

# Impact of Soil Phosphorus Loading on Water Quality in Alberta: A Review

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## SUMMARY

This study has four primary conclusions:

- research has increasingly identified phosphorus pollution from municipal, industrial and agricultural sources as a major threat to water quality;
- pollution risk increases with higher levels of soil phosphorus; however, site specific soil, hydrologic, and management characteristics also have considerable influence on water pollution risk;
- surface waters in Alberta are extremely sensitive to further phosphorus enrichment;
- a desirable long-range goal for Alberta is a balanced nutrient management approach to land application of nutrient-bearing materials, but a site specific approach to soil phosphorus management would be suitable for addressing the more immediate need to protect water quality.

An increasing amount of research has identified phosphorus (P) pollution from a variety of sources, including municipal, industrial, and agricultural, as a major threat to water quality. The Canada-Alberta Environmentally Sustainable Agriculture Agreement (CAESA) water quality assessment showed that phosphorus runoff from agricultural lands in Alberta is an issue that must be addressed. There is growing support to develop a strategy to manage phosphorus concentrations in the soil profile to minimize the risk of movement of phosphorus into surface water and groundwater. There have been concerns raised; however, that there is not enough science-based evidence to justify the implication that high soil phosphorus levels increase water pollution risk. This report examined the science-based evidence for the relationship between soil phosphorus and water pollution risk. It also investigated some ways soil phosphorus loading can be managed to minimize water pollution risk.

Concerns about the contribution of agricultural operations to nutrient enrichment of water bodies in Alberta has increased as the industry has intensified. Nitrogen and phosphorus often exceeded water quality guidelines for protection of aquatic life in streams in areas of high and moderately intensive agriculture. Phosphorus concentrations often exceeded water quality guidelines for protection of aquatic life in small lakes and irrigation canals in high intensity areas.

Alberta lakes, streams, and rivers differ from water bodies elsewhere in Canada or the United States. Many lakes and other surface water bodies in Alberta are naturally highly productive (eutrophic) and experience prolific algae and weed growth. Phosphorus is the primary plant nutrient controlling the level of phytoplankton growth in western Canadian lakes. Consequently, surface waters in Alberta are extremely sensitive to further phosphorus enrichment by internal or external sources. Further nutrient enrichment of surface waters in Alberta can have significant economic and environmental implications on public and animal health, recreation, tourism, and possibly even the agriculture industry.

The risk of phosphorus transport from land to water increases with phosphorus loading of soil. Research has shown that the concentration of dissolved phosphorus increases with higher soil test phosphorus levels. Soil phosphorus levels that would be common for many agricultural soils can, in some situations, produce dissolved phosphorus concentrations in runoff that are high

enough to exceed water quality guidelines. Although the soil phosphorus level is a major factor in the risk of phosphorus export to the water system, other factors, such as the site specific nature of the soil, the type of management, and the hydrologic nature of the site are critical to phosphorus export risk.

The most practical way to reduce high phosphorus levels in soils is through crop uptake; however, this can be a slow process. The rate of decline varies with soil type, crop, and management practices. Research from the Northern Great Plains shows the rate of decline of soil phosphorus ranges from 0.6 to 30 mg kg<sup>-1</sup> per year. Soils in the County of Lethbridge, Alberta that have undergone repeated heavy manure applications can typically have soil test phosphorus levels high enough that several decades could be needed to reduce phosphorus levels to moderate values.

A desirable long-range goal is to achieve balanced nutrient management planning, which requires that inputs be balanced with crop uptake. This is a strategy to manage loading from all nutrients and is comprehensive enough to address all nutrient loading practices, including those associated with manure application, food processing effluent application, and cropping practices. The United States is moving toward a comprehensive nutrient management planning approach to agricultural production and many states have started to address phosphorus loading. We have their experience to learn from as well.

It is recognized that the transition from current practices to managing inputs to balance crop use will be complex and require time. The process to regulate the intensive livestock industry, and the expansion of the food processing industry in Alberta have resulted in a need to develop phosphorus-based standards for Alberta soon. As an interim process, a site specific approach to soil phosphorus management such as the phosphorus index appears to be the most suitable. The phosphorus index is a practical method that will provide the most flexibility for operators, while minimizing risk to the environment. It must be designed so that it can be integrated into a watershed scale assessment.

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## INTRODUCTION

Alberta's agricultural industry has expanded significantly in the last 25 yr. Projections for growth were to reach 10-billion dollars in the primary and as much as 20-billion dollars in the value-added sector by the year 2005. Much of the value-added sector contribution has been in the intensive livestock industry.

Concerns about the contribution of agricultural operations to nutrient loading of water bodies in Alberta have increased as the industry has intensified. A recent water quality assessment (Canada-Alberta Environmentally Sustainable Agreement 1998) showed that nitrogen (N) and phosphorus (P) often exceeded water quality guidelines for protection of aquatic life in streams in high and moderately intensive agriculture areas. In addition, phosphorus often exceeded water quality guidelines for protection of aquatic life in small lakes and irrigation canals in high intensity areas.

One of the primary concerns regarding nutrient loading has been disposal of manure and food processing effluent. Food processing and intensive livestock operations require an adequate land base for disposal and it is often not economical to broaden the land base by hauling manure and effluent long distances. Runoff from agricultural land, particularly those areas enriched by nutrients from long-term manure application, has been identified as one of the major sources of non-point source pollution in other agricultural areas. Concern has particularly focused on phosphorus levels in runoff because of the sensitivity of aquatic systems to phosphorus concentrations.

In Alberta, the intensive livestock regulatory process and the expansion of the food processing industry have resulted in a need for leadership by Alberta Agriculture, Food and Rural Development in establishing acceptable guidelines and standards for organic-based phosphorus materials. There is a need to develop a plan to manage phosphorus loading in the soil that would allow intensive livestock operations, food processing, and other industries to plan future development and expansion in a manner that will protect the quality of surface water.

The objective of this report was to examine the science-based evidence for the relationship between soil phosphorus and water pollution risk, and to present options for development of a soil phosphorus management strategy in Alberta.

### Terms Used in this Report

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 soils 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  $mg\ kg^{-1}$ , 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  $\mu g\ L^{-1}$ , which is the same as parts per billion (ppb). In this report, phosphorus will be expressed as  $mg\ kg^{-1}$  or  $mg\ L^{-1}$  of elemental phosphorus. The relationship of some of the common reporting terms are presented in Table 1.

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

$\mu\text{g L}^{-1}$	=	ppb
$\text{mg L}^{-1}$	=	ppm
$\text{mg kg}^{-1}$	=	ppm
ppb	=	1000 x ppm
$\text{P}_2\text{O}_5$	=	$\text{P} \times 2.2914$
P	=	$\text{P}_2\text{O}_5 \times 0.4364$

Nutrient concentrations in soil are often expressed in terms of  $\text{kg ha}^{-1}$  for a given depth within the soil profile. To determine the nutrient concentration, the soil depth of interest and the soil bulk density must be known or have assumed values. A common soil depth for nutrient analysis is 15 cm. For example, converting 100 ppm of phosphorus to a nutrient content in the top 15 cm (0.15 m) of the soil would require the following steps.

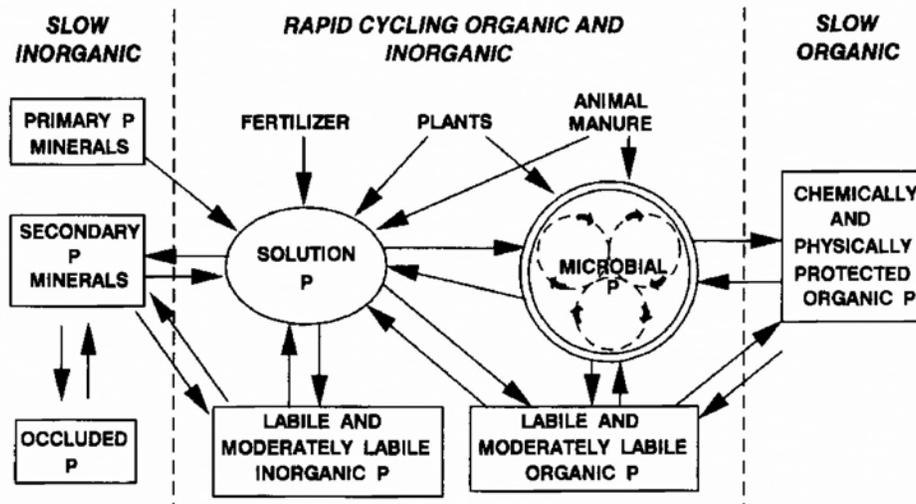
1. Soil bulk density assumed to be  $1.4 \text{ g cm}^{-3}$
2.  $100 \text{ ppm} = 100 \text{ mg kg}^{-1}$
3.  $(100 \text{ mg kg}^{-1} \times 10^{-6} \text{ kg mg}^{-1} \times 1.4 \text{ g cm}^{-3} \times 10^{-3} \text{ kg g}^{-1} \times 10^6 \text{ cm}^3 \text{ m}^{-3} \times 10^4 \text{ m}^2 \text{ ha}^{-1} \times 0.15 \text{ m depth}) = 210 \text{ kg ha}^{-1}$

# PHOSPHORUS IN SOIL, MANURE, AND ORGANIC MATTER

## The Phosphorus Cycle

Phosphorus exists in inorganic forms and organic forms within the soil. Phosphorus content varies with soil parent material, texture, and the management system used to input and remove phosphorus from the soil. Inorganic forms of phosphorus tend to dominate agricultural soils, typically at 50 to 75% of total phosphorus, but can range from 10 to 90% (Sharpley and Reikolainen 1997). Inorganic forms are found either adsorbed or absorbed to mineral fractions dominated by compounds of either aluminum (Al) or iron (Fe) in acidic soils, or calcium (Ca) in calcareous, alkaline soils. Organic phosphorus is generally in relatively labile nucleic acids, phospholipids, inositols, and fulvic acids, or in less soluble humic acids.

Figure 1 is a conceptualized soil phosphorus cycle (Chauhan et al. 1981). The cycle illustrates the relationships of “slow” (slowly available) inorganic and organic forms of soil phosphorus with the “rapid” (readily available) forms. Slow inorganic forms include primary and secondary minerals (e.g., calcium, iron, and aluminum phosphates), as well as unavailable (occluded) forms. The slow organic fraction consists of chemically and physically protected organic phosphorus compounds that are usually adsorbed onto aluminum, iron, and calcium surfaces. They can be mineralized either as soil organic matter is mineralized, or by specific enzyme activity as a response to demand by microbes and plants.



**Fig. 1.** The soil phosphorus (P) cycle and its measurable components (adapted from Chauhan et al. 1981; Stewart and Sharpley 1987).

Primary minerals in the soil parent geologic material dissolve through weathering and enter the solution pool. The solution phosphorus maintains an equilibrium with the labile inorganic phosphorus ( $P_i$ ) fraction such that, in any one soil a capacity factor, a ratio of solution phosphorus:labile phosphorus, is maintained for concentrations of phosphorus that are normal for cultivated soils. The capacity factor varies among different soils depending on the physical and chemical properties of the adsorbing colloids, and can range from  $<10$  to  $> 1000$  (Stewart and Sharpley 1987). Concentrations in excess of the capacity factor result in precipitation of secondary minerals. In highly weathered soils, such as tropical soils, secondary minerals can become occluded.

Plants take up phosphorus directly from the solution pool (Barber 1984). Any depletion in the solution pool is immediately replenished from the labile fraction. If the labile inorganic and solution pools are depleted, the secondary phosphorus minerals can move into the labile inorganic or the solution pools.

Microbial phosphorus, represented by the circling movements in Fig. 1, originates from microbial uptake of phosphorus from the solution pool. This is stimulated by additions of substrates, such as plant residues. When microbial cells are ruptured, either through lysis or predation, phosphorus is released in solution and labile organic ( $P_o$ ) forms, including RNA, phospholipids, acid soluble  $P_i$  and  $P_o$ , and DNA (Stewart and McKercher 1982). They can react with mineral and organic soil components to create a wide variety of different phosphorus compounds of different solubility or susceptibility to mineralization (Stewart and Sharpley 1987).

Phosphorus amendments, either organic or inorganic, are needed to maintain adequate available phosphorus in modern agricultural systems. A continuous drain on solution phosphorus from cultivation and crop removal will ultimately deplete the labile  $P_i$  and  $P_o$  pools. For organic amendments, the microbial activity has a central role in the phosphorus cycle, particularly by maintaining the labile phosphorus supply by replenishing the  $P_o$  pool. It is represented in Fig. 1 as a “wheel” rotating in response to carbon (C) inputs. Should the wheel be stopped due to lack of carbon inputs or partial soil sterilization, the supply of phosphorus to plants becomes limited by the size of the existing labile  $P_i$  and  $P_o$  pools (Stewart and Sharpley 1987).

Further evidence of the important role microbes play in phosphorus cycling dynamics was presented when fumigation-extraction techniques were developed to measure soil microbial biomass. Brookes et al. (1984) measured microbial phosphorus fluxes in soils in continuous wheat and in grassland. In the continuous wheat, the microbial phosphorus fluxes were comparable to the phosphorus uptake by the crop, and in grasslands, the fluxes were higher than the phosphorus uptake by the grass. Sharpley and Reikolainen (1997) suggested that understanding the microbial contribution to soil phosphorus dynamics may impact management practices. They cited that the practice of maximizing organic matter build-up in the fall may result in short-term tie-up of available phosphorus for crops in the following spring. However, this practice may result in enrichment of the soil surface layer with phosphorus, increasing the potential for higher phosphorus concentrations in spring runoff.

