]	0.015 *M* NH_4F 0.25 *M* ammonium acetate 0.25 *M* acetic acid	-best method for a wide range of soil pH levels in the prairie provinces -measures available P and K
Modified Kelowna[x]	0.015 *M* NH_4F 1.0 *M* ammonium acetate 0.5 *M* acetic acid	-best method for a wide range of soil pH levels in the prairie provinces -measures available P and K
Kelowna	0.015 *M* NH_4F 0.25 *M* acetic acid	-suitable for a wide range of soil pH levels

[z] EDTA is ethylene diamine tetraacetic acid.
[y] Used by Enviro-Test Labs.
[x] Used by Norwest Labs.

Two modified Kelowna methods have become the most accepted and widely used tests in Alberta. While they have been correlated with each other in tests (Table 5) (McKenzie et al. 1995), there is no provincial standard. One method is used by Norwest Labs, and the other is used by Enviro-Test Labs. Ashworth and Mrazek (1995) report that the concentration of acetic acid in Norwest Labs' extractant (0.5 M) reduces the risk of calcareous soils neutralizing the extractant.

A sample of equivalent STP values from common tests, derived from the equations in Table 5, is presented in Table 6. Comparison of tests can result in varying relationships due to differences in sample preparation and analysis techniques. An example is the regression equations developed by Qian et al. (1994):

$$\text{ETMK} = 0.82 + 0.92 \times \text{Olsen} \quad (1)$$

$$\text{ETMK} = -2.28 + 1.52 \times \text{Kelowna} \quad (2)$$

Where:
ETMK = Enviro-Test Labs' modified Kelowna test,
Olsen = Olsen test
Kelowna = Kelowna test

Table 5. Relationships between common soil test phosphorus methods and the Norwest method (McKenzie et al. 1995). The Norwest method is represented by x in the regression equations.

Extraction method (y)	Regression equation	r^2
Enviro-Test Modified Kelowna[z]	y = 4.038 + 0.941x	0.88
Miller-Axley	y = 3.258 + 0.717x	0.57
Olsen	y = -3.319 + 0.886x	0.76
Kelowna	y = 1.915 + 1.137x	0.86
Resin	y = -16.23 + 1.938x	0.51
Bray-1[y]	y = -4.08 + 1.103x	
Mehlich-3[x]	y = 13.004 + 1.037x	0.97

[z] Used by Enviro-Test Labs.
[y] Calculated from van Lierop (1988) for soils with pH < 7.0; no r^2 determined.
[x] From M. Amrani (personal communication).

Equation 1 predicts Enviro-Test modified Kelowna STP values from the Olsen test that are lower than those predicted with the equations in Table 5. For example, from Table 6 a Norwest modified Kelowna value of 10 mg kg^{-1} corresponds to an Enviro-Test modified Kelowna value of 13 mg kg^{-1} and an Olson value of 6 mg kg^{-1}. Equation 1 from Qian et al. (1994) predicts an Enviro-Test modified Kelowna value of 10 mg kg^{-1} from an Olsen value of 10 mg kg^{-1}.

Equation 2 predicts Enviro-Test modified Kelowna STP values from Kelowna tests that are higher than those predicted with the equations in Table 5. From Equation 2, a Kelowna value of

40 mg kg^{-1} will predict an Enviro-Test value of 58 mg kg^{-1}. Using Table 6, a Kelowna value of 47 mg kg^{-1} corresponds to an Enviro-Test value of 42 mg kg^{-1}. This suggests that the cross-referencing of STP methods requires careful design to ensure that variability between soils and lab techniques have been accounted for and standardized.

Table 6. Calculation of soil test phosphorus (STP) values from values of Norwest Labs' modified Kelowna analysis.

Norwest STP	Enviro-Test[z] STP	Miller-Axley[z] STP	Olsen[z] STP	Kelowna[z] STP	Bray-1[y] STP
10	13	10	6	13	7
20	23	18	14	25	18
40	42	32	32	47	40
60	60	46	50	70	62
80	79	61	68	93	84
100	98	75	85	116	107

[z] Based on equations from McKenzie et al. (1995).

[y] Based on equations modified from van Lierop (1988).

Ion exchange strips have been proposed by Qian et al. (1992) and Schoenau et al. (1993) as a technique for assessing available nitrogen, phosphorus, potassium, and sulphur. The strips adsorb ions directly from solution in a manner similar to uptake by roots. The strips are designed to be buried in situ and mimic root ion exchange.

A resin exchange probe, which uses the same principle, is now in commercial use by Western Ag Labs in Saskatoon, Saskatchewan, and has been tested in more than 600,000 ha of agricultural land in western Canada (J. Schoenau, personal communication). The probe offers the advantage that it measures phosphorus availability from the soil solution with time and in situ. Therefore, changes in phosphorus availability as a result of temperature changes and other site factors can be detected. Probes have had limited use in manured soils at this time; however, ease of use and potential for a closer approximation of crop nutrient uptake may result in this method becoming widespread for determination of STP.

Determination of Phosphorus Response Curves

Crop yield response to STP levels increases to a critical level, beyond which yield does not increase appreciably regardless of how much more phosphorus is applied (Qian et al. 1994; Ashworth and Mrazek 1995; McKenzie et al. 1995; Johnston and Poulton 1997). In the field, crop response is determined by several factors including soil, nutrient status, cropping history, management, and climate.

Kastens et al. (2000) modeled wheat response to STP and observed that STP had the most influence on wheat yield, even more than fertilizer phosphorus. Soil testing was used to obtain values for nutrients that would help predict the amount of nutrients needed to supplement the nutrient supply in the soil. Although a crop response to fertilizer will not always be obtained in a soil of low nutrient status, because of environmental and other limiting factors, a low nutrient status soil has a greater probability of response than a soil with a high nutrient status (Havlin et al. 1999).

Interpretations of Crop Responses to Soil Phosphorus and Fertilizer Phosphorus

Soil tests for fertility assessment are generally performed on soil sampled to 0.15 m depth from representative parts of a field. Interpretation of soil test results is used to predict the potential effect of soil nutrient levels on crop growth. Soil test phosphorus levels have been linked to crop use of phosphorus by assessing crop response in plots and/or measuring phosphorus in plant tissue analysis. Crop response interpretations are generally based on controlled plot experiments. Crop characteristics in a control plot set, with no fertilizer added, are measured and compared with enough treatment sets, with incremental amounts of fertilizer added, to assess optimum crop response. Crop growth stage characteristics are recorded but the primary comparison is to yield data, with the degree of response determined by the treatment yield-control yield ratio. This method is used for assessing crop nutrient requirements for optimum yield, whereas tissue analysis can be used to quantify nutrient uptake, and identify deficiencies and processes. Nutrient uptake by the herbage of pasture and hay crops has been considered a good method for estimating the quantity of fertilizer required for the crop in the next year (Nuttall 1980; McCartney et al. 1998).

The degree of sophistication for interpreting soil test results increases with the effort put into researching and understanding the relationship between soil tests and crop growth. The Alberta Soil Test Advisory Group (1998) identified three levels of sophistication in soil test interpretation. Initially, when a soil test is developed it only indicates whether there is a deficiency (limitation) or a sufficiency (no limitation) of a nutrient. For that nutrient, this results in one of two recommendations, no fertilization or an amount considered adequate.

The second stage of development is to divide the soil test values into categories. Soil tests for available nutrients are often categorized as being low, medium, or high, based on the probability of response to application of the nutrient in question. An example is presented in Table 7.

The final stage is to fully calibrate the soil test values with crop response using regression techniques so that an infinite number of categories could be obtained (Barber 1973). For calibration, the relationship of the soil test result for an available nutrient to crop growth is based on how much of that nutrient is utilized by the crop. The soil test result provides only a relative measure of nutrient supply as correlated to crop response (Alberta Soil Test Advisory Group 1998) and should be considered an index of nutrient availability and potential yield response (Havlin et al. 1999).

Table 7. Example of the second stage of development of soil test interpretation where soil test results are split into three categories (Alberta Soil Test Advisory Group 1998).

Soil test level	Probability of response	Fertilizer required
Low	High	High
Medium	Medium	Medium
High	Low	Low

Because of the many factors influencing crop growth, interpretation of crop response data for fertilizer recommendations must consider environmental factors such as soil moisture, precipitation, temperature, local soil and landscape conditions, crop rotation, and cropping history (Ashworth and Mrazek 1995; McKenzie et al. 1995). Recommendations from some soil test labs include input from local sources, such as the producer or local fertilizer agent. Fertilizer recommendations should consider all these factors, plus economic conditions, and the goals of the producer. Barber (1973) identified four methods for determination of phosphorus fertilizer rates based on the objectives of the producer:

- adding enough phosphorus to build the soil to the desired level for the most economic production for several years (e.g., a rate of 60 kg ha^{-1} for a corn crop on a soil with low phosphorus levels),
- adding enough phosphorus to give the maximum net return on the immediate crop, neglecting residual benefits (e.g., a rate of 30 kg ha^{-1} for a corn crop on a soil with low phosphorus levels),
- fertilizing for a period of 3 to 4 yr at a uniform annual rate that will give the highest net return for the period (e.g., an annual rate of 20 kg ha^{-1} for the period, for corn crop on a soil with low phosphorus levels),
- fertilizing for a period of 3 to 6 yr by calculating the total requirement for the period and then applying the phosphorus fertilizer at the most effective times to realize the greatest net return for the period (e.g., a rate of 45 kg ha^{-1} initially for a corn crop on a soil with low phosphorus levels, followed by perhaps one other application during the period).

Therefore, fertilizer recommendations for the same soil test levels and crop can vary depending on local conditions, economics, and the goals of the producer.

The philosophy in Alberta is to only recommend application of nutrients lacking in the soil (Alberta Soil Test Advisory Group 1998). Soil test recommendations are based on field research, which measured yield increase from several rates of fertilizer applied to soils with various soil test levels. To achieve optimum yields, large quantities of fertilizer need only be applied to soils with low test levels, moderate quantities of fertilizer to soils with medium test levels and low quantities to soils with high test levels. Recommendations are specific for the crop to be grown and the soil-climatic area. The recommendations are designed only for the next growing season, and this allows determination of economic returns based on current prices.

Interaction and Application Factors

Crop utilization of phosphorus is significantly enhanced when the appropriate balance of nutrients is available. Nitrogen, in particular, enhances phosphorus uptake by increasing top and root growth, altering the plant metabolism and increasing the solubility and availability of phosphorus (Tisdale et al. 1985). Crop uptake of phosphorus also increases with increasing soil temperature, moisture, aeration, and soil biological activity. Phosphorus availability to crops is most favorable in a pH range of 6.0 to 6.5 (Havlin et al. 1999). Availability is decreased at low pH levels by oxides of iron and aluminum, and at high pH by calcium and magnesium.

Fertilizer application methods also influence crop response. McKenzie et al. (1998) examined phosphorus response of irrigated alfalfa from 1994 through 1996. They found that for soils initially low in STP, annual applications of 40 kg ha^{-1} (about 22 mg kg^{-1}) of fertilizer phosphorus resulted in higher yields during a 3-yr period than a single preplant application of 120 kg ha^{-1} (about 67 mg kg^{-1}) of phosphorus.

Soon (1997) used combinations of fertilizer applications prior to forage seeding (preplant) and annual fertilizer treatments of a brome - red clover mix in a fine-textured Gray Luvisol near Beaverlodge. The effect of an annual application of 30 kg ha^{-1} of phosphorus (about 17 mg kg^{-1}) per year resulted in higher yields and higher phosphorus uptake than a single preplant application of 90 kg ha^{-1} (about 50 mg kg^{-1}) of phosphorus alone. They concluded that a single preplant application of 45 kg ha^{-1} (about 25 mg kg^{-1}) of phosphorus followed by an annual application of up to 30 kg ha^{-1}of phosphorus was the most efficient for crop herbage yield.

The mobility of phosphorus is relatively low in the soil, and plant roots take up nutrients primarily from within 2 mm of the root surface (Nye and Tinker 1977). Therefore, banding and seed placement, rather than broadcasting, have been successful methods for improving annual crop response to fertilizer (Malhi et al. 1993; Havlin et al. 1999). In Saskatchewan, Wagar et al. (1986) found the most effective treatment was where an initial broadcast application was used to elevate the STP to optimum levels, followed by small annual applications applied with the seed. For annual crops, regardless of placement methods, it is important to maintain optimum STP levels for best yields (Fixen and Halvorson 1992).

On forage crops, however, Soon (1997) and Simons et al. (1995) reported no beneficial effect of banding versus broadcast of phosphorus fertilizer on herbage yield. Banding at depth has been shown to cause serious damage to alfalfa crops (Leyshon 1982), thus, broadcast applications are commonly used to maintain phosphorus nutrition once forage crops have been established.

Residual Phosphorus Effects

Total phosphorus in surface soils of North America varies from 0.005 to 0.15% (Havlin et al. 1999). Although some prairie soils are high in total phosphorus, most prairie soils are low in plant-available phosphorus (Havlin et al. 1999). Introduction of phosphorus in commercial fertilizer or manure on an annual basis initiates the process of phosphorus accumulation in the soil. Since crops do not utilize all the fertilizer phosphorus or manure phosphorus in the year applied, residual amounts are left in the soil. Subsequent crops, again using only a portion of the annually applied phosphorus, use the fraction of the residual phosphorus that becomes available that crop year. Long-term annual application of fertilizer phosphorus has resulted in an accumulation of inorganic phosphorus (P_i) and labile phosphorus forms (McKenzie et al. 1992a, b). A decrease in organic phosphorus (P_o) forms was observed by Tran and N'dayegamiye (1995). Long-term annual manure applications maintained P_o levels, but increased total phosphorus (P_t) and labile phosphorus levels (Tran and N'dayegamiye 1995).

Agricultural soils must have a pool of residual phosphorus that is larger than the phosphorus uptake requirements for any single crop to ensure adequate crop nutrition. To ensure optimum yields, managers tend to apply phosphorus fertilizer at rates in excess of crop demand, causing soil phosphorus levels to increase from very low to medium and high during this century (Sibbesen and Sharpley 1997).

Economic analysis to compare optimum STP levels under long-term land tenure to STP levels under short-term land tenure have been presented by Fixen and Halvorson (1991, 1992) and Kastens et al. (2000). Economic advantage could be gained if optimum STP levels increased as the period of land tenure increases. For example, optimum STP levels for land tenure of 20 yr should be at least double the optimum STP level for 2 yr. Similarly, in areas where yield potential is high, long-term optimum STP levels should be higher than long-term optimum levels in areas where yield potential is low, such as more arid areas (Fixen and Halvorson 1992). For long-term crop planning, creating a sufficient pool of residual phosphorus in the soil was considered part of good economic management, and the benefit can increase if levels are higher in more productive areas.

Starter Phosphorus Fertilizer

In soils with high phosphorus levels, withholding phosphorus application altogether may not produce satisfactory crop response. Withers et al. (1994) found cereal yields began to decline after 3 yr of no phosphorus applications on high phosphorus soils. Use of a small amount of commercial fertilizer phosphorus as a starter on high STP soils has resulted in crop yield increases in several studies (Griffith 1992; Sibbesen and Sharpley 1997; Havlin et al. 1999; Roberts and Johnston 2001). Griffith (1992) proposed the following possible reasons for crop response to starter phosphorus applications that have been observed in soils with high phosphorus levels.

- Higher crop yields than were obtained in the original calibration studies.
- Increased use of minimum tillage.
- Increased use of equipment and practices that result in increased soil compaction.
- Earlier planting dates into cooler soils.
- Inadequate attention to proper soil pH levels for optimum nutrient efficiency.

Soil conditions appear to be an important factor. Tisdale et al. (1985) found that starter phosphorus fertilizer helped early crop growth under cool, wet soil conditions. Griffith (1992) showed forage and grain yields increased with starter phosphorus under highly acid soil conditions. Griffith (1992) also found that corn response to starter phosphorus in South Dakota was greater in crops following fallow than for recropping.

The use of starter phosphorus fertilizer can result in a buildup of soil phosphorus levels for several years. Figure 2 shows a trend of wheat yield increase with the use of starter phosphorus in a fallow - wheat - wheat rotation at Swift Current, Saskatchewan, and a corresponding increase in STP levels even at these low application rates (Roberts et al. 1999).