When phosphorus is applied to soil, there is generally an increase in the available phosphorus

content, although the fate of applied phosphorus is not always the same as that of applied nitrogen. The magnitude of the increase is a function of soil properties such as clay content, organic carbon, iron, aluminum, and calcium carbonate (CaCO<sub>3</sub>) content. Applied phosphorus can be taken up by the crop or converted to the tissue component of soil microflora and microfauna. However, most of the applied phosphorus is either weakly or strongly adsorbed on to aluminum, iron, or calcium compounds (Syers and Curtin 1988). Once the initial adsorption reaction has occurred, added phosphorus is gradually fixed (absorbed) to the compounds, resulting in a portion of the fixed phosphorus being unavailable for plant uptake (Sharpley and Reikolainen 1997). Although fixation was once considered irreversible, it is now known that phosphorus can be slowly released back into solution when available phosphorus levels are depleted. An estimated 25% of applied phosphorus is available to plant roots; whereas, the rest is quickly adsorbed by the soil components and over time released for plant use (Morgan 1997).

Phosphatase enzymes associated with plant roots and microorganisms play a key role in phosphorus availability, particularly in the hydrolysis of organic phosphorus. There is a wide range of soil microorganisms that have the capability, through their phosphatase activities, to mineralize all known organic phosphates of plant origin. The phosphatase activity is strongly influenced by temperature. It is also influenced by moisture, pH, and organic carbon (Tisdale et al. 1985).

Continued application of phosphorus in excess of crop demand will increase phosphorus levels to a point of environmental concern and possibly to agronomic concern. In the case of commercial fertilizers, economic factors dictate that care be taken to ensure that application rates do not exceed crop demands. In manure application, the philosophy is often to use the land for manure disposal. In these cases, to reduce the transport costs, manure is often repeatedly applied to the same land base at rates where nutrients consistently exceed crop demand, and nutrient accumulation can lead to environmental risk.

### **The Phosphorus Content of Manure and Organic Waste Applied to Land**

Agricultural land is a sink for the application of a variety of materials, including production inputs (commercial fertilizers, pesticides, and irrigation water) and waste by-products (livestock manure, industrial and municipal wastewater, and sludge).

**Manure.** Recovery of phosphorus is relatively efficient in crop production compared to animal production, with 56 to 76% of the input phosphorus recovered in crops, relative to 10 to 34% in animals (Sharpley and Reikolainen 1997). A variety of factors can affect the nutrient content of manure such as animal type, manure management system (solid or liquid), storage methods, amount and type of bedding used, application method, animal diet, composting techniques, and climate. As a result, the nutrient content and physical properties of animal manure are highly variable (Table 2). For example, DeLuca and DeLuca (1997) reported that the phosphorus content of beef feedlot manure, from values cited in the literature, ranged from 0.1 to 0.8%, averaging 0.4%.

There are no standard methods for testing the phosphorus content of solid animal waste;

however, a method proposed to the United States Department of Agriculture is a modification of the Olsen method for soil phosphorus testing (Self-Davis and Moore 1998).

**Table 2.** Nitrogen (N) and phosphorus (P) content of manures from various type of livestock (Alberta Agriculture, Food and Rural Development 1999a; Intensive Livestock Operations Committee 1995).

Type of livestock		Moisture <sup>z</sup> (%)	Total N <sup>z</sup> (kg Mg <sup>-1</sup> )	Total P <sup>z</sup> (kg Mg <sup>-1</sup> )	N/P	P (%)
beef	open lot	50	10.0	2.4	4.2	0.24
dairy	free stall	92	4.0	0.9	4.4	0.09
	tie stall	80	5.0	0.9	5.6	0.09
hogs	all	96	3.5	1.1	3.2	0.11
poultry	layers - solid	60	16.0	12.2	1.3	1.22
	layers – liquid	90	9.6	7.3	1.3	0.73
	broilers	35	18.6	6.5	2.9	0.65
	breeders	35	19.7	13.1	1.5	1.30
turkey	all	35	18.6	6.5	2.9	0.65
sheep	all	50	7.0	2.0	3.5	0.20
horse			6.0	1.3	4.6	0.13

<sup>z</sup>Values are based on averages from a variety of sources, and actual farm values may vary greatly.

**Municipal wastes.** Municipal wastes include storm-drain water, liquid sewage with suspended solids, and solid material generated by households and businesses. Storm-drain water is usually diverted directly into a watercourse, such as a river. Solid material from households and businesses is taken to land-fill sites. Municipal sewage is treated before release into the environment.

Municipal sewage is about 99% liquid with suspended and dissolved organic and inorganic materials, and a large number of microorganisms. Sewage treatment facilities remove floating matter and grit, and reduce suspended solids, oil, grease, dissolved organic matter, dissolved nutrients, and microorganisms. Sewage treatment facilities generate two types of wastes: treated effluent and sewage sludge. The latter is also referred to as biosolids. The treated effluent is discharged to either land or water. Land application methods generally include irrigation (Alberta Environmental Protection 1997a), rapid infiltration (Alberta Environmental Protection and City of Red Deer 1981), and wetland disposal (Alberta Environmental Protection, date unknown). Municipal effluent generally contains between 2 and 6 mg L<sup>-1</sup> total phosphorus, 10 to 20 mg L<sup>-1</sup> total nitrogen, and 5 to 40 mg L<sup>-1</sup> total potassium (K) (Alberta Environmental Protection 1997a). Biosolid material, which is collected from settling ponds, typically contains about 10% solids and 90% water. Total phosphorus, total nitrogen, and total potassium content are about 4%, 5.5%, and 0.35% on a dry-weight basis, respectively (Barl and McKenzie 1995). The most common biosolid disposal methods are sanitary landfilling, incineration, permanent lagoon storage, and

land application (Alberta Environmental Protection 1997b). Land application of biosolids is usually carried out by injection.

**Food processing wastewater.** Food processing facilities often require large quantities of water of which a major portion becomes wastewater. This type of wastewater contains significant amounts of nutrients and organic material. Barl and McKenzie (1995) reported 42 to 72 mg L<sup>-1</sup> total phosphorus, 75 to 211 mg L<sup>-1</sup> total nitrogen, 466 to 707 mg L<sup>-1</sup> total potassium, and 1% total solids in potato processing wastewater. Wastewater can be diverted into existing municipal sewage treatment facilities if processing plants are within or near municipal infrastructures. However, food processing plants that do not have access to municipal services must develop alternative methods for handling wastewater. Land application is generally the most effective method of disposal. Wastewater is temporarily held in holding ponds, followed by irrigating onto selected parcels of land. An alternative method is to divert the wastewater to wetlands for processing.

### Methods of Phosphorus Analysis

Analytical techniques are targeted to identify five fractions of phosphorus: total phosphorus (P<sub>t</sub>), dissolved phosphorus (P<sub>d</sub>), particulate phosphorus (P<sub>p</sub>), biologically-available phosphorus (BAP), and plant available phosphorus. Water analysis techniques were generally designed to identify P<sub>t</sub>, P<sub>d</sub>, P<sub>p</sub>, or BAP. Soil analysis techniques were generally designed to identify either P<sub>t</sub> or plant available phosphorus; however, BAP, P<sub>d</sub>, and P<sub>p</sub> have become important factors when assessing agricultural phosphorus contributions to water quality.

When assessing potential phosphorus transport from runoff, variability in runoff volume as a result of climate, soils, and agronomic factors plays a larger role in determining phosphorus loss than does a soil test (Sibbsen and Sharpley 1997). Care should be taken that soil testing is not the only criterion used when determining the potential for phosphorus transport from runoff (Haygarth and Jarvis 1999).

**Analysis of phosphorus in soils.** Relating soil chemical and physical properties to the potential for phosphorus transport from surface runoff requires a different approach to sample collection than that required for soil fertility analysis. For most agricultural soils, samples collected to a depth of 2 cm would accurately define the effective depth for interaction between surface soil and runoff for rainfall intensities of less than 50 mm hr<sup>-1</sup>. For medium to coarse textured soils on slopes greater than 12% that are subject to high intensity rainfall (>100 mm hr<sup>-1</sup>), the sampling depth should be 4 cm (Coale 1998).

*Total phosphorus* - Total phosphorus (P<sub>t</sub>) includes all inorganic and organic forms of phosphorus in the soil. Analysis of P<sub>t</sub> is accomplished by converting all forms of phosphorus to orthophosphate (PO<sub>4</sub><sup>-3</sup>), and then analyzing the PO<sub>4</sub><sup>-3</sup> content using colorimetric or inductively coupled plasma (ICP) spectroscopic techniques. Conventional methods use strong reagents and high temperatures to digest and dissolve all the soil phosphorus, then the sample is filtered, and the filtrate is analyzed. Common methods include the perchloric acid digestion method (Olsen and Sommers 1982), and the sulfuric acid / hydrogen peroxide / hydrofluoric acid digestion method (Bowman 1988).

*Available phosphorus* - Most soil phosphorus analytical methods are used to identify phosphorus levels available for crop use. The extractants used are weaker than the digestion reagents used for total phosphorus. They are targeted at potentially-available phosphorus, which is only a portion of the total phosphorus in the soil sample. 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 ( $\text{PO}_4^{-3}$ ) content. The tests are differentiated by the extractant used. A summary of the more common tests is presented in Table 3.

Analysis method	Extractant	Comments
Olsen	0.5 M $\text{NaHCO}_3$ at pH 8.5	-common method for assessing crop-available P in the United States -applies best to soils with pH > 7
Mehlich-1	0.2 M $\text{CH}_3\text{COOH}$ 0.25 M $\text{NH}_4\text{NO}_3$ 0.015 M $\text{NH}_4\text{F}$ 0.013 M $\text{HNO}_3$ 0.001 M EDTA <sup>z</sup>	
Mehlich-3	0.2 M $\text{CH}_3\text{COOH}$ 0.25 M $\text{NH}_4\text{NO}_3$ 0.015 M $\text{NH}_4\text{F}$ 0.013 M $\text{HNO}_3$ 0.001 M EDTA <sup>z</sup>	-common method for assessing crop-available P in the United States
Bray I	0.03 N $\text{NH}_4\text{F}$ 0.025 N HCl at pH 3.5	-not suited for calcareous soils
Bray (strong)	0.015 M $\text{NH}_4\text{F}$ 0.25 M ammonium acetate 0.25 M acetic acid	
modified Kelowna <sup>y</sup>	0.015 M $\text{NH}_4\text{F}$ 0.25 M ammonium acetate 0.25 M acetic acid	-best method for a wide range of soil pH levels -standard soil P test for the Prairie Provinces
Kelowna	0.015 M $\text{NH}_4\text{F}$ 0.25 M ammonium acetate	

<sup>z</sup> EDTA is ethylene diamine tetraacetic acid.

<sup>y</sup> There are two versions of the modified Kelowna, with slightly different strengths of extractants.

The numerous extraction methods all have some advantages and limitations depending upon the soil type for which they are 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 favoured more in some parts of the world than others. Soil pH, mineralogy, and organic matter content are major factors in accuracy. For example, the Bray I, which is not suitable for calcareous soils, is accurate for non-calcareous California soils

(Vaughan and Jones 1980; referenced in McKenzie 1989). Care must be taken to make sure the extraction method is suitable for the soil conditions.

The most common extraction method worldwide is likely the Olsen method (Tiessen and Moir, 1993). In Alberta, the most common method is the modified Kelowna method, because of its suitability over a wide range of soil pH values. While efforts have been made to adopt standard tests, there is no consistency among regions. Similarly, there is no standard on what constitutes a high soil test phosphorus value, and values will depend on the type of test used.

Although most tests are correlated to crop response, there is little direct correlation to environmental factors such as surface runoff. While these tests have been used to describe the relationship between available phosphorus in the soil and  $P_d$  in the runoff, they have limitations. First, they represent the  $P_d$  in the runoff, and while  $P_d$  is an important water quality parameter, there is a considerable amount of  $P_p$  in runoff that would be undetected (Daniel et al. 1998). This fraction can potentially become available for aquatic plant growth. Secondly, the Mehlich-3 test, which uses strong acids, removes not only the readily available phosphorus fraction, but also portion of the slowly available phosphorus fraction (Self-Davis et al. 1998). The test would therefore tend to overestimate the  $P_d$  fraction in runoff. 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.

*Biologically available phosphorus* - Biologically available phosphorus (BAP) has been defined as, “the amount of inorganic phosphorus that a phosphorus-deficient algal population can utilize over a period of 24 hours or longer” (Sonzogni et al. 1982). It includes dissolved phosphorus and a portion of the particulate phosphorus that is available for algal uptake (Sharpley and Smith 1993). Algal uptake has been closely related to amounts of phosphorus extracted from soils or lake sediments by iron-oxide impregnated paper strips (Sharpley, 1993). It requires a 16-hr extraction time, which makes it difficult for labs to process large numbers of samples quickly. Sharpley et al. (1994) suggested that some routine soil tests are well correlated with the iron-oxide measure and could be used as a preliminary assessment. The iron oxide method could then be used as a special test for more intensive management cases.

**Analysis of phosphorus in freshwater.** Inorganic phosphorus is found either in the inorganic or organic form in freshwater systems and either can contribute to the  $P_d$  or  $P_p$  fraction. The form and fraction of phosphorus, as well as the physical, biological, and chemical characteristics of the receiving water, govern the availability of phosphorus for growth of algae (Sonzogni et al. 1982).

Phosphorus is the nutrient controlling the level of phytoplankton productivity in western Canadian lakes (Prepas and Trew 1983). Algal growth (primary production) in freshwater systems is dependant on the biological availability of phosphorus. Much of the phosphorus in runoff from agricultural lands in Alberta is in the dissolved and dissolved reactive fractions (Anderson et al. 1998; Cooke and Prepas 1998), which are the forms of phosphorus that are more readily available for primary production. Consequently, high dissolved phosphorus concentrations in runoff from agricultural lands likely increase the severity of primary

productivity in phosphorus-sensitive water bodies in Alberta.