Relationship Between Plant-available Phosphorus and Water Quality Risk

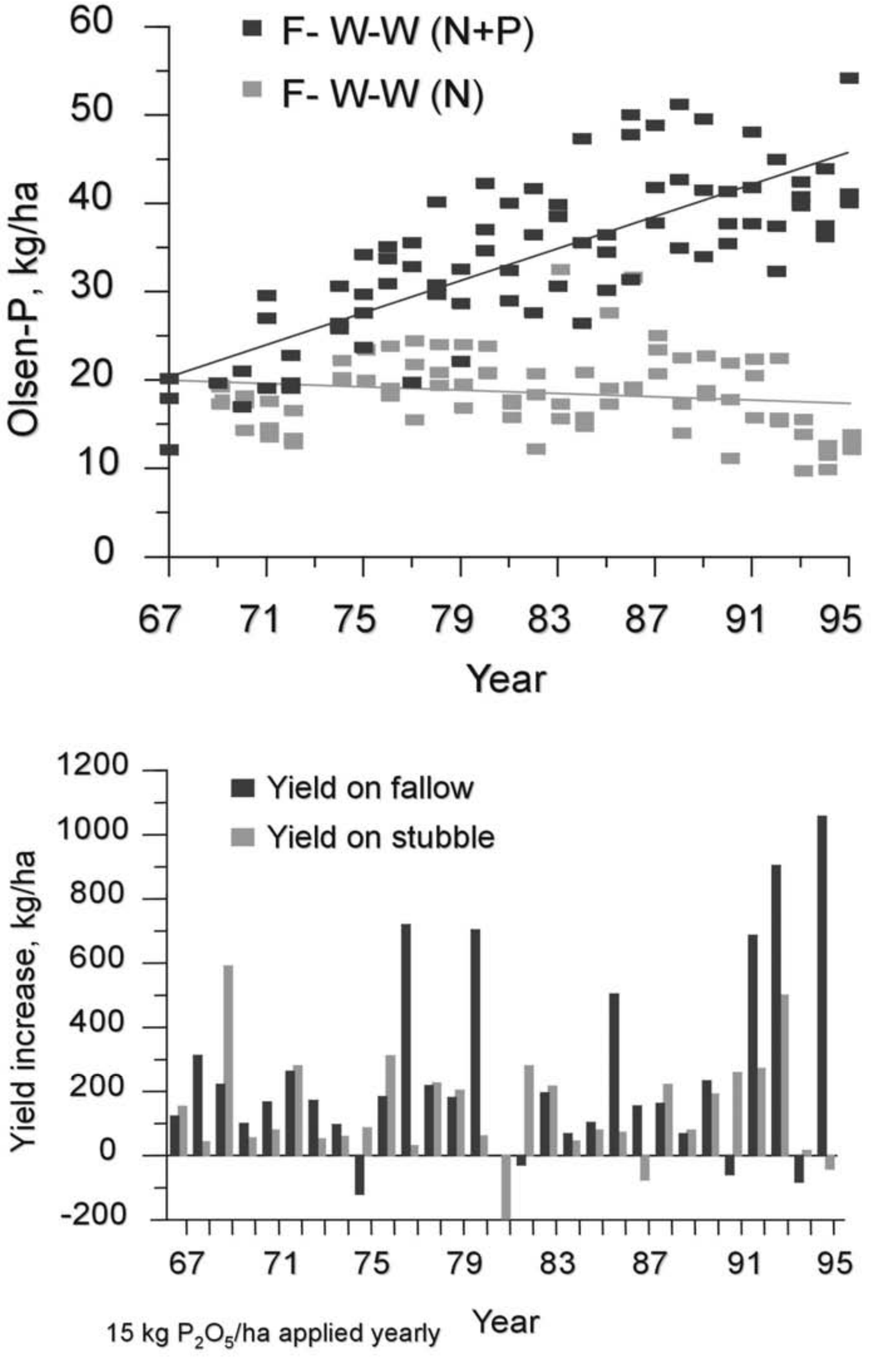
Optimum crop production requires additional input of soil phosphorus, and a small buildup of soil phosphorus is desirable. Since applications of starter fertilizer can even increase soil phosphorus levels with time, care must be taken to ensure that levels do not become high enough to be an unacceptable risk to water quality. Farm managers will be expected to take greater responsibility for maintaining soil phosphorus levels for good crop production without unacceptable risk to water quality. However, do farmers have applicable means for assessing risk on their farms?

Ekert et al. (2000) presented criteria that farmers can use to assess and quantify environmental risk. The criteria are based on using the production potential of the land most efficiently, but at the same time, keeping the impacts on soil, water, biota, and air within tolerable limits. These criteria include establishing scientifically-acceptable tolerability ranges for risk, development of convincing and feasible actions and goals, and are relatively simple, reproducible, and economically acceptable. The concept is holistic and points out that phosphorus should not be looked at in isolation of the other fertility factors.

The potential for soil phosphorus to impact water quality has been extensively reviewed by Howard et al. (2006). Methods to assess soil phosphorus risk, including the soil phosphorus index, the single limit approach, use of percent saturation, and nutrient management planning were all discussed and evaluated as potential tools for managing phosphorus to minimize the risk of degrading water quality. However, finding a practical means to measure soil phosphorus and relate its risk to water quality has yet to be agreed upon in the literature.

Because STP is widely used in crop management, a considerable knowledge base exists in understanding how the chemical extraction processes relate to phosphorus in different soils. Commercial labs are also set up to perform routine STP analysis at a relatively low cost. As we begin to address environmental issues, will STP be a suitable tool for identifying risk? If producers are to monitor their soils for environmental risk, it would be practical to have environmental soil phosphorus levels determined by STP methods, since producers would require only one set of soil samples and one type of analysis. Versions of the soil phosphorus index use STP as the measurement for soil phosphorus in assessing the vulnerability of a site to contribute phosphorus to the water system (Sharpley et al. 1999; Hilborn and Stone 2000).

While it may be practical and convenient to use STP as a test for water quality risk, care must be taken to ensure other factors affecting the potential for phosphorus transport in surface runoff are considered. First of all, phosphorus transport sensitivity requires a different approach to



15 kg P_2O_5/ha applied yearly

Fig. 2. Wheat response to starter phosphorus fertilizer with increasing soil test phosphorus (P) levels in a fallow-wheat-wheat rotation at Swift Current, Saskatchewan (Roberts et al. 1999).

sample collection than that required for soil fertility analysis. For most agricultural soils, samples collected to a depth of 20 to 40 mm would accurately define the effective depth for interaction between surface soil and runoff for rainfall intensities (Coale 1998). Second, some STP tests, such as the Mehlich-3 test, which uses strong acids, remove more phosphorus forms than just the readily available phosphorus fraction (Self-Davis et al. 1998). These tests would, therefore, tend to overestimate the dissolved phosphorus (P_d) fraction in runoff. Because of the wide variety of STP tests, care must be taken to ensure any regional environmental guidelines or standards provide correlation for several soil tests that may be used, or have been used, in the region. The third consideration is that environmental risk is not strictly related to dissolved phosphorus. While dissolved phosphorus is an important water quality parameter, there is a considerable amount of particulate phosphorus in runoff that would be undetected (Daniel et al. 1998). This fraction can potentially become available for aquatic plant growth.

Sharpley et al. (1996) suggested that for an environmental test, distilled water or a dilute salt solution (e.g., 0.01 M $CaCl_2$) would be better suited to assess the P_d fraction. They stated that such methods would need further evaluation before they could be recommended as a standard procedure.

DETERMINATION OF AGRONOMIC THRESHOLDS FOR SOIL PHOSPHORUS

Agronomic thresholds are determined from yield response curves. The curves illustrate the non-linear relationship between crop yield and STP, and are determined by regression analysis. A common approach to analyzing the data is to use relative yield. Yield response curves from these data typically follow a hyperbolic equation of the form shown in Equation 3.

$$RY = P / (b_o + b_1 \times P) \qquad (3)$$

Where:
RY = relative yield = (crop yield in control / maximum crop yield) × 100
P = soil test phosphorus
b_o and b_1 are constants

A major consideration in determining agronomic thresholds from these relationships is the choice of where on the curve to set the threshold. This is usually some percentage of the maximum yield. Sibbesen and Sharpley (1997) reviewed literature from Canada, the United States, and Europe and identified a range of 90 to 100% of maximum yield has been used to determine agronomic thresholds (Table 8). Fixen and Halvorson (1991, 1992) reported that attaining a relative yield of 95% was essentially the same as maximum yield; however, they argued that the difference of 5% can be of substantial economic importance for long-term yield planning.

The relative yield approach to interpreting crop response curves has been criticized for statistical reasons (Nelson and Anderson 1977), and actual yield increases may be preferred for statistical accuracy. However, Cerrato and Blackmer (1990) analyzed the same corn-nitrogen response data using actual yield increases and five different statistical models. Each model was highly correlated to the data ($r^2 > 0.90$), but all resulted in greatly different optimum nitrogen levels. They showed that the choice of statistical model used was a major factor in predicting optimum nutrient response. Mallarino and Blackmer (1992) showed the relative yield approach was no better or worse than using the actual increases. In their study, the greatest influence on the variations in determining the critical concentration for phosphorus was the choice of regression method used to fit curves to the data. These studies raise questions about how crop yield response data should be interpreted for determining agronomic thresholds. No standard criteria have been set.

Annual Crops

Two studies summarized considerable information about agronomic thresholds from outside of Alberta. Sharpley and Tunney (2000) reported average agronomic thresholds for non-vegetable crops for eight American states (Table 9). The agronomic thresholds ranged from 7 to 65 mg kg^{-1} based on equivalent Norwest modified Kelowna values. Sibbesen and Sharpley (1997) identified agronomic thresholds below 30 mg kg^{-1} for Canada and the United States (Table 8). They found research from Europe reported higher thresholds, likely because of higher yield potential in Europe. Thresholds varied greatly in Europe, even within the same country.

Table 8. Agronomic thresholds for soil test phosphorus (P) calibrated in field experiments in Europe, the United States, and Canada (Sibbesen and Sharpley 1997).

Soil test P method	Critical level (mg kg^{-1})	Calibration basis	Crop	Number of trials	Duration of trials (years)	Region, soils	Reference
DL + CAL	15 26 37	90% rel. yield 95% rel. yield 97.5% rel. yield	2/3 cereals + 1/3 sugar beets, potato, maize	150	1-3	Germany, various	Koster and Schachtschabel (1983)
CAL	74[z] 83 118[z]	Economic P application, Mitcherlich	72% cereals 28% sugar beets, potato, maize	82	3-13	Germany, loess + loamy soils	Munk (1985)
CAL DL Olsen H_2O	30[y] 37[y] 13[y] 5	No yield response to P application above level	Winter wheat + winter barley + sugar beets	105	1	Germany, loess	Baumgartel (1989)
H_2O	18[x]	As Munk (1985)		55	6-10	Germany	Munk and Rex (1990)
H_2O	10[x]	Max. yield	3/4 cereals +1/4 sugar beets	6	15	Germany, loess	Jungk et al. (1993)
DL	50-60	95% rel. yield	Rotation[w]	1	42	Germany, phaeozem	Stumpe et al. (1994)
H_2O	9 14 20	90% rel. yield 95% rel. yield 97.5% rel. yield	Potato	37	1	Netherlands	Van der Paauw (1977)
Olsen	25 20 33 20	Max. yield minus 1 SE= 97-98% rel. yield, Mitcherlich	Potato Sugar beets Spring barley Winter wheat	1	9	England, sandy clay loam	Johnston et al. (1986)
Olsen	21-35	Yield reduction below level	Cereals + root crops	7	20	Denmark, various	Sibbesen and Sharpley (1997)
Olsen	10	As Baumgartel (1989)	Winter wheat	4	6	Canada, chernozems	Read et al. (1973)
Mehlich-1	14	95% rel. yield	Maize + soybean	41	2-3	Alabama, low CEC soils	Whitney et al. (1985)
Bray-1	15 22	As Baumgartel (1989)	Maize Wheat	4	12	Nebraska, mollisols	McCallister et al. (1987)
Mehlich-3 Bray-1	19[x] 18[x]	Cate and Nelson (1971)	Maize	67	1	Pennsylvania, various	Beegle and Oravec (1990)
Mehlich-1 Mehlich-3	16 27	95% rel. yield	Maize + soybean	1	33	North Carolina, Fie sandy loam	McCollum (1991)
Bray-1 Mehlich-3 Olsen	11 11 5	95% rel. yield	Maize	25	1	Iowa, various	Mallarino and Blackmer (1992)
Bray-1	16-20	Economic P application	Maize + soybean	1	15	Iowa, typic haplaquoll	Webb et al. (1992)

[z] Critical levels refer to yield levels of 37 to 55, 55 to 70 and 70 to 105 grain equivalents ha^{-1}, where one grain equivalent = 0.1 t grain, 0.4 t sugar beets or 0.5 t potatoes.

[y] Calculated from relations in Table 7.2, Sibbesen and Sharpley (1997).

[x] Assuming a soil density of 1.1 Mg m^{-3}

[w] Lucerne, Lucerne, potato, winter rye, sugar beets, spring barley.

Table 9. Agronomic threshold soil test phosphorus (P) values (Sharpley and Tunney 2000) and equivalent values using the Norwest modified Kelowna test.

State	Agronomic threshold value for soil test P (mg kg^{-1})	Soil test P method	Threshold values based on Norwest modified Kelowna method (mg kg^{-1})
Arkansas	50	Mehlich-3	65
Delaware	25	Mehlich-1	N/A
Idaho	12	Olsen	7
Ohio	40	Bray-1	40
Oklahoma	30	Mehlich-3	44
Michigan	40	Bray-1	40
Texas	44	Texas A & M	N/A
Wisconsin	20	Bray-1	18

Malhi et al. (1993) compared yield responses for phosphorus applied at 15 kg ha^{-1} to barley in central Alberta. They found that the number of sites with a significant yield response decreased with increasing STP levels from 68% responding at STP levels below 5.5 mg kg^{-1} to only 22% responding at STP levels greater than 16.5 mg kg^{-1}. Read et al. (1973) reported that wheat response to added phosphorus reached a plateau at 20 to 40 kg ha^{-1} (10 to 20 mg kg^{-1}) on four Chernozemic soils in Manitoba and Saskatchewan.

McKenzie et al. (2001) studied pea response to fertilizer phosphorus in several Alberta soils. They found where STP levels were below 30 kg ha^{-1} (15 mg kg^{-1}), 16 of 31 trials had a significant seed yield increase to added phosphorus, whereas in soils with STP levels greater than 30 kg ha^{-1} (15 mg kg^{-1}), only one of 17 trials showed an increase in yield.

Roberts and Johnston (2001) stated that there is no agronomic need for to STP levels to be above 100 kg ha^{-1} (55 mg kg^{-1}).

Crop phosphorus removal rates were used as another indicator of agronomic thresholds. Pierzynski and Logan (1993) reported mean phosphorus concentrations, yield, and phosphorus removal rates for several commercial crops grown in the United States. Crops relevant to Alberta are presented in Table 10. Crop removal rate data in Table 10 suggest that annual crops relevant to Alberta remove phosphorus at an average rate of 6.1 mg kg^{-1} for grains, 3.7 mg kg^{-1} for grain straw, 11 mg kg^{-1} for potato, sugar beets and sunflower, and 16 mg kg^{-1} for forages.

Mallarino and Blackmer (1992) investigated several different statistical models to determine critical STP concentrations (similar to agronomic thresholds but defined in terms of probability of obtaining economic benefits, rather than yield increases) for phosphorus in corn. Their results showed a range of critical concentrations (agronomic thresholds) from 3 to 30 mg kg^{-1} (Norwest modified Kelowna equivalent), depending on the statistical analysis and data handling methods used.

Table 10. Yield and phosphorus (P) removal for selected United States crops that are relevant to Alberta (adapted from Pierzynski and Logan 1993).