*Total, dissolved, and particulate phosphorus* - Total phosphorus ( $P_t$ ) is the summation of  $P_p$  and  $P_d$ , and it accounts for all inorganic and organic phosphorus forms. Digestion and detection principles are similar to soil  $P_t$  analysis, but the reagents are different. Potassium persulfate digestion as described by Menzel and Corwin (1965) and modified by Prepas and Rigler (1982) is the routine chemical digestion method for the determination of  $P_t$  in freshwater.

Dissolved phosphorus is the fraction of phosphorus that is not retained by a 0.45  $\mu\text{m}$  pore membrane filter. It is comprised of organic and inorganic fractions. Much of the dissolved organic phosphorus is inert, while dissolved inorganic phosphorus is more readily available for biological use. However, the measurement of dissolved inorganic phosphorus is not a direct measure of the bioavailability of phosphorus in aquatic systems.

Particulate phosphorus is the phosphorus fraction that is adsorbed onto particulate materials including organic debris or soil particles that contain iron- or aluminum-hydrous oxides, or iron-phosphorus, aluminum-phosphorus, or calcium-phosphorus minerals (Sonzogni et al. 1982). In standard water analysis,  $P_p$  concentrations are not measured directly, but are calculated as the difference between  $P_t$  and  $P_d$  concentrations. While  $P_d$  is, for the most part, immediately available for biological uptake, the availability of  $P_p$  to aquatic organisms is limited. It can however, provide a variable, but long-term source of phosphorus in lakes (Sharpley et al. 1992).

*Biologically available phosphorus* - Although  $P_t$  represents a variable, long-term source of phosphorus to aquatic systems, the biological availability of phosphorus is critical in evaluating the risk of phosphorus loading and subsequent eutrophication of surface waters. Dissolved inorganic phosphate (mainly as  $\text{H}_2\text{PO}_4^-$  or  $\text{HPO}_4^{2-}$  in the pH range of most natural waters) and orthophosphate ( $\text{PO}_4^{3-}$ ) are the inorganic forms of phosphorus most readily available to aquatic plants for biological production. Other forms of phosphorus ( $P_d$  and  $P_p$ ) can be converted to  $\text{PO}_4^{3-}$  through natural biological processes or hydrolysis (Pote and Daniel 1998).

Dissolved reactive phosphorus (DRP), as determined by the molybdenum blue reaction on undigested samples, is an estimate of orthophosphate in fresh water systems (Murphy and Riley 1962). The chemical extraction of DRP in freshwater tends to overestimate the biological availability of phosphorus (Sonzogni et al. 1982). A true measure of the potential biologically available (bioavailable) phosphorus (BAP) in freshwater is by evaluating the growth response of test organisms (e.g., algae; *Selenastrum* sp.) to phosphorus in labour-intensive bioassays. This method is very time consuming and costly. Therefore, the chemical extraction of DRP is a preferred method to estimate BAP.

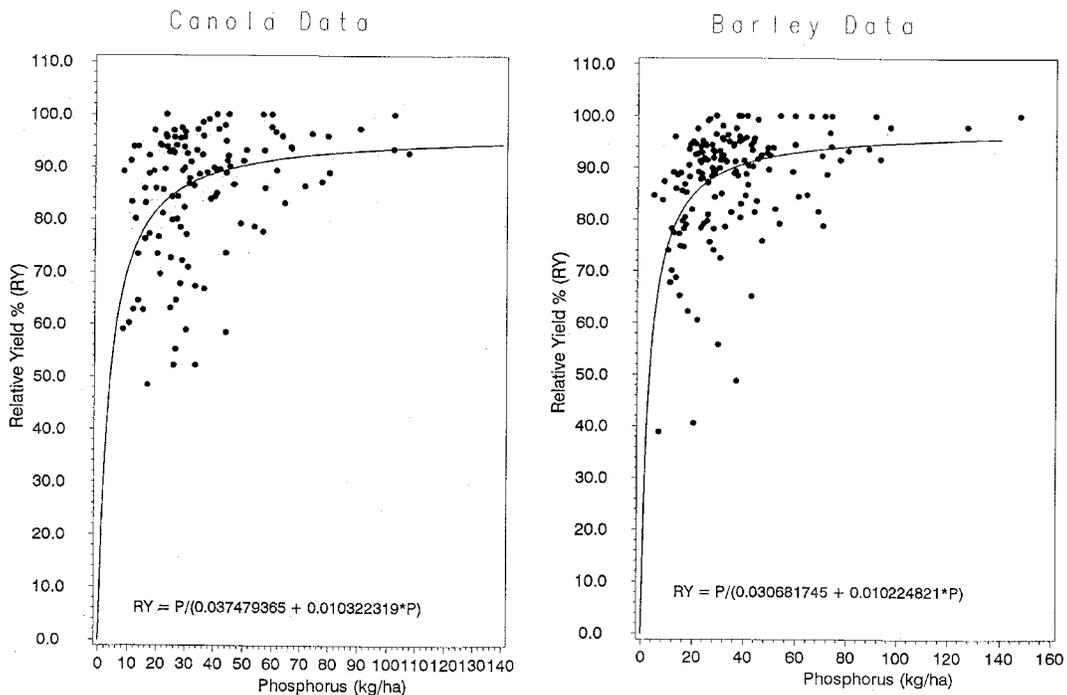
Analysis of BAP and  $P_t$  have distinct roles to play in assessing accelerated eutrophication risk. When analyzing water samples, determination of BAP is critical for assessing the immediate risk of phosphorus loading to the water system. When assessing the long-term risk of a water system, many researchers and watershed managers want to know the  $P_t$  content (Pote and Daniel 1998).

## IMPACT OF EXCESS PHOSPHORUS LEVELS

### Soil Phosphorus and Crops

**Impact of high soil phosphorus on crop response.** The mobility of phosphorus is relatively low compared to nitrogen, therefore plant roots have a lower probability of contacting phosphorus. During active phosphorus uptake periods, plant roots get most of their phosphorus from within 2 mm of the root surface (Nye and Tinker 1977, referenced in Sibbsen and Sharpley 1997). Also, agricultural crops take up only 5 to 10% of the applied fertilizer in the first year (Greenwood et al. 1980) with the remainder originating from the residual soil phosphorus (Sibbsen and Sharpley 1997). Consequently, 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, and as a result, soil phosphorus levels have increased from very low to medium and high during this century (Sibbsen and Sharpley 1997).

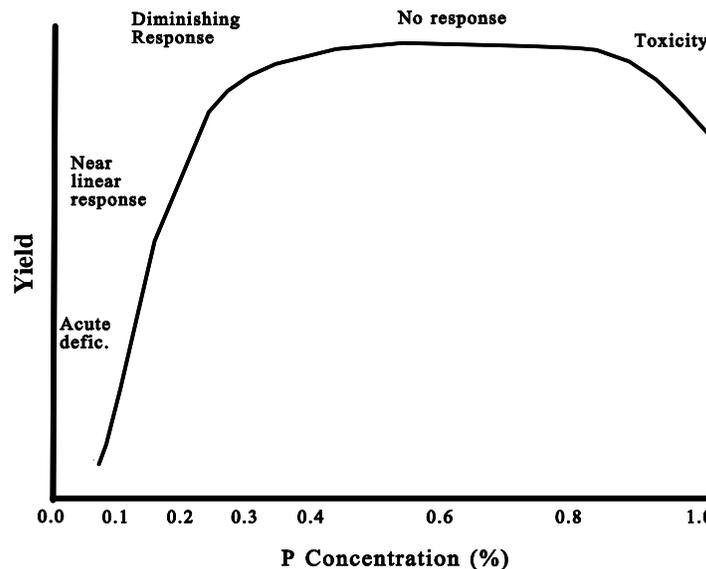
Crop yield response to phosphorus levels will increase to a critical level, beyond which yields do not appreciably increase regardless of how much phosphorus is applied (McKenzie et al. 1995; Johnston and Poulton 1997) (Fig. 2).



**Fig. 2.** The relationship of soil test phosphorus to yield of barley and canola in Alberta (adapted from McKenzie et al. 1995).

The information available does not present a clear trend about whether the impact of excessive soil phosphorus on crop yield will decrease solely in response to soil phosphorus. Tinker (1980) discussed the influence of high levels of available soil phosphorus on reduced mycorrhizal infection in plants, causing reduced uptake of zinc and copper. Janzen et al. (1993) also reported that increased levels of fertilizer phosphorus interfered with the uptake of zinc and copper; however, similarly-high rates of phosphorus from manure applications did not appear to interfere with zinc and copper uptake (Chang et al. 1994). The high availability of micronutrients in manure may prevent the uptake suppression effects observed from high rates of fertilizer phosphorus (Dormaer and Chang 1995).

Ozanne (1980) examined yield response to phosphorus concentrations in plant tissue and suggested that when phosphorus concentrations exceed 0.8%, toxicity may occur (Fig. 3). Plant tissue concentrations may provide a more precise relationship with plant response since they are independent of soil factors.



**Fig. 3.** General relationship between yield and the concentration of phosphorus (P) in plant tissue (adapted from Ozanne 1980).

Continued accumulation of phosphorus in the soil will result in an increased risk to the environment before agronomic problems appear. It is difficult to single out soil phosphorus levels alone in assessing agronomic problems related to manure application, because other components in the manure can potentially act to enhance or reduce crop performance. When considering land application of manure, municipal sewage, and food processing effluent, all nutrients and their potential impact on the soil, water, crops, and air should be considered.

**Using crops to reduce high soil phosphorus levels.** Using crops to remove phosphorus has

been proposed as the most practical way to reduce phosphorus in soils with high phosphorus levels (Dormaar and Chang 1995; Daniel et al. 1998). The rate of decline of phosphorus in soils with phosphorus levels well above those required for optimum crop growth varies with soil type and management. Sharpley and Reikolainen (1997) presented research results showing a range in the rate of decline from 0.6 to 30 mg kg<sup>-1</sup> yr<sup>-1</sup> (Table 4) for soils in the Northern Great Plains. At these rates, several decades would be needed to reduce phosphorus to acceptable levels in fields where soil test phosphorus levels are in excess of 400 mg kg<sup>-1</sup>.

**Table 4.** Decrease in available soil phosphorus following phosphorus application (adapted from Sharpley and Reikolainen 1997).

Soil <sup>z</sup>	Crop	Time (yr)	Available soil phosphorus			Reference <sup>y</sup> and location	
			Method	Initial (mg kg <sup>-1</sup> )	Final (mg kg <sup>-1</sup> )		Decline (mg kg <sup>-1</sup> yr <sup>-1</sup> )
Thurlow, l	Small grains	9	Olsen	13	4	1.0	Campbell 1965; Montana
		9		20	4	1.8	
		9		60	6	6.0	
Haverhill, cl	Wheat/fallow	14	Olsen	40	25	1.1	Cox et al. 1981; Saskatchewan
		14		74	33	2.9	
		14		134	69	4.6	
Portsmouth, fsl Sceptre, c	Small grains	8	Mehlich-1	23	18	0.6	Cox et al. 1981; Saskatchewan
		9		54	26	3.1	
	Wheat/fallow	Olsen	8	45	18	3.4	
			8	67	18	6.1	
			8	147	40	13.4	
Williams, l	Wheat/barley	16	Olsen	26	8	1.1	Halvorson and Black 1985; Montana
		16		45	14	1.9	
Carroll, cl	Wheat/flax	8	Olsen	71	10	7.6	Spratt et al. 1980; Manitoba
		8		135	23	14.0	
		8		222	50	21.5	
Waskada, l	Wheat/flax	8	Olsen	48	9	4.9	Spratt et al. 1980; Manitoba
		8		88	23	8.1	
		8		200	49	18.9	
Waskada, cl	Wheat/flax	8	Bary	140	50	11.3	Wagar et al. 1986; Manitoba
		8		320	80	30.0	

<sup>z</sup> cl - clay loam; fsl - fine sandy loam; l - loam; c - clay.

<sup>y</sup> Referenced in Sharpley and Reikolainen (1997).

Crop utilization of phosphorus is enhanced when a 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 favourable at a pH range of 6.0 to 6.5. Availability is decreased at low pH levels by oxides of iron and aluminum and at high pH by calcium and magnesium.

In areas with excessive soil test phosphorus levels, withholding phosphorus application altogether may only produce short-term success. Withers et al. (1994, referenced in Sharpley and Reikolainen 1997) found that after 3 yr of no phosphorus application to high phosphorus soils, crop yields began to decline. Rather than no phosphorus application, it may be better to use small amounts of phosphorus. Use of small amounts of phosphorus as a starter fertilizer has successfully reduced the need for larger phosphorus applications in vegetable crops, and there is potential for this practice to apply to other crops as well (Sharpley and Reikolainen 1997). Tisdale et al. (1985) stated that application of a small amount of phosphorus in the seedbed helped early crop establishment under cold, wet conditions. Management practices that improve crop performance will result in improved utilization of phosphorus.

### **Impact of Soil Phosphorus Levels on Phosphorus Mobility and Water Quality**

Water is highly sensitive to phosphorus accumulation. Eutrophication of lakes can become greatly accelerated when phosphorus levels in the water are between 0.01 to 0.02 mg L<sup>-1</sup>. This is an order of magnitude more sensitive than soil solution levels for phosphorus considered critical for plant growth, which range from 0.2 to 0.3 mg L<sup>-1</sup> (Daniel et al. 1998).