Crop	P removal (kg ha^{-1})	P removal [z] (mg kg^{-1})	Reference [y]
Annual crops (grain)			
Barley grain (*Hordeum vulgare L.*)	7.4	4.1	2
Corn grain (*Zea mays L.*)	25.8	14.3	2
Flax grain (*Linum usitatissimum L.*)	4.9	2.7	1
Oat grain (*Avena sativa L.*)	9.7	5.4	2
Rye grain (*Secale cereale L.*)	4.9	2.7	2
Sorghum grain (*Sorghum vulgare Pers.*)	12.3	6.8	2
Wheat grain (*Triticum aestivum L.*)	12.3	6.8	2
Annual crops (straw)			
Barley straw (*Hordeum vulgare L.*)	2.5	1.4	2
Corn stover (*Zea mays L.*)	17.9	9.9	2
Flax straw (*Linum usitatissimum*)	2.5	1.4	1
Oat straw (*Avena sativa L.*)	7.4	4.1	2
Rye straw (*Secale cereale L.*)	3.9	2.2	2
Sorghum stover (*Sorghum vulgare Pers.*)	9.7	5.4	2
Wheat straw (*Triticum aestivum L.*)	2.5	1.4	2
Annual crops (other)			
Sugar beet roots (*Beta vulgaris saccharifera L.*)	24.6	13.7	1
Potato (*Solanum tuberosum L.*)	16.8	9.3	1
Sugar beet tops (*Beta vulgaris saccharifera L.*)	16.8	9.3	1
Sunflower (*Helianthus annuus L.*)	19.6	10.9	3
Forage crops			
Alfalfa (*Medicago sativa L.*)	34.7	19.3	1
Fescue, tall (*Festuca arundinacea Schreb.*)	39.2	21.8	1
Red clover (*Trifolium pratense L.*)	22.4	12.4	1
Sweet clover (*Melilotus alba Desr.*)	34.7	19.3	1
Timothy (*Phleum pratense L.*)	14.6	8.1	1

[z] Calculated from P removal rates (kg ha^{-1}) using assumptions in section 1.6.

[y] 1 = McVickar and Walker 1978; 2 = Eakin 1976; 3 = Potash and Phosphate Institute 1985

Note: All values are expressed on a fresh-weight basis.

Forage Crops

Forage crop response to STP levels is often complex, since weather can result in major fluctuations in forage herbage yields. It has been suggested that perhaps no accurate estimation of nutrient requirements can be made on a year-to-year basis (Bittman et al. 1997). It has been shown by Malhi et al. (1992a, b) that growing alfalfa or bromegrass with no application of phosphorus can deplete STP levels and decrease yields. Bromegrass yield declined with phosphorus application on a soil with STP levels of 33 mg kg^{-1} (Malhi et al. 1992b).

Loeppky et al. (1999) correlated fertilizer response of smooth bromegrass, alfalfa, crested wheatgrass, and intermediate wheatgrass to available soil nitrogen and phosphorus. Regression equations developed from responses averaged for the period of 1989 to 1990 suggested that the rate of yield increase in response to fertilizer phosphorus decreased as STP increased beyond 16 mg kg^{-1}. The nature of the regression equations made extrapolation beyond the limits of the field data (0 to 16 mg kg^{-1} P) difficult to interpret; therefore, yield responses to phosphorus beyond 20 mg kg^{-1} could not be determined.

Malhi et al. (1992a) compared alfalfa yields following a one-time preplant application of fertilizer phosphorus at rates up to 180 kg ha^{-1} (100 mg kg^{-1}) of phosphorus at two sites in Alberta. They found no yield advantage at phosphorus application rates more than 120 kg ha^{-1} (67 mg kg^{-1}). They also found yield response was greater at the Lacombe site than at the Botha site, where the initial STP levels were higher (18 and 27 mg kg^{-1}, respectively).

In a similar study to Malhi et al. (1992a), Malhi et al (1992b) found a bromegrass yield advantage to preplant fertilizer phosphorus rates above 60 kg ha^{-1} (33 mg kg^{-1}) in only 1 out of 5 yr. In both studies, the residual effect of initial fertilizer phosphorus applications influenced yields for more than 5 yr. Nuttall et al. (1980) found significant phosphorus responses to a bromegrass-alfalfa mixture on a soil at Melfort, Saskatchewan, where the STP level ranged from 3.7 to 28.6 mg kg^{-1}.

McCartney et al. (1998) determined nutrient uptake from long-term forage plots on Luvisolic soils in northeastern Saskatchewan. Table 11 presents average nutrient uptake levels for bromegrass-alfalfa, Russian wild rye, and a pasture with a grass-legume mix. The study found significant interactions between nitrogen, phosphorus, and sulphur, with the availability of nitrogen being the limiting nutrition factor during the 11-yr period. Seasonal climatic variability resulted in annual phosphorus uptake ranging from 3.8 to 18.3 kg ha^{-1} (2 to 10 mg kg^{-1}) during this period.

Table 11. Forage crop average annual phosphorus (P) uptake (kg ha^{-1}) from 1978 to 1989 (McCartney et al. 1998).

Fertilizer treatment (kg ha^{-1})	Brome-alfalfa	Grass-legume	Russian wild rye
No fertilizer	3.8	1.9	4.9
N @ 45, P @ 20 (11 mg kg^{-1})	9.1	5.5	9.3
N @ 90, P @ 20 (11 mg kg^{-1})	11.5	7.0	10.8

McCartney et al. (1998) reported that STP accumulated in the soil as a result of annual applications of fertilizer applied at rates of 90, 20, and 23 kg ha^{-1} for nitrogen, phosphorus, and sulphur, respectively. Soil test phosphorus levels increased from 13.0 to 30.5 kg ha^{-1} (7 to 17 mg kg^{-1}) in the fertilized plots, as compared to increases from 8.3 to 9.6 kg ha^{-1} (4.6 to 5.3 mg kg^{-1}) in the non-fertilized plots. The long-term applications resulted in a trend toward increasing STP levels during the 11-yr period, but there was no trend toward a corresponding increase in phosphorus uptake. They observed that the annual herbage yield response to nitrogen and phosphorus fertilizers was weakly related to soil tests. They concluded, however, that during 3-yr periods, nutrient uptake combined with soil nutrient tests gave an adequate estimate of crop nutrient removal and the amount of fertilizer required to maintain soil nutrient levels.

For white clover, Singh and Sale (2000) found that coarse root density and the root water conductance increased with increasing rates of fertilizer phosphorus up to levels of 150 mg kg^{-1}. This resulted in an increased ability for the stands to withstand drought. The study was a pot experiment conducted for a 56-d period, and neither yield nor the long-term effects of the added phosphorus were reported.

The literature shows that forage crops require additional phosphorus to maintain yields; however, agronomic thresholds for phosphorus are not clearly identified. Forage crops in some studies have shown decreased response to added phosphorus when STP levels are higher than 20 mg kg^{-1}, and nutrient uptake data show that common forage crops remove less than 20 mg kg^{-1} annually. Alfalfa response, however, has been observed even when enough fertilizer phosphorus has been added to bring STP levels to an equivalent of greater than 60 mg kg^{-1}.

Determination of Agronomic Thresholds from Alberta Data

The data in Fig. 3 represent a wide range of Alberta soils for wheat, barley, canola (McKenzie et al. 1995), and pea (McKenzie et al. 2001). The data indicate that crop response to phosphorus occurs primarily in the range of 20 to 60 mg kg^{-1} STP. For STP levels greater than 60 mg kg^{-1}, there were no canola responses, and few pea, barley, and wheat responses.

The data show that relative yield (RY) does not increase more than 2% once the soil phosphorus levels exceed 55 mg kg^{-1}, and the RY values for wheat, barley, and canola reach 100% (no yield response from added phosphorus) in a range of STP from 20 to 60 mg kg^{-1}. There are only two cases, one in the barley data and one in the wheat data, where RY was below 100% (still a potential for a phosphorus response) when the soil test phosphorus was more than 70 mg kg^{-1}.

To determine an agronomic threshold from the data, a point on the slope of the curve was chosen where the relative yield increase was 1.0% for a corresponding increase of 10 mg kg^{-1} (about 18 kg ha^{-1} phosphorus) in soil phosphorus. This point was referred to as the zero return point, because the increase in yield was insignificant to the cost of raising the soil phosphorus level by 10 mg kg^{-1}. The zero return point corresponds to 91, 92, 93, and 96% of maximum yield for canola, barley, wheat, and pea, respectively.

The data in Table 12 show agronomic thresholds for canola, barley, wheat, and pea can be established using this approach, at 60 mg kg^{-1} for canola and 50 mg kg^{-1} for barley, wheat, and

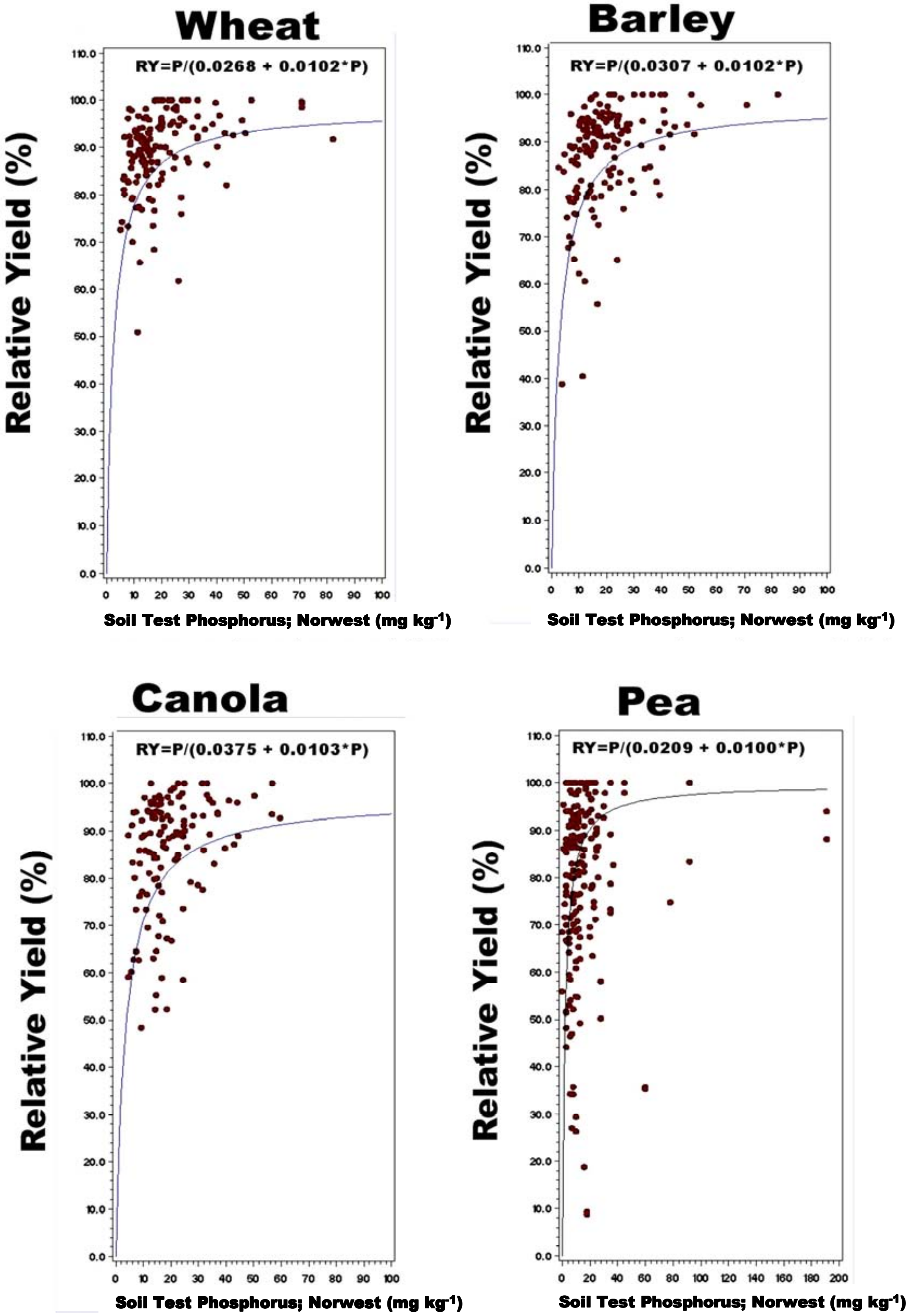


Fig. 3. Correlation of relative yield of wheat, barley, canola, and pea with soil test phosphorus for all soil zones in Alberta (modified from McKenzie et al. 1995).

Table 12. Crop response (% increase) to added phosphorus (P) and zero return point for all sites in Alberta (data from McKenzie et al. 1995 and McKenzie et al. 2001).

Soil test P (mg kg^{-1})	Canola	Barley	Wheat	Pea
10	71.1	75.3	77.6	82.7
20	82.0	85.1	86.6	90.5
30	86.4	88.9	90.1	93.5
40	88.8	91.0	92.0	95.0
50	90.3	92.3	93.1	96.0
60	91.4	93.2	93.9	96.6
70	92.1	93.8	94.5	97.1
80	92.7	94.3	94.9	97.4
90	93.1	94.7	95.3	97.7
100	93.5	95.0	95.5	98.0
zero return point = 1% (mg kg^{-1})	60	50	50	50
zero return point = 2% (mg kg^{-1})	40	40	30	30

pea. For comparison, if the zero return point was set at a 2% increase in yield for a corresponding 10 mg kg^{-1} increase in STP, the agronomic thresholds would be reduced to 40 mg kg^{-1} for canola and barley, and 30 mg kg^{-1} for wheat and pea.

Phosphorus response curves for Luvisolic, Dark Gray, Black, Thin Black, Dark Brown, and Brown soils were analyzed separately by McKenzie et al. (1995). Relative yield values from response curves for each crop and soil are presented in Appendix 1. Analysis of the data using the zero return point approach resulted in a wide range of STP values. This was attributed to the relatively small datasets for some of the soils (e.g., Brown soils) and the zero return point approach lost meaning as the slopes of the curves were much steeper or flatter than those for the grouped data in Table 12.

Whalen and Chang (2001) studied manure application to barley plots for a 16-yr period in Lethbridge, Alberta. Their conclusion that annual applications of 30 and 60 Mg ha^{-1} of manure (67 and 134 kg ha^{-1} phosphorus, equivalent to 37 and 75 mg kg^{-1}) provided three times the available phosphorus and ultimately, assuming all phosphorus in the manure was used by the crop, five to six times the amount of phosphorus recommended for barley. These rates are lower than the amounts derived from the interpretation of the data from McKenzie et al (1995).

Some vegetable crops, particularly potato, have higher thresholds. Pierzynski and Logan (1993) reported phosphorus agronomic thresholds in the United States from Kelling et al. (1991) ranging from 11 to 20, 6 to 13, and 81 to 110 mg kg^{-1} (Bray-1) for corn, soybean, and potato, respectively, in Wisconsin. In North Carolina, McCollum (1991) noted that agronomic thresholds for potato were double that for corn. Warnke et al. (1987) recommended available phosphorus levels of 112 to 168 kg ha^{-1} (62 to 93 mg kg^{-1}) as being desirable for vegetable crops in Michigan.

For Alberta, however, McKenzie et al. (2000, 2002) reported potato yields in southern Alberta soils did not respond to high levels of phosphorus fertilizer. Soil test phosphorus levels in the soils at seven study sites ranged from 12 to 30 mg kg^{-1}. Typical phosphorus application rates by farmers are from 60 to 75 kg ha^{-1} phosphorus (33 to 42 mg kg^{-1}). In field scale replicated experiments, there was no increase in yield or improvement in tuber quality beyond 25 kg ha^{-1} phosphorus (14 mg kg^{-1}) fertilizer applied. On calcareous soils (above 8% $CaCO_3$ in the 0.0 to 0.30 m layer), potatoes could respond to fertilizer phosphorus at soil test levels as high as 70 mg kg^{-1} (R.C. McKenzie, personal communication).

The literature shows that agronomic thresholds vary from crop to crop, and thresholds for a crop type are not clearly defined. Use of crop-specific agronomic thresholds for planning purposes is confounded by crop rotations. Based on the Alberta data, there is no evidence to indicate there is any practical yield advantage to STP levels greater than 60 mg kg^{-1} for most crops.

IMPLICATIONS FOR MANAGEMENT OF ORGANIC PHOSPHORUS SOURCES

Manure as a Crop Nutrient Source

A major difference between animal manure and commercial fertilizer is that some of the nutrients in manure are in organic form and must be mineralized before they are available to the plant. Therefore, manure acts as a slowly available nutrient source. While manure is an inexpensive source of nutrients, its nutrient content is variable, and nutrient availability depends on the manure characteristics and their relationship with the soil. Manure application guidelines strongly recommend regular manure sampling and analysis for nutrient content.

Commercial fertilizer is designed in physical form and nutrient content for the best placement and utilization by crops, such as banding or seed placement. Use of manure reduces placement options, since banding and placement with the seed are impractical for raw manure. The nutrient balance of manure is also not matched to crop requirements. Low nitrogen-to-phosphorus ratios can result in a need for fertilizer nitrogen when manure is applied at rates to match crop phosphorus requirements, or in soil phosphorus loading with time when manure is applied at rates to meet crop nitrogen requirements. Manure has relatively low concentrations of nutrients compared to commercial fertilizers, resulting in the need to handle large volumes of water and organic carbon material with little or no nutrient value. Thus, producers using manure instead of commercial fertilizer need different equipment, must move higher volumes per unit weight of nutrient, and must consider issues such as odour. Good crop management requires additional sampling and analysis of manure, usually at an extra cost.