Alberta Environmental Protection water quality criteria to control eutrophication in surface water in Alberta use a maximum concentration of 0.05 mg L<sup>-1</sup> of phosphorus. The United States Environmental Protection Agency (USEPA) has guidelines that phosphorus concentration should not exceed 0.05 mg L<sup>-1</sup> for streams entering lakes and reservoirs, and 0.025 mg L<sup>-1</sup> for the lakes and reservoirs themselves. For the prevention of plant nuisances in streams and other flowing water not directly entering lakes and reservoirs, the phosphorus concentration should not exceed 0.10 mg L<sup>-1</sup> (Daniel et al. 1998).

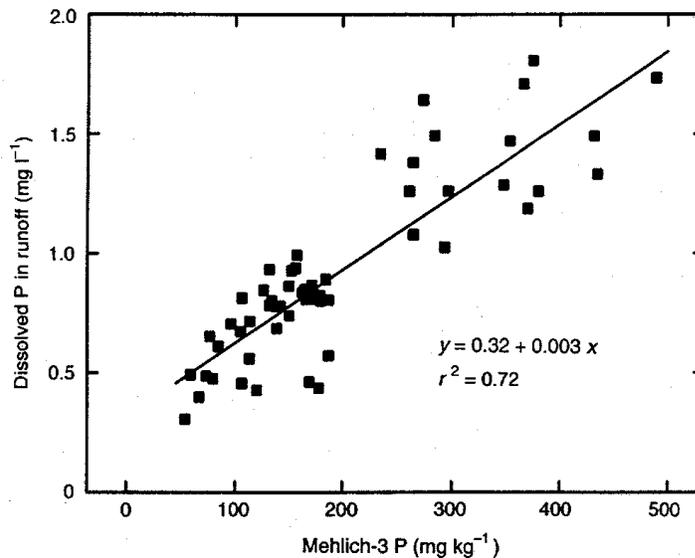
Eutrophication is the process of nutrient enrichment of surface waters. Excessive nutrients, like nitrogen and phosphorus, in freshwater promote the growth of aquatic plants and phytoplankton (algae). While nitrogen and phosphorus are essential elements for aquatic plant and algal growth, certain species of phytoplankton can use or 'fix' nitrogen from the atmosphere. Therefore, phosphorus tends to be the limiting nutrient controlling phytoplankton productivity in aquatic systems in western Canada (Prepas and Trew 1983). Biological productivity in aquatic systems requires a relatively low concentration of phosphorus relative to nitrogen. Uhlmann and Albrecht (1968, referenced in Gibson, 1997) applied a carbon:phosphorus:nitrogen ratio of 105:15:1 to freshwater biota. This implies that freshwater organisms are 15 times more susceptible to changes in phosphorus levels than to changes in nitrogen.

Nutrient enrichment of surface waters promotes biological productivity and disrupts the natural balance of biological systems. Once nutrient supplies are exhausted, oxygen levels in the water are depleted as a result of the death and decomposition of the biota. This results in the suffocation of more sensitive or commercially important aquatic organisms, particularly fish. Additional effects of excessive biological productivity include increased water temperatures, impede water flow and navigation, increased rate of water loss through evaporation, and increased sedimentation, which decreases the water body volume. Highly eutrophic waters used for drinking water supplies can also develop unacceptable taste and odour problems in the

finished water. Blooms of cyanobacteria (blue-green algae) contribute to summer fish kills, unpalatability of drinking water, and formation of trichloromethane during water chlorination. Consumption of the cyanobacterial blooms, or the water-soluble neuro- and hepato-toxins that they release when they die, can be harmful to humans and livestock (Lawton and Codd 1991; referenced in Daniel et al. 1998). Periodic blooms of cyanobacteria have occurred in lakes and dugouts in Alberta (Kotak et al. 1993; Kotak et al. 1994). Therefore, the eutrophication of surface waters can be potentially catastrophic (Haygarth and Jarvis 1999) with significant economical and environmental impacts on society.

Non-point source pollution from agriculture was identified by the USEPA to the United States Congress as the major source of contamination of streams and lakes. Specifically, eutrophication was identified as the critical problem in those surface waters with degraded quality, with agriculture affecting 60% of the river contamination, 50% of the lake contamination, and 34% of estuary contamination (Parry 1998). Nitrogen and phosphorus were the leading contaminants in lakes and estuaries, and the third leading contaminant in rivers.

The risk of phosphorus export from land to water increases with increasing soil test phosphorus levels, primarily from increased dissolved phosphorus ( $P_d$ ). Figure 4 shows a linear increase in the  $P_d$  concentration in runoff as soil test phosphorus increases. Data from Europe suggest that at higher soil test phosphorus levels the amount of  $P_d$  in runoff increases exponentially (Sibbsen and Sharpley 1997).

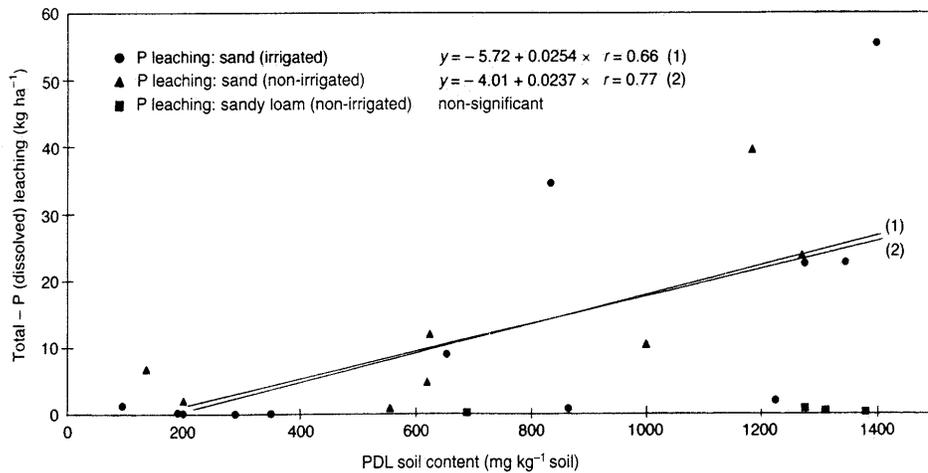


**Fig. 4.** Relationship between soil test phosphorus (P) content of surface soil (0 to 2 cm) and dissolved phosphorus concentration of surface runoff from fescue in Arkansas (adapted from Pote et al. 1996).

Dissolved phosphorus concentrations in leachate have been shown to increase proportionally

with soil test phosphorus levels. Figure 5 presents data from Germany relating soil test phosphorus, measured as percentage double-lactate soluble phosphorus (PDL), to dissolved phosphorus in lysimeters.

Soil phosphorus test levels alone are not necessarily a reliable predictor of phosphorus export to water systems. Relationships between soil test phosphorus and  $P_d$  vary as a function of management and soil type. Sharpley et al. (1996) reported that on the same soil type, regression slopes between  $P_d$  and soil test phosphorus were lower for grass than for cultivated land, suggesting that the vegetative cover was protecting the soil, and reducing  $P_d$  concentrations in the runoff. In addition to the level of phosphorus in the soil, the potential loss of phosphorus from agricultural watersheds is a function of local hydrologic and soil factors and management.



**Fig. 5.** Results of lysimeter experiments of phosphorus (P) leaching as a function of phosphorus soil content as a result of increased slurry application (adapted from Meissner et al. 1997).

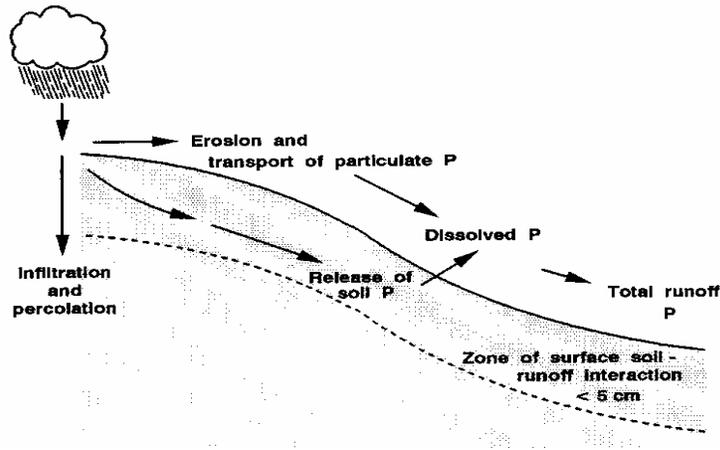
### How Different Soil, Landscape Management, and Environmental Factors Affect Phosphorus Mobility

While much research has been directed toward understanding the dynamics of phosphorus in the soil, the hydrologic controls that link the spatially variable phosphorus sources, sinks, temporary storages, and transport processes within a watershed are less well understood (Gburek and Sharpley 1998). Effective control of phosphorus losses requires a more thorough understanding of the hydrologic processes within a given watershed. Haygarth and Jarvis (1999) consider hydrology the most important factor in the phosphorus transport regime.

While off-site movement of phosphorus may have little or no financial impact on the farmer, its impact may be felt many kilometres away and after a buildup over a considerable time period. By the time the impact is felt, the farming practices that contributed to the problem may have

been in place for generations and may be difficult to rectify.

It is generally considered that the dominant process for phosphorus export from watersheds is surface runoff, and contributions from subsurface flow and leaching are of relatively less concern (Sharpley and Syers 1979; Sharpley and Reikolainen 1997; Sims et al. 1998; Daniel et al. 1998). Surface runoff includes phosphorus attached to particulates ( $P_p$ ) and phosphorus dissolved in the water ( $P_d$ ). The highest concentrations of phosphorus are typically found in surface runoff (Lennox et al. 1997), although this does not necessarily result in the highest amount of phosphorus transport. Quantification of phosphorus transport by runoff is complex and controlled by temporal and spatial factors, including climate (Fig. 6).



**Fig. 6.** Phosphorus (P) transport processes (adapted from Sharpley et al. 1996).

In humid climates, runoff is generated from only a small number of source areas. These areas may expand and contract with time, varying rapidly during a storm as a function of temperature, soil, topography, groundwater, and antecedent moisture status (Gburek and Pionke 1995). Runoff from these areas is limited by moisture storage, rather than by infiltration capacity, since antecedent soil moisture levels tend to be high.

In more arid areas, runoff is limited by infiltration rate rather than moisture storage. Areas within the catchment can alternate between sources and sinks for surface flow as a function of soil properties, rainfall intensity and duration, and antecedent moisture conditions. If we assume surface runoff is the primary means of phosphorus export, then in these cases if surface runoff does not occur, phosphorus exports are negligible (Brookes et al. 1997).

The export of phosphorus by subsurface flow or leaching has not been considered of major importance. This is because in most soils the phosphorus concentration of water has been thought to decrease with depth as it percolates through the profile, a result of adsorption of phosphorus by phosphorus deficient subsoils (Stamm et al. 1998). Exceptions include peaty or acid soils, sandy soils and waterlogged soils (Daniel et al. 1998). Several cases have been identified, however,

where the contribution of dissolved phosphorus from subsurface flow may be substantial (Ryden et al. 1973; Hergert et al. 1981a, b; Culley et al. 1983; Heckrath et al. 1995; Hawkins and Scholefield 1996, all referenced in Stamm et al. 1998 ). Ryden et al. (1973) cited eight cases where phosphorus concentrations in tile drain water were higher than levels usually associated with eutrophication. They identified two cases where the phosphorus export in subsurface flow equaled or exceeded values typically found in surface runoff. In cases where the transport process was identified, phosphorus export was by preferential flow through macropores was a major factor.

Xue et al. (1998) reported that tile drains made significant contributions of dissolved phosphorus to the total river load. They also showed that the tile drain load was strongly event-driven, with the highest loads corresponding to heavy rain events. Stamm et al. (1998) showed that preferential flow through macropores was contributing to high soluble phosphorus levels in tile drain water under manured grasslands. Phosphorus leaching by preferential flow was also demonstrated by Jensen et al. (1998) in laboratory soil column tests.

Leaching of phosphorus has been observed in organic soils where adsorption capacity is low due to low pH, low clay content, or complexing of aluminum and iron. Also coarse-textured soils, and areas prone to shallow water tables, are at higher risk of having phosphorus transported by subsurface flow, as are soils with high phosphorus levels due to over-fertilization or excessive manure applications (Sims et al. 1998).

Use of water quality guidelines alone should not be the only criterion to control phosphorus levels in runoff. Daniel et al. (1998) identified cases where runoff from non-manured, non-fertilized land exceeded the  $0.100 \text{ mg L}^{-1}$  criteria, creating a situation that was very difficult to manage. They suggested considering the relationship between phosphorus loading and watershed characteristics on a site specific and water use basis. For example, lakes used for water supply or swimming will benefit from low phosphorus loading, whereas lakes used for fish production may benefit from a more moderate level of phosphorus loading. The factors that should be considered include proximity to phosphorus-sensitive water, land use, runoff and leaching potential, mean depth of water bodies, and hydraulic residence time.

## CONTROLLING PHOSPHORUS LEVELS IN THE ENVIRONMENT

### Single Limit Approach

Several American states have adopted or proposed guidelines for maximum phosphorus levels in the soil, as shown in Table 5. The single limit approach offers a quick method that requires soil testing as the basis for establishment. Land managers can easily plan the land base needed for their application needs.