Manure, however, has benefits beyond being a nutrient source. The addition of organic carbon to soil can improve physical and chemical characteristics. Robertson and McGill (1989) reported that long-term annual application of 9 Mg ha^{-1} to a Luvisolic soil at the University of Alberta’s long-term research plots at Breton, Alberta, resulted in one of the highest yielding treatments and did not change the pH. Izaurralde et al. (2001) determined that for the 51-yr treatment history at the Breton plots, manure additions to a wheat-fallow system resulted in a net increase in soil organic carbon, whereas the control and fertilizer treatments resulted in a net loss. Manure treatments also resulted in the highest above-ground carbon productivity.

Impact of Manure on Forms and Fractions of Phosphorus

For nutrient management, it is important to understand not only the amount of phosphorus in manure but also the forms of phosphorus in the manure and how they influence the phosphorus forms in the soil once manure has been added. Phosphorus content of manure is variable between the species of animal, within a given species, and within a management practice for a given species. Similarly, phosphorus forms vary from one species of manure to another, as illustrated in Table 13.

DeLuca and DeLuca (1997), citing values from the literature, reported that the total phosphorus content of beef feedlot manure ranged from 0.1 to 0.8% by weight, averaging 0.4%. Sharpley and Moyer (2000) stated that phosphorus concentrations varied as a result of diet, manure collection, storage, and treatment. In citing literature, they reported coefficients of variation ranging from 30 to 100%.

Table 13. Forms of phosphorus (P), inorganic plus organic, as a percentage of total P in various manure and compost samples (Sharpley and Moyer 2000).

	Percentage of total P				
	Dairy		Poultry		Hog
P Form	Manure	Compost	Manure	Compost	slurry
Water soluble	63	16	34	22	23
$NaHCO_3$ (labile)	11	37	29	39	15
NaOH (moderately labile)	13	11	3	11	51
Acid (slowly available)	1	33	32	27	10

Manure application has resulted in increased levels of moderately labile phosphorus and total phosphorus in the soil after a single application (Qian and Schoenau 2000a) and after long-term applications (Campbell et al. 1986; Dormaar and Chang 1995; Tran and N'dayegamiye 1995). Campbell et al. (1986) and Qian and Schoenau (2000a) reported that long-term manure application gradually improves the phosphorus-supplying capacity of soils. Dormaar and Chang (1995) reported that relatively high levels of phosphorus, 15 to 46%, were in soluble or labile forms following 20 yr of manure application.

On previously non-manured soils, however, Qian and Schoenau (2000a) found that a single hog manure addition had little effect on phosphorus availability in the soil. Hog manure is high in labile forms of phosphorus (Sharpley and Moyer 2000; Qian and Schoenau 2000a); however, despite the high proportion of labile phosphorus forms, application of the liquid hog manure did not appreciably increase the labile phosphorus forms in the soil (Table 14). This suggests that the most soluble forms of phosphorus in the soil are not affected by manure during the short term, but long-term, repeated applications result in increased levels of these forms. MnKeni and MacKenzie (1985) explained the increases in more available forms of phosphorus in long-term manure studies as the result of the cumulative effect of repeated manure additions saturating phosphorus fixation sites in the soil; therefore, reducing phosphorus adsorption.

Qian and Schoenau (2000a) reported that phosphorus from manure had changed rapidly into more stable forms within 2 wk. They suggested that environmental risk of phosphorus from manured lands degrading water quality is probably lower in the early years of manure application and increased with repeated applications, where manure was applied in excess of crop removal rates for several years.

When compared to fertilizer applications, Qian and Schoenau (2000a) reported that even high additions of urea had little influence on the phosphorus forms in the soil, suggesting the addition of nitrogen alone was not impacting phosphorus transformations. Campbell et al. (1986) reported variable effects of phosphorus in commercial fertilizer and manure on different forms of soil phosphorus, depending on rates of application and the initial level and distribution of phosphorus in the soil profile. McKenzie et al. (1992a, b) reported that for a Luvisolic soil and a Chernozemic soil, addition of phosphorus fertilizer increased P_i forms; whereas, addition of nitrogen fertilizer indirectly led to an increase of P_o forms. Cropping with no fertilizer or manure inputs resulted in conversion of more stable phosphorus forms to more labile forms and a continuous drain on all phosphorus forms (McKenzie et al. 1992a, b).

Table 14. Forms of phosphorus (P) two weeks and sixteen weeks following a single application of manure and urea, in a Black Chernozem (Qian and Schoenau 2000a).

Phosphorus form following application		Soil P content (mg kg^{-1})					
		Two weeks			Sixteen weeks		
		No nitrogen	100 mg kg^{-1} nitrogen	400 mg kg^{-1} nitrogen	No nitrogen	100 mg kg^{-1} nitrogen	400 mg kg^{-1} nitrogen
Manure							
Resin (labile P_i)		37	36	36	36	35	36
$NaHCO_3$ (labile)	P_i	20	25	24	21	25	25
	P_o	6.0	1.7	2.4	7.6	5.1	6.2
NaOH (mod. labile)	P_i	39	39	36	32	32	33
	P_o	120	139	133	103	116	120
Dil. HCl (slowly available)		217	226	229	196	190	193
Conc. HCl (least avail.)	P_i	50	46	44	42	46	46
	P_o	132	135	141	165	171	173
Modified Kelowna					16.7	17.1	16.9
Total P		710	723	728	708	723	728
Urea							
Resin		37	36	36	36	35	34
$NaHCO_3$ (labile)	P_i	20	21	22	21	24	23
	P_o	6.0	4.1	4.3	7.6	6.1	7.0
NaOH (mod. labile)	P_i	39	39	42	32	33	32
	P_o	120	123	122	103	103	113
Dil. HCl (slowly available)		217	210	200	196	192	185
Conc. HCl (least avail.)	P_i	50	45	47	42	46	44
	P_o	132	131	127	165	167	167
Modified Kelowna					16.7	16.6	15.9
Total P		710	719	709	708	717	716

Qian and Schoenau (2000b) reported that when hog manure had been applied to two Saskatchewan soils, the phosphorus supply to a canola crop was constant or increased through the growing season. Sharpley (1996) found that release of phosphorus from manured soils initially dropped rapidly, followed by a more gradual release of phosphorus with time. The rate of phosphorus release depended upon soil type, and more specifically on the phosphorus sorption saturation of the soil. Their results suggest that under similar STP levels and cropping, soil type would control the rate of phosphorus availability to crop from manure phosphorus sources.

Beauchemin and Simard (2000) compared an area where phosphorus additions were primarily from long-term fertilizer sources to an area where phosphorus sources were primarily from long-term manure application. They reported higher concentrations of P_t, P_o, water-soluble phosphorus, and STP in the B and C horizons in the area dominated by manure application. In the A horizon, STP levels were essentially the same, but P_t and P_o levels were higher in the manured areas. Their study indicated that in medium and coarse textured soils of eastern Canada, long-term manure applications have contributed to downward movement of a wide variety of phosphorus forms.

Application of composted beef manure has resulted in higher STP levels and increased the long-term levels of bioavailable phosphorus compared to that of manure (Eghball and Power 1999; Schwartz and Dao 2000). Schwartz and Dao (2000) calculated that 47% and 71% of manure and compost phosphorus, respectively, become extractable and/or available during a 25-mo cropping period.

Although regular manure application results in a different proportion of the inorganic and organic soil phosphorus forms, for soil testing and crop fertility recommendations, STP levels are interpreted the same way regardless of whether they are from fertilized or manured soils (J. Ashworth, personal communication).

Other Organic Phosphorus Sources

Municipal biosolids, in the absence of heavy metal or other contaminant concerns, are generally applied to land at rates in balance with the nitrogen requirements of the agricultural crop (Zebarth et al. 2000). Cogger et al. (1999) reported higher nitrogen recovery in the second year of application than in the first, when biosolids were applied to forage crops. The fertilizer equivalency (i.e., the ratio of the apparent recovery of biosolid nitrogen in comparison to the apparent recovery of fertilizer nitrogen) averaged 32% and 50% for the first and second years of application, respectively. Higher nitrogen recovery in the second year was also observed in dryland wheat (Cogger et al. 1998). In both cases, delayed mineralization of nitrogen was a factor.