**Table 5.** Guidelines for maximum levels of phosphorus (P) in soils (adapted from Sibbsen and Sharpley 1997).

Location	Critical level for soil P (mg kg <sup>-1</sup> )	Management recommendations (when at or above limit)
Arkansas	150	<ul style="list-style-type: none"> <li>• apply no P from any source.</li> <li>• minimize erosion by using constant cover.</li> <li>• provide buffers next to streams.</li> <li>• overseed pastures with legumes to aid P removal.</li> </ul>
Delaware	120	<ul style="list-style-type: none"> <li>• apply no P from any source.</li> </ul>
Ohio	150	<ul style="list-style-type: none"> <li>• reduce or eliminate erosion.</li> <li>• reduce or eliminate P additions.</li> </ul>
Oklahoma	130; 200	<ul style="list-style-type: none"> <li>• 130-200 mg kg<sup>-1</sup>, half rates of P on all soils.</li> <li>• &gt; 200 mg kg<sup>-1</sup>, P rate not to exceed crop removal.</li> </ul>
Michigan	75; 150	<ul style="list-style-type: none"> <li>• 75-150 mg kg<sup>-1</sup>, P rate not to exceed crop removal.</li> <li>• &gt; 150 mg kg<sup>-1</sup>, no P addition from any source.</li> </ul>
Texas	200	<ul style="list-style-type: none"> <li>• P rate not to exceed crop removal.</li> </ul>
Wisconsin	75; 150	<ul style="list-style-type: none"> <li>• 75-150 mg kg<sup>-1</sup>: rotate to P-demanding crops and reduce manure application rates.</li> <li>• &gt; 150 mg kg<sup>-1</sup>, no manure applications.</li> </ul>

A major difficulty in the acceptance of a single limit approach is the scientific basis for establishment of a soil test phosphorus level that represents a water hazard. The database relating soil test phosphorus to phosphorus in runoff is limited to a few soils and cropping systems. In addition, the risk of phosphorus loss to the water system as a function of soil test phosphorus

level varies with soil type (Sharpley 1995) and hydrologic parameters (Sharpley et al. 1999). Also, soil tests would need to be standardized to apply meaningful limits.

Because of the economic implications brought about by limiting manure applications to a given land base, industry is reluctant to accept imposition of a single limit and is vigorously challenging their scientific basis (Daniel et al. 1998). The impact of phosphorus pollution on other industries has been a factor driving regulation in some states. For example, the protection of marine-based industries, such as the shellfish industry, from the effects of phosphorus contamination in coastal estuaries was a major factor in the recent enactment of manure regulations in Virginia.

### **Phosphorus Index**

The phosphorus index was introduced by the United States Department of Agriculture (USDA) as a tool to assess the various landforms and management practices to determine a risk for phosphorus export to the water system (Lemunyon and Gilbert 1993). A ranking with the phosphorus index shows the relative risk of phosphorus movement compared to other sites. When the parameters of the index are analyzed, it will be apparent that some factors are disproportionately high. These factors can then be addressed as the basis for planning corrective soil and water management. For example, adjacent fields having similar soil test phosphorus levels but different susceptibilities to runoff and erosion, based on soils, topography, and/or land use, would have different phosphorus application strategies.

At its initiation, the phosphorus index was in a simplified form, using a limited number of landform characteristics that required readily-available field data. It was intended to evolve into a more complex form in which a computer model would relate landform characteristics to the risk of phosphorus loss from the site (Lemunyon and Gilbert 1993). The original index had eight site characteristics and five classes of phosphorus loss for each characteristic. Each characteristic and class was assigned a weighting factor. The class factor doubled for each increment in severity (Table 6)

The weighted site characteristic  $\times$  class products were summed to provide a rating for the vulnerability of the site. The higher the rating the more vulnerable the site is to significant off-site phosphorus transport. Site vulnerability ratings were divided into four categories (Table 7).

The index was intended for use by field staff who work with producers. It can reveal the degree of phosphorus loss risk from management practices on specific landforms. It can also be used by planners working at regional or watershed levels to identify high risk areas that can be targeted for priority action. The index can also be used to assess the relative impact of conservation practices on a number of sites.

Stevens et al. (1993) found that the phosphorus index was very sensitive to fertilizer phosphorus application rates and methods, but not sensitive enough to differentiate sites based on site factors controlling erosion and runoff. Beyond this there has been very little field validation of the phosphorus index, with individual states proceeding on their own to validate it. Heathwaite

(1997) argued that a phosphorus index does not take into account watershed catchment characteristics, notably hydrologic parameters and the nature of the drainage network, and cautioned that care should be taken that it is used to identify and prioritize sensitive sites within a watershed rather than as a watershed assessment tool.

**Table 6.** Phosphorus (P) index, initial version (adapted from Lemunyon and Gilbert 1993).

Site characteristic (weight)	Phosphorus loss rating (Value)				
	None (0)	Low (1)	Medium (2)	High (4)	Very high (8)
Soil erosion (1.5)	Not applicable	< 11.2 Mg ha <sup>-1</sup>	11.2-22.4 Mg ha <sup>-1</sup>	22.4-33.6 Mg ha <sup>-1</sup>	> 33.6 Mg ha <sup>-1</sup>
Irrigation erosion (1.5)	Not applicable	Tailwater recovery or QS < 6 for very erodible soils or QS < 10 for other soils	QS > 10 for erosion resistant soils	QS > 10 for erodible soils	QS > 6 for very erodible soils
Runoff class (0.5)	Negligible	Very low or Low	Medium	High	Very high
Soil P test (1.0)	Not applicable	Low	Medium	High	Excessive
P fertilizer application rate (0.75)	None applied	1.1-33.6 P <sub>2</sub> O <sub>5</sub> kg ha <sup>-1</sup>	34.7-101 P <sub>2</sub> O <sub>5</sub> kg ha <sup>-1</sup>	102-168 P <sub>2</sub> O <sub>5</sub> kg ha <sup>-1</sup>	> 168 P <sub>2</sub> O <sub>5</sub> kg ha <sup>-1</sup>
P fertilizer application method (0.5)	None applied	Placed with planter deeper than 5.08 cm	Incorporated immediately before crop	Incorporated > 3 months before crop or surface applied < 3 months before crop	Surface applied > 3 months before crop
Organic P source application rate (1.0)	None applied	1.1-33.6 P <sub>2</sub> O <sub>5</sub> kg ha <sup>-1</sup>	34.7-67.2 P <sub>2</sub> O <sub>5</sub> kg ha <sup>-1</sup>	68.3-101 P <sub>2</sub> O <sub>5</sub> kg ha <sup>-1</sup>	> 101 P <sub>2</sub> O <sub>5</sub> kg ha <sup>-1</sup>
Organic P source application method (1.0)	None	Injected deeper than 5.08	Incorporated immediately before crop	Incorporated > 3 months before crop or surface applied < 3 months before crop	Surface applied to pasture, or > 3 months before crop

**Table 7.** Phosphorus index, site vulnerability ratings (adapted from Lemunyon and Gilbert 1993).

Rating from total of weighted products	Site vulnerability category
< 8	low
8-14	medium
15-32	high
> 32	very high

Sharpley et al. (1999) modified the phosphorus index to apply to a watershed scale. They separated source factors (fertilizer and organic applications) and transport factors (runoff and erosion) for site vulnerability classification within a watershed (Tables 8 and 9). To better represent the relationship of surface runoff and soil phosphorus, as well as the potential for surface runoff to contribute to stream flow, they multiplied the transport factors, and multiplied the final transport and source characteristics for a site. Under this method, the transport and source factors must coincide to identify a site as highly vulnerable to phosphorus loss. In the original index, a site could be identified as highly vulnerable to runoff based on high source factors alone, even if no runoff occurred.

Sharpley et al. (1999) used two site assessment indices, the modified phosphorus index coupled with an nitrogen index, to assess watersheds for nutrient management sensitivity. The structure of the nitrogen index and site vulnerability classification (Tables 10 and 11) was derived from the phosphorus index, and the principles of nitrogen leaching described in Kissel et al. (1982). An overall site vulnerability rating (Table 12) was derived by coupling the modified phosphorus index and the nitrogen index.

**Table 8.** Modified phosphorus (P) index (adapted from Sharpley et al. 1999).

Factors (weight)	<i>Phosphorus transport potential (Value)</i>				
	None (0.6)	Low (0.7)	Medium (0.8)	High (0.9)	Very high (1.0)
Soil Erosion <sup>z</sup>	Negligible	< 10	10 – 20	20 - 30	> 30
Irrigation erosion (1.0)	Negligible	Infrequent irrigation on well- drained soils	Moderate irrigation on soils with slopes <5%	Frequent irrigation on soils with slopes of 2 to 5%	Frequent irrigation on soil with slopes >5%
Runoff Class (1.0)	Negligible	Very low or low	Medium	High	Very high
Contributing distance, m (1.0)	None (0.2)	Low (0.4)	Medium (0.6)	High (0.8)	Very high (1.0)
	>170	170 - 130	130 - 180	80 - 30	<30
Factors (weight)	<i>Phosphorus source potential (Value)</i>				
	None	Low (1)	Medium (2)	High (4)	Very high (8)
Soil test P (1.0) <sup>y</sup>	<10	30-Oct	30 - 100	100 - 200	>200
Fertilizer P rate (0.75)	None	1 - 15	16 - 45	46 - 75	>75
Application method for fertilizer (0.5)	None	Placed with planter or injected deeper than 5 cm	Incorporated immediately before crop	Incorporated >3 months or surface applied <3 months before crop	Surface applied >3 months before crop
Organic P rate (1.0) <sup>x</sup>	None	1 - 15	16 - 30	30 - 45	>45
Application method for organic source (1.0)	None	Placed with planter or injected deeper than 5 cm	Incorporated immediately before crop	Incorporated >3 months or surface applied <3 months before crop	Surface applied >3 months before crop

<sup>z</sup>Units for soil erosion are Mg ha<sup>-1</sup>.

<sup>y</sup>Units for Mehlich-3 soil P are mg kg<sup>-1</sup>.

<sup>x</sup>Units for P application are kg ha<sup>-1</sup>.

**Table 9.** Site vulnerability based on the modified P index (adapted from Sharpley et al. 1999).

Site vulnerability	Total phosphorus index rating value <sup>z</sup>
low	< 5
medium	5 – 9
high	10 – 22
very high	> 22

<sup>z</sup> Phosphorus index rating = (erosion × runoff × return period) × Σ (source characteristic × weight).

**Table 10.** Nitrogen (N) index (adapted from Sharpley et al. 1999).

Factors	<i>Leaching potential from transport factors (Value)</i>				
	None	Low (1)	Medium (2)	High (4)	Very high (8)
Texture	Clay	Clay loam to silty clay loam	Loam to silt loam	Loamy fine sand to coarse sandy loam	Sand
Permeability <sup>z</sup>	<1.5	1.6 - 4	4.1 - 14.9	15 - 50	>50

Factors	<i>Leaching potential from source factors (Value)</i>				
	None	Low (1)	Medium (2)	High (4)	Very high (8)
Fertilizer N <sup>y</sup>	None	1 - 50	51 - 150	151 - 300	>300
Application method for fertilizer	None	Placed with planting	Incorporated immediately before crop	Surface applied >3 months before crop or incorporated <3 months before crop	Incorporated >3 months before crop
Manure N <sup>y</sup>	None	1 - 50	51 - 150	151 - 300	>300
Application method for manure	None	Placed with planting	Incorporated immediately before crop	Surface applied >3 months before or incorporated <3 months before crop	Incorporated >3 months before crop

<sup>z</sup> Units for permeability are cm hr<sup>-1</sup>.

<sup>y</sup> Units for N application are kg ha<sup>-1</sup>.

**Table 11.** Site vulnerability based on the nitrogen index (adapted from Sharpley et al. 1999).

Site vulnerability	Total nitrogen index rating value <sup>z</sup>
low	< 3
medium	3 – 8
high	9 – 18
very high	> 18

<sup>z</sup> Nitrogen index rating = (texture rating × permeability rating) × Σ(source characteristic rating × weight).

**Table 12.** Site vulnerability rating, based on the coupled phosphorus (P) index and nitrogen index (adapted from Sharpley et al. 1999).

Index rating		Generalized interpretation of the phosphorus index
Phosphorus	Nitrogen	
<5	< 3	<b>Low</b> potential for P loss. If the current farming practices are maintained there is a low probability of adverse impacts on surface waters.
5 – 8	4 – 8	<b>Medium</b> potential for P loss. The chance for adverse impacts on surface waters exists and some remediation should be taken to minimize the probability of P loss.
9 - 22	9 – 18	<b>High</b> potential for P loss and adverse impacts on surface waters. Soil and water conservation measures and nutrient management plans are needed to minimize the probability of P loss.
> 22	> 18	<b>Very high</b> potential for P loss and adverse impacts on surface waters. All necessary soil and water conservation measures and nutrient management plans must be implemented to minimize the probability of P loss.

Sites were selected within a watershed, and soil samples were taken on a 30-m grid to determine soil phosphorus levels. Transport factors were derived from soil survey data, and source factors were determined from farmer surveys in the watershed. The nitrogen and phosphorus indices were then applied at a 5-m cell scale and integrated over the entire watershed. The result was a sensitivity map of the watershed for nitrogen and another map for phosphorus based on the criteria in Tables 9 and 11.

Sharpley et al. (1999) demonstrated that the modified indices provided greater flexibility in managing sites within a watershed. In the test watershed, use of a single limit of 200 mg kg<sup>-1</sup> would have resulted in 33% of the watershed (67% of the cultivated land) being ineligible for further manure application. With their index approach, only 1% of the watershed presented a high risk to phosphorus loss from manure application.