Zebarth et al. (2000) found application of municipal biosolids to forage grass resulted in an increased cumulative uptake of micronutrients, especially copper (Cu). Forage copper values in the first year reached levels of possible concern for some animal species.

Food processing effluent nutrient distribution must be known before it is used in long-term application to land. Barl and McKenzie (1995) reported that processing effluent from a potato processing plant had potassium levels that ranged from 466 to 707 mg kg^{-1}, values that are about 10 times the level of phosphorus and six times the level of nitrogen in the effluent. If this effluent was applied at the conventional nitrogen or phosphorus rates, it would quickly accumulate potassium levels in soils. Excessive potassium levels are capable of having a negative impact on crops (R.H. McKenzie, personal communication) and are capable of leaching to groundwater in sandy soil (Havlin et al. 1999).

Because nutrient levels in organic phosphorus sources tend not to be matched to crop uptake, and nutrient movement into the water system can degrade water quality, care must be taken to understand the complete nutrient status of the soil and the organic phosphorus source. Regular testing and nutrient planning should be part of any long-term management of organic phosphorus sources.

CONCLUSIONS

Basis for Fertilizer Phosphorus Recommendations

Soil test phosphorus results ultimately form the basis for crop response and fertilizer recommendations. The most sophisticated soil fertility interpretations result from a large database of field research on specific crop responses and STP values for a variety of soil and climatic conditions. There are also several philosophies upon which fertilizer recommendations for phosphorus can be based. In Alberta, the philosophy is to only recommend application of nutrients lacking in the soil, as opposed to intentionally building up a nutrient reserve.

There is no standard method of analysis for STP. While the modified Kelowna method is the preferred technique in the Canadian prairies, there are two versions in commercial use. It may be desirable to specify one version of the modified Kelowna as the standard test for the agronomic threshold. Other soil phosphorus test methods can be used if the results can be compared with confidence to the standard test.

The resin membrane probe is used in situ and measures a phosphorus supply rate or flux during the growing season. The probe simulates plant uptake of phosphorus better than the conventional soil phosphorus tests. This probe is now in commercial use as a tool for soil phosphorus availability assessment and crop phosphorus requirements. It has not been used extensively with manured soils; however, it may be the future method of choice for soil phosphorus testing.

Because phosphorus is a key element in crop production and environmental sustainability, the industry must maintain a careful balance between optimum production and environmental sustainability. Monitoring soil phosphorus levels will be a key tool for assessing environmental risk. Soil phosphorus tests are a practical, proven method to assess soil phosphorus levels; however, they were designed to measure crop nutrient status and fertilizer requirement, not risk to water quality. The processes governing crop uptake of phosphorus from the soil are different from those governing phosphorus enrichment of water; therefore, care must be taken when using soil test phosphorus data for assessing environmental risk.

Agronomic Thresholds for Phosphorus in Alberta

A moderate buildup of soil phosphorus levels is part of good crop management. There are economic and production advantages to building up STP levels, and the optimum levels increase with increased yield potential and land tenure. Therefore, long-term optimum crop production will improve with higher STP levels. Risk to water quality also increases with increasing STP levels. Managers must maintain a balance of soil phosphorus that is high enough to provide optimum crop production, but low enough to maintain environmental quality. Determining the levels of soil phosphorus that define the balance is a major challenge.

The Alberta data show that an agronomic threshold of 60 mg kg^{-1} for all soils and major crops would provide the most flexibility for crop production in Alberta. Exceptions, such as potato in calcareous soils in southern Alberta where the agronomic threshold is about 70 mg kg^{-1}, should be addressed on a crop and site-specific basis.

Evidence of agronomic thresholds and crop removal rates in the literature suggest that the thresholds for annual and forage crops could be lower. Agronomic limits are based on yield response curves. There is no standard way of determining an agronomic threshold of soil phosphorus for a crop. Crop yield response to phosphorus is specific to crop type and to local conditions such as climate and soil type. Therefore, agronomic thresholds can be expected to have some variability.

The role of excess soil phosphorus in reducing water quality has placed a new emphasis on the importance of agronomic thresholds in nutrient management. More research is needed to expand the Alberta database of crop response to STP and to look at other methods to interpret the data for identifying agronomic thresholds.

Implications for Application of Phosphorus from Organic Sources

Long-term application of commercial fertilizer or manure has gradually increased STP levels; whereas, a single application of manure, at either light or heavy rates, has little effect on the labile forms of phosphorus in the soil.

In early years of manure application, the relatively high levels of soluble and labile phosphorus in manure are rapidly fixed by the soil. This rate of phosphorus adsorption by the soil decreases with repeated manure additions due to a cumulative effect that saturates fixation sites with phosphorus. Under long-term repeated applications, there is an increase in the percentage of soluble and labile forms of phosphorus, which can more readily move into runoff and groundwater. This suggests that the risk to water quality by phosphorus is less likely to occur in the early years of manure application, but that the risk will increase from long-term repeated manure applications where phosphorus is applied in excess of crop removal.

Commercial laboratories do not generally differentiate between manure phosphorus and commercial fertilizer phosphorus in the soil when recommending phosphorus rates for crops. There is no evidence to suggest that STP results from manured soils should be interpreted differently than STP results from non-manured soils.

The proportion of nutrients in organic sources is not matched to crop requirements and the phosphorus forms in organic sources are generally mineralized more slowly than the phosphorus forms in commercial fertilizer phosphorus. Research is needed to develop ways to manage cropping and soils to ensure that phosphorus supply does not exceed crop demand when organic phosphorus sources are applied to land.

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Appendix 1. Calculated crop response to added phosphorus (P) for Alberta soils.

Crop response to added phosphorus (control as percent of maximum treatment yield) for individual soils of Alberta (data from McKenzie et al. 1995).

Soil test P (mg kg^{-1})	Canola	Barley	Wheat
	Average for all soil zones		
10	71.1	75.3	77.6
20	82.0	85.1	86.6
30	86.4	88.9	90.1
40	88.8	91.0	92.0
50	90.3	92.3	93.1
60	91.4	93.2	93.9
70	92.1	93.8	94.5
80	92.7	94.3	94.9
90	93.1	94.7	95.3
100	93.5	95.0	95.5
	Luvisolic soils		
10	55.4	55.9	68.2
20	70.7	71.7	79.5
30	77.8	79.2	84.2
40	81.9	83.5	86.7
50	84.6	86.3	88.3
60	86.5	88.3	89.4
70	87.9	89.8	90.2
80	89.0	91.0	90.8
90	89.9	91.9	91.3
100	90.6	92.6	91.7
	Dark Gray soils		
10	55.7	70.4	78.7
20	70.5	81.6	87.2
30	77.4	86.2	90.5
40	81.3	88.7	92.2
50	83.9	90.2	93.2
60	85.7	91.3	94.0
70	87.1	92.1	94.5
80	88.1	92.7	94.9
90	88.9	93.2	95.2
100	89.6	93.5	95.4

Soil test P (mg kg^{-1})	Canola	Barley	Wheat
	Black soils		
10	71.2	79.2	80.3
20	83.6	88.0	88.8
30	88.8	91.3	92.0
40	91.6	93.1	93.7
50	93.4	94.2	94.8
60	94.6	95.0	95.5
70	95.5	95.5	96.0
80	96.2	95.9	96.4
90	96.8	96.3	96.8
100	97.2	96.5	97.0
	Thin Black soils		
10	90.3	79.0	80.3
20	91.5	87.4	86.9
30	91.9	90.7	89.3
40	92.1	92.4	90.6
50	92.3	93.4	91.4
60	92.3	94.1	91.9
70	92.4	94.6	92.3
80	92.5	95.0	92.5
90	92.5	95.3	92.8
100	92.5	95.6	93.0
	Dark Brown soils		
10	86.4	79.7	72.3
20	90.0	86.6	84.6
30	91.2	89.2	89.7
40	91.9	90.6	92.5
50	92.3	91.5	94.2
60	92.6	92.0	95.4
70	92.7	92.4	96.3
80	92.9	92.7	97.0
90	93.0	93.0	97.5
100	93.1	93.2	97.9
	Brown soils		
10		88.2	95.1
20		91.7	95.6
30		92.9	95.8
40		93.5	95.9
50		93.9	95.9
60		94.1	96.0
70		94.3	96.0
80		94.4	96.0
90		94.6	96.0
100		94.6	96.1