### Percent Saturation Approach

Sibbsen and Sharpley (1997) presented an approach to phosphorus management used in the Netherlands based on soil phosphorus-saturation characteristics. The Netherlands has a national strategy to limit phosphorus entry into surface water and groundwater. One of the ways to attain this goal has been to identify a soil phosphorus level above which phosphorus inputs must be matched by crop removal. Rather than a single limit for all soils based on soil test phosphorus, the limit is based on the relationship between soil phosphorus level and the potential for dissolved phosphorus (P<sub>d</sub>) to enter the water system. Specifically, as the amount of phosphorus

sorbed to soil components increases,  $P_d$  concentration increases. An index for the soil phosphorus, called sorption-saturation, is calculated as the percent of  $P_d$  extracted from the soil relative to the phosphorus sorption capacity. The index is relatively independent of soil type. In the Netherlands a sorption-saturation value of 25% has been established as the critical limit, above which phosphorus concentrations in leachate and runoff become unacceptable.

Sharpley (1995) measured the relationship of soil test phosphorus (Mehlich-3) to  $P_d$  concentrations in runoff for ten soils ranging from coarse to fine texture. Comparing the soil test phosphorus to  $P_d$  concentration revealed no consistent relationship from one soil to another. A  $200 \text{ mg kg}^{-1}$  soil test level corresponded to a  $P_d$  concentration of  $0.28 \text{ mg L}^{-1}$  in one soil and  $1.36 \text{ mg L}^{-1}$  in another. When the sorption saturation for each soil was calculated, a clear relationship describing  $P_d$  as a function of sorption saturation emerged.

Once calibrated for a specific soil test, the phosphorus sorption-saturation approach has the potential to describe the capability for wide range of soils to release phosphorus into the water system. It also offers an advantage in indicating how close a soil is to being an environmental risk from phosphorus loading. For example, soils with sorption-saturation levels near a critical limit (e.g., 25%) should not receive phosphorus inputs, whereas those with lower sorption-saturation levels could receive more phosphorus inputs. Therefore, the approach becomes a sliding scale for phosphorus inputs based on the soils capability to release phosphorus into the water system.

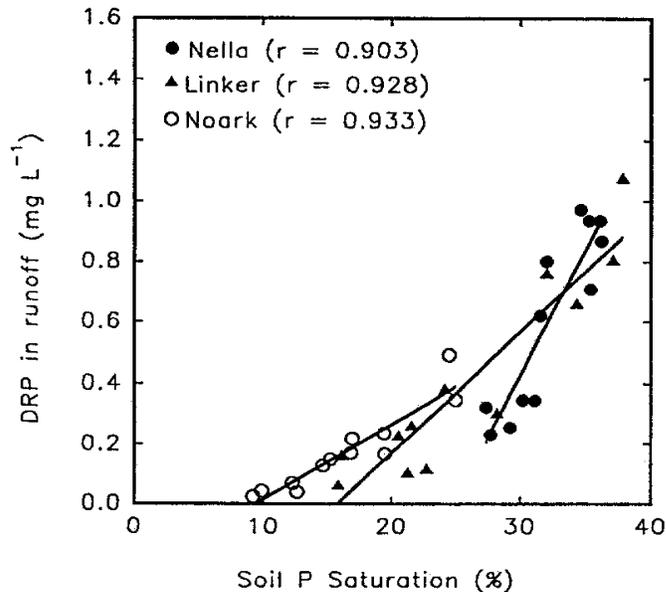
Prediction of phosphorus movement into water systems should not rely on soil factors alone, however. Pote et al. (1999) tested the percent saturation approach to predict phosphorus concentrations in runoff in field plots. The relationship between percent saturation and  $P_d$  concentrations in runoff within a soil series was highly correlated, but it was not consistent across different soil series (Fig. 7). The variability in runoff volumes on some soil series accounted for much of the inconsistency.

## **Nutrient Management Planning**

Nutrient management planning is being used by every state in the United States with noteworthy programs in Maryland, Pennsylvania, and Wisconsin (Daniel et al. 1997). It offers advantages by being a means of cutting costs and preserving water quality without jeopardizing yields, and is generally thought to present a win-win situation to animal feeding operations (AFOs) and the public. The United States Draft National Strategy for AFOs (USDA/USEPA 1998) proposes setting a national performance expectation that all AFOs develop a technically sound and economically stable comprehensive nutrient management plan (CMNP) for their operation.

The technical components and details of nutrient management planning will be site specific, and therefore, vary from one location to another; however, there are fundamental components that should be common to all planning. The most fundamental component is the concept that the farm planning is based on a nutrient budget, where there is a storage of nutrients on the farm in livestock, crops, and soil. Nutrients are imported into the farm in various forms including

fertilizer, feed, and even atmospheric (through fixation of nitrogen). Forms of nutrients leaving the farm include livestock and livestock products (e.g., milk and eggs), crops, manure, and crop residues. Nutrients can also leave the farm by volatilization to the atmosphere, erosion, runoff, and leaching. The goal is to balance nutrient inputs and outputs to keep soil storage levels and outputs through volatilization, erosion, runoff, and leaching to target levels that are safe to the environment. Daniel et al. (1997) breaks the components into two sets: institutional and technical.



**Fig. 7.** Relationship between phosphorus (P) saturation (oxalate method) of surface soil and dissolved reactive phosphorus (DRP) in runoff in three Ultisols (adapted from Pote et al. 1999).

Institutional components are those directed at planning, education, and infrastructure developments that ensure an effective result. An example is that in areas with intense AFO activity, management of large manure volumes may be improved by more effective transportation systems. From a planning perspective, institutional approaches are needed to manage watersheds; set water quality goals; inform the public; integrate the variety of agencies, industries, and institutions that are stakeholders in the watershed; and develop approaches to prioritize those watersheds in most need of nutrient management planning. An example is the Wisconsin priority watershed program, which focuses a limited supply of resources where they can get the most results. Nutrient management plans are being developed by the private sector and are reimbursed at no cost to the landowner.

Institutional components also include a way of ensuring compliance from AFOs. This could involve development of monitoring and enforcement strategies. For example, Maryland has a program to assist farmers with construction of manure management facilities. To qualify, the farm must have a CNMP in place.

When developing plans, the institutional framework should include ways of integrating private sector and public sector activities. Generally the private sector has advantages in doing the planning, given the proper direction and supervision. The public sector should retain the role of determining who can do the planning (e.g., through licensing or accreditation) and which plans are sound.

The technical components recommended by Daniel et al. (1997) to be incorporated into nutrient management planning include quantity of manure produced, nutrient content of the manure, and nutrient availability. Nutrient availability is tied to land application practices and has potential to offset some fertilizer costs. Good application practices can result in more nutrients available for cropping in the following year or two. Other technical components include soil testing for nitrogen and phosphorus, identification and avoidance of environmentally sensitive areas, setting realistic yield goals, and timing of manure application.

The CNMPs proposed by the United States National Strategy for AFOs must meet clearly defined nutrient management goals and identify the measures and schedules for attaining these goals (USDA/USEPA 1998). They should be site specific and written to meet the needs of the AFO owner and/or operator and conditions of the farm. They should address, at a minimum, feed management, manure handling and storage, land application of manure, land management, record keeping, and management of other manure utilization options. The other options would apply to cases such as vulnerable watersheds, and include composting, sale, and use of manure for power generation. Plans should also address other potential pollutants such as pathogens. Plans should also be periodically reviewed and revised in cases where expansion is planned, or changes in manure management or in the AFO operation are considered. Development of the CNMP will be the responsibility of the operator, with assistance as needed from certified industry staff, government specialists, private consultants, and other qualified vendors. The recommended primary technical reference is the National Resource Conservation Service (NRCS) Field Office Technical Guide.

The National Strategy proposes using voluntary programs as the principal means of implementation. The implementation strategy would focus on locally-led conservation efforts, environmental education, and technical and financial assistance. The AFOs would need to implement CNMPs before qualifying for financial assistance.

## FACTORS INFLUENCING THE ALBERTA SITUATION

Alberta lakes, streams, and rivers differ from water bodies found elsewhere in Canada or the United States. Climate, landscape (including soils, topography, and ground cover), hydrology, and the inherent water chemistry influence the complex and dynamic freshwater systems in Alberta. Many lakes and other surface water bodies in Alberta are naturally highly productive (or eutrophic) and experience prolific phytoplankton (algae) and macrophyte (plant) growth. Consequently, surface waters in Alberta are extremely sensitive to further phosphorus enrichment either by internal or external sources. Further nutrient enrichment of surface waters in Alberta can have significant economic and environmental implications on public and animal health, the recreation and tourism industries as well as detrimental effects to aquatic life. Careful phosphorus management on the landscape is critical to maintain or improve water quality in Alberta.

### Industrial Development and Expansion

Lamb-Weston, which has recently constructed a \$100-million potato processing plant near Taber, Alberta, has requested soil phosphorus loading guidelines to assess land area requirements for irrigating with wastewater effluent. McCain's is building a similar plant in the region and plan to use the effluent for irrigation. Several other industries in Lethbridge have also approached Alberta Agriculture, Food and Rural Development for phosphorus loading guidelines.

Alberta Environment, in response to industry pressure, is looking to Alberta Agriculture, Food and Rural Development for leadership in establishing safe phosphorus levels. As a temporary working solution, a 200 mg kg<sup>-1</sup> upper limit for phosphorus in the top 15 cm of the soil was proposed. Lamb-Weston has accepted this value, and developed its wastewater irrigation system accordingly. The other processing industries are also expected to accept this value.

There is an opportunity for the agri-food sector in Alberta to grow to \$20 billion in value-added shipments and \$10 billion in farm cash receipts by the year 2005 (Alberta Agriculture, Food and Rural Development 1999b). Development and expansion of intensive livestock operations and food processing companies will be a key factor in the growth of the agri-food sector. Without clear guidelines regarding maximum soil loading of nutrients such as nitrogen and phosphorus, producers must guess at the land base required for their operations. Governments who make decisions on processing and intensive livestock operation (ILO) development applications, also need consistent guidelines on which to base their decisions. The Livestock Regulatory Stakeholder Advisory Group (LRSAG), which developed the regulation of the intensive livestock industry in Alberta has accepted nitrogen-based guidelines for manure application, but has recognized that phosphorus-based standards for manure application will be needed in the near-future. The Expert Technical Committee, which was commissioned by the LRSAG to develop the industry operating standards as part of the regulatory process, has requested that phosphorus-based standards for manure application be developed by the year 2001.

## **Municipal Waste Disposal**

Municipal wastewater that is not discharged into water is applied to land. Guidelines for application of municipal wastewater have been developed by Alberta Environmental Protection (Alberta Environmental Protection 1997c). Draft guidelines have been developed specifically for the irrigation method of disposing municipal wastewater (Alberta Environmental Protection, 1997a). These draft guidelines will replace previous guidelines prepared in 1984 (Alberta Environmental Protection 1984). Similar approaches are used as required for natural irrigation water such as determining the suitability of the wastewater and land for irrigation. The major difference between municipal wastewater and high quality irrigation water is that wastewater has higher concentrations of living and nonliving organic material, nitrogen, phosphorus, and in some cases, higher concentrations of sodium (Na) and salts. Low concentrations of grease, oil, detergents, and certain metals may also be present, but these are generally at concentrations that do not adversely impact crops or land if applied by irrigation methods (Alberta Environmental Protection 1997a). Typical phosphorus, nitrogen, and potassium contents of municipal wastewater can range from 2 to 6, 10 to 20, and 4 to 40 mg L<sup>-1</sup>, respectively (Alberta Environmental Protection 1997a). If the nutrient content of a wastewater sample was assumed to be 4 mg L<sup>-1</sup> phosphorus, 15 mg L<sup>-1</sup> nitrogen, and 22 mg L<sup>-1</sup> potassium, then an application of 15 cm of wastewater would deliver 6 kg ha<sup>-1</sup> of phosphorus, 22.5 kg ha<sup>-1</sup> of nitrogen, and 33 kg ha<sup>-1</sup> of potassium. A large amount of wastewater would be required to deliver a substantial amount of phosphorus, based on these values.

Specific draft guidelines have also been developed for the application of municipal biosolids to agricultural land (Alberta Environmental Protection 1997b). These guidelines will replace previous guidelines developed in 1982 (Alberta Environmental Protection 1997b). As mentioned on page 6, there are several methods used to dispose of municipal biosolids. However, there are major programs in Alberta that use the land application method, such as the City of Edmonton's Nutri-Gold program and the City of Calgary's CALGRO program. Both programs solicit the farming community for land that could be used to receive biosolids. The CALGRO program has been operating since 1983. The biosolid material is injected by CALGRO at a rate of 14 Mg ha<sup>-1</sup> on a dry-weight basis. The biosolid material contains about 4% phosphorus, 5.5 % nitrogen, 0.35% potassium, on a dry-weight basis, and about 10% solid material (Barl and McKenzie 1995). At this rate, about 560 kg ha<sup>-1</sup> of phosphorus, 770 kg ha<sup>-1</sup> of nitrogen, and 49 kg ha<sup>-1</sup> potassium would be applied. The phosphorus and nitrogen rates are certainly well above the nutrient requirements of any crops. The CALGRO program applied an average of 18,950 Mg (dry-weight basis) of biosolids onto 1,400 ha of farm land each year from 1984 to 1992 (Barl and McKenzie 1995). Biosolid material was applied only on the same parcel of land once every 3 yr, provided the land continued to meet the application criteria.

## **Food Processing Wastewater Disposal**

Guidelines were developed by Alberta Environmental Protection for the approval of land treatment facilities for the treatment of industrial wastes including food processing wastes (Alberta Environment 1988). The approval of land treatment facilities was under the provisions of the Clean Water Act, which was consolidated with other acts in the Environmental Protection

and Enhancement Act in 1993.

The nutrient content of wastewater processing plants tends to be higher than for municipal wastewater. Barl and McKenzie (1995) reported 42 to 72 mg L<sup>-1</sup> total phosphorus, 75 to 211 mg L<sup>-1</sup> total nitrogen, 466 to 707 mg L<sup>-1</sup> total potassium for wastewater from a potato processing plant. If the nutrient content of a wastewater sample was assumed to be 55 mg L<sup>-1</sup> phosphorus, 150 mg L<sup>-1</sup> nitrogen, and 580 mg L<sup>-1</sup> potassium, then an application of 15 cm of wastewater would deliver 82.5 kg ha<sup>-1</sup> of phosphorus, 225 kg ha<sup>-1</sup> of nitrogen, and 870 kg ha<sup>-1</sup> of potassium. The amount of food processing wastewater required to meet nutrient requirements of crops would be less than for municipal wastewater.

### **Manure Disposal on Land**

In Alberta, studies of soils that have received manure at rates of 34 Mg ha<sup>-1</sup> or higher for more than 15 yr are showing very high phosphorus levels in the upper soil profile (top 15 cm). In the County of Lethbridge, Alberta, soil test phosphorus levels in the top 15 cm of manured soils are typically 100 to 400 mg kg<sup>-1</sup> but some soil phosphorus levels in excess of 675 mg kg<sup>-1</sup>, which is equal to 6370 kg ha<sup>-1</sup> of 11-51-0 fertilizer, have been measured in the area.

Current manure application guidelines in Alberta use nitrogen as the basis for nutrient loading. Implementing maximum loading levels based on phosphorus would have complications. There has been considerable experience in relating nitrogen-based applications to crop requirements. In southern Alberta, nitrogen availability has been based on a decay series by Pratt et al. (1973). This series estimates the available nitrogen as 35, 15, 10, 7.5, 5 and 4% of the total residual nitrogen in the first, second, third, fourth, fifth, and sixth years following application. Little is known about how much phosphorus would be available for crop use in a given year from manure application, and estimates have varied from 25 to 50%. Since not all of the phosphorus would be available immediately, application based on the total phosphorus content in the manure would potentially result in insufficient phosphorus being available for the crop. Application rates based on available phosphorus would result in a continual loading of phosphorus in the soil from the residual, unavailable phosphorus. Operators could require as much as four to six times the land base that is now required for nitrogen-based manure disposal (McKenzie et al. 1999).

## OPTIONS TO ACHIEVE SAFE PHOSPHORUS LEVELS IN SOIL

The following summary of the pros and cons of the phosphorus management strategies described on pages 19 to 27 is presented for consideration when developing a land application strategy to ensure environmentally safe levels of phosphorus.

### Single Limit Approach

pros:

- Easy to implement.
- Relatively easy to monitor.
- Simplifies long-range planning.

cons:

- Does not allow for site specific variation in risk of phosphorus movement, which is controlled by site specific factors such as soil type and landform. A single limit may be too high for one site but too conservative for another
- Scientific validation has been challenged .
- Dependent on soil test methods that are not standardized.

### Phosphorus Index

pros:

- Addresses the soil and landform factors controlling phosphorus movement into the water system.
- Allows sensitive areas to be identified and targeted for special management.
- Allows relative comparisons of the impact of management practices.
- Provides more flexibility than the single limit approach, and still minimizes risk.
- Provides extension opportunities that would assist producers and land managers.

cons:

- Needs to be fully developed as a tool.
- Weighting factors are best estimates.
- Little field validation information available.
- Field evaluations are more complex than the single limit or percent saturation approach.

### Percent Saturation Approach

pros:

- Strong correlation with soil type.
- Independent of soil test procedure.

- Potential to apply to a wide range of soil types and existing soil phosphorus levels.

cons:

- Limited information or research available.
- Limited information on saturation capacity for Alberta soils.
- Does not address landform or hydrologic issues.

## **Nutrient Management Planning**

pros:

- Flexible, addresses a wide range of options for nutrient management and not tied to land application alone.
- Not specific to any one nutrient, looks at the whole farm and feeding operation.
- Can apply to wide variety of agricultural operations, including animal feeding, food processing, and cropping.
- Has been tried by some American states.

cons:

- Complex and needs considerable information for planning; however, the principles are similar to those used for commercial fertilizer management.
- Feasibility of an operation attaining a nutrient balance is in question.
- Requires standards for nutrient loading. In areas where inputs are exceeding crop uptake, considerable time may be needed to arrive at a balanced nutrient management practice? Some form of phosphorus limit may be necessary as an interim measure, while land managers adopt this approach.
- Monitoring would be expensive.

There is a growing consensus that the water quality problems now facing society can best be solved using a whole-watershed approach (Daniel et al. 1998). Watershed assessment and management generally requires a combination of water quality monitoring, spatial data collection, and modelling. The accuracy will depend on good experimental results that can be used for model validation, and reliable regional data on the factors governing phosphorus transport. The key data identified by Daniel et al. (1998) were land use and management practices, soil texture, and topography. Additional factors were identified by Cassell et al. (1998) as industrial activity, population, and municipal waste technologies. Climate and hydrological factors play an important role. For example, phosphorus transport varies widely with individual storm events (Xue et al. 1998), and runoff can be variable even within a soil series (Pote et al. 1999). Methods that include assessment and integration of these factors, based on science wherever possible, are more likely to achieve the desired goals when applied in the field.

Nutrient management planning has been proposed by the United States Draft National Strategy for AFOs (USDA/USEPA 1998) as the way for AFO's to preserve water quality.

Because it considers all nutrients, it can apply to all products applied to land, not just manure. It therefore has advantages in planning for food processing and municipal waste application, where phosphorus may not always be the nutrient of concern. Balanced nutrient management appears to be the only way to minimize the risk of excess nutrients in the soil or water, and therefore should be a long-range goal for Alberta.

The phosphorus index approach links landscape conditions, climate, management, and soil factors at a site specific scale. It is a practical method that can provide a high degree of flexibility for operators, while minimizing risk to the environment. Because it provides the opportunity to work with producers and operators, it also has value as a tech-transfer tool. To address the immediate issue of controlling phosphorus to minimize water pollution risk, a site specific approach, such as the phosphorus index, should be developed. The approach should be designed to be integrated into a watershed-scale assessment.

## CONCLUSIONS

An increasing amount of research has identified phosphorus pollution, from agricultural and non-agricultural sources, as a major threat to water quality. The Canada-Alberta Environmentally Sustainable Agriculture Agreement (CAESA) water quality assessment showed that phosphorus runoff from agricultural lands in Alberta is an issue that must be addressed. There is growing pressure to establish a strategy to manage phosphorus concentrations in the soil profile to minimize the movement of phosphorus into surface water resources.

Concerns about the contribution of agricultural operations to nutrient loading of water bodies in Alberta has arisen as the industry has intensified. The CAESA water quality assessment showed that nitrogen and phosphorus often exceeded water quality guidelines for protection of aquatic life in streams in high and moderately intensive agriculture areas. In addition, phosphorus also often exceeded water quality guidelines for protection of aquatic life in small lakes and irrigation canals in high intensity areas.

Alberta lakes, streams, and rivers differ from water bodies found elsewhere in Canada or the United States. Many lakes and surface water bodies in Alberta are naturally highly productive (or eutrophic) and experience prolific growths of phytoplankton (algae) and macrophyte (weed). Phosphorus is the primary plant nutrient controlling the level of phytoplankton growth in western Canadian lakes. Consequently, surface waters in Alberta are extremely sensitive to further phosphorus enrichment either by internal or external sources.

The effects of phosphorus enrichment in aquatic systems in Alberta are complex. Eutrophication, has many negative effects on aquatic ecosystems that include killing of sport fish and other desirable aquatic species, increased water treatment problems, and decreased clarity and odour. These can have negative impacts on the recreation and tourism industry. Eutrophication also results in periodic massive growths of cyanobacteria, which poison water to the extent that it can kill livestock. Therefore, further nutrient enrichment of surface waters in Alberta can have significant economic and environmental implications on public and animal health, recreation, tourism, and possibly even the agriculture industry.

The risk of phosphorus export from land to water increases as phosphorus loading of soil increases. There are clear relationships showing that the concentration of dissolved phosphorus in runoff and leaching increases with higher soil test phosphorus levels. Dissolved phosphorus concentrations can exceed Alberta Environment guidelines for runoff at soil test phosphorus levels that would be common for many agricultural soils.

Agriculture is not the only contributor. The City of Calgary has applied municipal biosolids to land at rates of over 500 kg ha<sup>-1</sup> of phosphorus. Even though application on the same piece of land was restricted to once every 3 yr, the rates were still well above crop requirements.

The only practical way to reduce high phosphorus levels in soils is through crop uptake. The rate of decline varies with soil type, crop type, and management practices. Research results show that in the Northern Great Plains, the rate of decline of soil phosphorus ranges from 0.6 to 30 mg

$\text{kg}^{-1} \text{yr}^{-1}$ . Soils in the County of Lethbridge that have undergone repeated heavy manure applications can typically have soil test phosphorus levels high enough that several decades could be needed to reduce phosphorus levels to moderate values.

There is currently enough scientific evidence to support development of a phosphorus management strategy in Alberta. Additional site specific information on phosphorus behavior in the landscape would greatly enhance the relevance of any strategy, however. Any phosphorus strategy must consider not only the current level of phosphorus in the soil, but also the site specific-nature of the soil, the type of management, and the hydrologic factors associated with it.

Water quality is a complex issue of which agriculture is only one factor. Eutrophication is only one threat to water quality. While phosphorus may be the key factor in managing eutrophication, it is difficult to treat in isolation, especially when animal and organic wastes contain a variety of nutrients in forms that themselves have a range of complexities. Also while the application of manure and food processing wastes on to crop land are at the centre of the issue, water quality can be at risk from the nutrient load in other crop land as well. In considering a strategy for managing land application of manure, food processing effluent, and organic agricultural material, it should be part of larger overall strategy to address the broader issues of water quality.

A desirable long-range goal is to achieve a balanced nutrient management approach; however, the factors needed to successfully implement this in Alberta must be defined. A timeline for change, and identification of interim steps and possible infrastructure support will be key components in the strategy. The United States is moving toward a comprehensive nutrient management planning approach to agricultural production and many states have started to address phosphorus loading. We have their experience to learn from as well.

The process to regulate the intensive livestock industry, and the expansion of the food processing industry in Alberta have accelerated the need to develop phosphorus-based standards for Alberta. Standards or guidelines would allow intensive livestock operations, food processing, and other industries to plan future development and land application strategies in a manner that will protect water quality. The phosphorus index is a practical method that will provide the most flexibility for operators, while minimizing risk to the environment. It addresses the site specific factors that research has identified as critical to the accurate prediction of phosphorus export. A site specific approach, such as the phosphorus index, that can be integrated into a watershed-scale assessment, appears to be the most suitable way to develop phosphorus-based standards for Alberta.

## REFERENCES

- Alberta Agriculture, Food and Rural Development. 1999a.** Addendum to the Code of Practice for the Safe and Economic Handling of Animal Manures. Alberta Agriculture, Food and Rural Development, Edmonton, Alberta. 21 pages.
- Alberta Agriculture, Food and Rural Development. 1999b.** Ministry Business Plan 1999/2000 to 2001/2002. Alberta Agriculture, Food and Rural Development, Edmonton, Alberta.
- Alberta Environment. 1988.** Guidelines for the land treatment of industrial wastes. Environmental Protection Services, Alberta Environment.
- Alberta Environmental Protection. (date unknown).** Guidelines for the approval and design of natural and constructed treatment wetlands for water quality improvement.
- Alberta Environmental Protection. 1984.** A practical guide to municipal wastewater irrigation - discussions and guidelines.
- Alberta Environmental Protection. 1997a.** Guidelines for municipal wastewater irrigation (draft). Standards and Guidelines Branch, AEP. 22 pages.
- Alberta Environmental Protection. 1997b.** Guidelines for the application of municipal wastewater sludges to agricultural lands (draft). Standards and Guidelines Branch, AEP. 29 pages.
- Alberta Environmental Protection. 1997c.** Standards and guidelines for municipal waterworks, wastewater, and storm drainage systems. Standards and Guidelines Branch, EP. 358 pages.
- Alberta Environmental Protection and City of Red Deer. 1981.** Rapid infiltration - a design manual.
- Anderson, A.-M., D.O. Trew, R.D. Neilson, N.D. MacAlpine, and R. Borg. 1998.** Impacts of agriculture on surface water quality in Alberta. Part I: Haynes Creek Study. Alberta Environmental Protection, Edmonton, Alberta.
- Barber, S.A. 1984.** Soil Nutrient Bioavailability. Wiley-Interscience, John Wiley and Sons, New York.
- Barl, B. and R.C. McKenzie. 1995.** Potato processing liquid effluent feasibility study of sustainable disposal alternatives. Alberta Agriculture, Food and Rural Development, Brooks, Alberta. CAESA Research Program project no. RES-044-93. 84 pages.
- Bowman, R.A. 1988.** A rapid method to determine total phosphorus in soils. *Soil Sci. Soc. Am. J.* **52**:1301-1304.
- Brookes, P.C., G. Heckrath, J. DeSmet, G. Hofman, and J. Vanderdeelen. 1997.** Losses of phosphorus in drainage water. Pages 253-272 *in* Phosphorus Loss from Soil to Water, H. Tunney, O.C Carton, P.C. Brookes and A.E. Johnston (eds.). CAB International, New York.
- Brookes, P.C., D.S. Powlson, and D.S. Jenkinson. 1984.** Phosphorus in the soil microbial biomass. *Soil Biol. Biochem.* **16**:169-175.
- Canada-Alberta Environmentally Sustainable Agriculture Agreement. 1998.** Agricultural impacts on water quality in Alberta: An initial assessment. Alberta Agriculture, Food and Rural Development. Edmonton, Alberta. 95 pages.
- Cassell E.A., J.M. Dorioz, R.L.Kort, J.P. Hoffman, D.W. Meals, D. Kirschtel, and D.C. Braun. 1998.** Modelling phosphorus dynamics in ecosystems: Mass balance and dynamic simulation approaches. *J. Environ. Qual.* **27**:293-298.
- Chang, C., H.H. Janzen, and T. Entz. 1994.** Long term manure application effects on nutrient uptake by barley. *Can. J. Plant Sci.* **74**:327-330.

- Chauhan, B.S., J.W.B. Stewart, and E.A. Paul. 1981.** Effects of labile inorganic phosphate status and organic carbon additions on the microbial uptake of phosphorus in soils. *Can J. Soil Sci.* **61**:373-386.
- Coale, F.J. 1998.** Sample collection, handling, preparation and storage. *In Methods of Analysis for Soils Sediments, Residuals, and Waters.* Draft. G.M. Pierzynski (ed.). USDA-CSREES Regional Comm. SERA-IEG 17. Southern Cooperative Series Bull. TBA.
- Cooke, S.E. and E.E. Prepas. 1998.** Stream phosphorus and nitrogen export from agricultural and forested watersheds on the Boreal Plain. *Can. J. Fish. Aquat. Sci.* **55**:2292-2299.
- Culley, J.L.B., E.F. Bolton, and V. Bernyk. 1983.** Suspended solids and phosphorus loads from a clay soil: I. Plot studies. *J. Environ. Qual.* **12**:493-498.
- Daniel, T.C., O.T. Carton, and W.L. Magette. 1997.** Nutrient management planning. Pages 205 - 224 *in Phosphorus Loss from Soil to Water*, H. Tunney, O.C Carton, P.C. Brookes and A.E. Johnston (eds.). CAB International, New York.
- Daniel, T.C., A.N. Sharpley, and J.L. Lemunyon. 1998.** Agricultural phosphorus and eutrophication: A symposium overview. *J. Environ. Qual.* **27**:251-257.
- DeLuca, T.H. and D.K. DeLuca. 1997.** Composting for feedlot manure management and soil quality *J. Prod. Agric.* **10**:235-241.
- Dormaer, J.F. and C. Chang. 1995.** Effect of 20 annual applications of excess feedlot manure on labile soil phosphorus. *Can. J. Soil Sci.* **75**:507-512.
- Gburek, W.J. and H.B. Pionke. 1995.** Management strategies for land based disposal of animal wastes: Hydrologic implications. Pages 313-323 *in Impact of Animal Manure and the Land-Water Interface*, K. Steele (ed.). Lewis Publishers, CRC Press, Boca Raton, Florida.
- Gburek, W.J. and A.N. Sharpley. 1998.** Hydrologic controls on phosphorus loss from upland agricultural watersheds. *J. Environ. Qual.* **27**:267-277.
- Gibson, C.E. 1997.** The dynamics of phosphorus in freshwater and marine environments. Pages 119-136 *in Phosphorus Loss from Soil to Water*, H. Tunney, O.C Carton, P.C. Brookes and A.E. Johnston (eds.). CAB International, New York.
- Greenwood, D.J., T.J. Cleaver, M.K. Turner, J. Hunt, K.B. Neindorf, and S.M.H. Loquens. 1980.** Comparison of the effects of phosphate fertilizer on the yield: Phosphate content and quality of 22 different vegetable and agronomic crops. *J. Agric. Sci.* **95**:457-469.
- Hawkins, J.M.B. and D. Scholefield. 1996.** Molybdate-reactive phosphorus losses in surface and drainage waters from permanent grassland. *J. Environ. Qual.* **25**:727-732.
- Haygarth, P.M. and S.C. Jarvis. 1999.** Transfer of phosphorus from agricultural soils. *Adv. Agron.* **66**:195-249.
- Heathwaite, A.L. 1997.** Sources and pathways for phosphorus loss from agriculture. Pages 205-224 *in Phosphorus Loss from Soil to Water*, H. Tunney, O.C Carton, P.C. Brookes and A.E. Johnston (eds.). CAB International, New York.
- Heckrath, G., P.C. Brookes, P.R. Poulton, and K.W.T. Goulding. 1995.** Phosphorus leaching from soils containing different phosphorus concentrations in the Broadbalk experiment. *J. Environ. Qual.* **24**:904-910.
- Hergert, G.W., D.R. Bouldin, S.D. Klausner, and P.J. Zwerman. 1981a.** Phosphorus concentration-water flow interactions in the effluent from manured land. *J. Environ. Qual.* **10**:338-344.
- Hergert, G.W., S.D. Klausner, D.R. Bouldin, and P.J. Zwerman. 1981b.** Effects of dairy

manure on phosphorus concentrations and losses in tile effluent. *J. Environ. Qual.* **10**:345-349.

**Intensive Livestock Operations Committee. 1995.** Code of Practice for the Safe and Economic Handling of Animal Manures. AGDEX 400/27-2. Alberta Agriculture, Food and Rural Development, Edmonton, Alberta. 38 pages.

**Janzen, H.H., M.J. Clapperton, and A.M. Johnston. 1993.** Suppression of Zn and Cu uptake by phosphorus fertilization in long-term wheat rotations. Pages 42-49 *in* Report of Progress of the Sustainable Cropping Systems Research Study, R.C. Izurralde, H.H. Janzen and H.P. VanderPluym (eds.). Alberta Agricultural Research Institute, Edmonton, Alberta.

**Jensen, M.B., P.R. Jorgensen, H.C.B. Hansen, and N.E. Nielsen. 1998.** Biopore mediated subsurface transport of dissolved orthophosphate. *J. Environ. Qual.* **27**:1130-1138.

**Johnston, A.E. and P.R. Poulton. 1997.** Defining critical levels of available phosphorus for agricultural crops. Pages 441-445 *in* Phosphorus Loss from Soil to Water, H. Tunney, O.C Carton, P.C. Brookes and A.E. Johnston (eds.). CAB International, New York.

**Kissel, D.E., O.W. Bidwell, and F.J. Klentz. 1982.** Leaching classes of Kansas soils. Kansas Experimental Station Bull. No. 6641. Manhattan, Kansas.

**Kotak, B.G., S.L. Kenefick, D.L. Fritz, C.G. Rousseau, E.E. Prepas, and S.E. Hrudey. 1993.** Occurrence and toxicological evaluation of cyanobacterial toxins in Alberta lakes and farm dugouts. *Water Research* **27**:495-506.

**Kotak, B.G., E.E. Prepas, and S.E. Hrudey. 1994.** Blue green algal toxins in drinking water supplies: Research in Alberta. *Lake Line* **14**:37-40.

**Lawton, L.A. and G.A. Codd. 1991.** Cyanobacteria (blue-green algae) toxins and their significance in UK and European waters. *J. Inst. Environ. Manage.* **5**:460-465.

**Lemunyon, J.L. and R.G. Gilbert, 1993.** The concept and need for a phosphorus assessment tool. *J. Appl. Agric.* **6**:483-486.

**Lennox, S.D., R.H. Foy, R.V. Smith, and C. Jordan. 1997.** Estimating the contribution from agriculture to the phosphorus load in surface water. Pages 430-431 *in* Phosphorus Loss from Soil to Water, H. Tunney, O.C Carton, P.C. Brookes and A.E. Johnston (eds.). CAB International, New York.

**McKenzie, R.H. 1989.** Mechanisms controlling soil phosphorus dynamics in chernozemic and luvisolic soils. Ph.D. Thesis, Dept of Soil Science, University of Saskatchewan, Saskatoon, Saskatchewan. 258 pages.

**McKenzie, R.H., L. Kryzanowski, K. Cannon, E. Solberg, D. Penney, G. Coy, D. Heaney, J. Harapiuk, and N. Flore. 1995.** Field evaluation of laboratory tests for soil phosphorus. Final Report. Alberta Agricultural Research Institute Project No. 90-M230. Alberta Agriculture, Food and Rural Development, Edmonton Alberta. Pages 21-23.

**McKenzie, R.H., B.M. Olson, F.J. Larney, and J.G. Davis. 2000.** Applying manure based on either nitrogen or phosphorus content. Pages 270-275 *in* Proc. 37th Annual Alberta Soil Science Workshop, Medicine Hat, Alberta.

**Meissner, R., H. Rupp, and J. Seeger. 1997.** Threat of phosphorus leaching from intensively farmed agricultural soils in the central reaches of the River Elbe. Pages 430-431 *in* Phosphorus Loss from Soil to Water, H. Tunney, O.C Carton, P.C. Brookes and A.E. Johnston (eds.). CAB International, New York.

**Menzel, D.W. and N. Corwin. 1965.** The measurement of total phosphorus in seawater based on the liberation of organically bound fractions by persulfate oxidation. *Limnol. Oceanogr.* **10**:280-282.

- Morgan, M.A. 1997.** The behavior of soil and fertilizer phosphorus. Pages 137-150 in Phosphorus Loss from Soil to Water, H. Tunney, O.C Carton, P.C. Brookes and A.E. Johnston (eds.). CAB International, New York.
- Murphy, J.H. and J.P. Riley. 1962.** A modified single solution method for the determination of phosphorus in natural waters. *Anal. Chim. Acta.* **27**:31-36.
- Nye, P. and P.B. Tinker. 1977.** Soil Movement in the Soil-Root System. Studies in Ecology, Volume 4. Blackwell Scientific Publications, Oxford. 342 pages.
- Olsen, S.R. and L.E. Sommers. 1982.** Phosphorus. *In Methods of Soil Analysis. Part 2, 2nd Ed.* Agronomy No. 9, American Society of Agronomy, Madison, Wisconsin. 416 pages.
- Ozanne, P.G. 1980.** Phosphate nutrition in plants- a general treatise. *In The Role of Phosphorus in Agriculture*, F.E. Khasawneh, E.C. Sample and E.J. Kamprath (eds.). American Soc. Agron., Crop Sci. Soc of Am. and Soil Sci. Soc. Am., Madison, Wisconsin. 910 pages.
- Parry, R. 1998.** Agricultural phosphorus and water quality: A U.S. Environmental Protection Agency perspective. *J. Environ. Qual.* **27**:258-261.
- Pote, D.H. and T.C. Daniel. 1998.** Analyzing for total P and total dissolved P in water samples. *In Methods of Analysis for Soils Sediments, Residuals and Waters. Draft.* G.M. Pierzynski (ed.). USDA-CSREES Regional Comm. SERA-IEG 17. Southern Cooperative Series Bull. TBA.
- Pote, D.H., T.C. Daniel, D.J. Nichols, A.N. Sharpley, P.A. Moore Jr., and D.R. Edwards. 1999.** Relationship between phosphorus levels in three ultisols and phosphorus concentration in runoff. *J. Environ. Qual.* **28**:170-175.
- Pote, D.H., T.C. Daniel, A.N. Sharpley, P.A. Moore Jr., D.R. Edwards, and D.J. Nichols. 1996.** Relating extractable soil phosphorus to phosphorus losses in runoff. *Soil Sci. Am. J.* **60**:855-859.
- Pratt, P.F., F.E. Broadbent, and J.P. Martin. 1973.** Using organic wastes as nitrogen fertilizers. *California Agriculture* **27(6)**:10-13.
- Prepas, E.E. and F.H. Rigler. 1982.** Improvements in quantifying the phosphorus concentrations in lake water. *Can. J. Fish. Aquat. Sci.* **39**:822-829.
- Prepas, E.E. and D.O. Trew. 1983.** Evaluation of the phosphorus-chlorophyll relationship for lakes off the precambrian shield in Western Canada. *Can. J. Fish. Aquat. Sci.* **40**:27-35.
- Ryden, J.C., J.K Syers, and R.F. Harris. 1973.** Phosphorus in runoff and streams. *Adv. Agron.* **25**:1-45.
- Self-Davis, M.L. and P.A. Moore, 1998.** Determining water soluble phosphorus in animal manure. *In Methods of Analysis for Soils Sediments, Residuals and Waters. Draft.* G.M. Pierzynski (ed.). USDA-CSREES Regional Comm. SERA-IEG 17. Southern Cooperative Series Bull. TBA.
- Self-Davis, M.L., P.A. Moore, and B.C. Joern. 1998.** Determination of water and/or salt-extractable phosphorus. *In Methods of Analysis for Soils Sediments, Residuals and Waters. Draft.* G.M. Pierzynski (ed.). USDA-CSREES Regional Comm. SERA-IEG 17. Southern Cooperative Series Bull. TBA.
- Sharpley, A.N. 1993.** An innovative approach to estimate bioavailable phosphorus in agricultural runoff using iron oxide-impregnated paper. *J. Environ. Qual.* **22**:597-601.
- Sharpley, A.N. 1995.** Dependence of runoff phosphorus on soil phosphorus content. *J. Environ. Qual.* **24**:920-926.
- Sharpley, A.N., S.C. Chapra, R. Wedepohl, J.T. Sims, T.C. Daniel, and K.R. Reddy. 1994.** Managing agricultural phosphorus for protection of surface waters: Issues and options. *J.*

Environ. Qual. **23**:437-451.

**Sharpley, A.N., T.C. Daniel, J.T. Sims, and D.H. Pote. 1996.** Determining environmentally sound soil phosphorus levels. *J. Soil Water Conserv.* **51**:160-166.

**Sharpley, A.N., P. Kleinman, W. Gburek, and G. Folmar. 1999.** Developing and integrated nutrient management approach for land-applied manure at a watershed scale. Pages 478-488 *in* Manure Management '99; Proceedings of a Tri-provincial Conference on Manure Management. Saskatchewan Agriculture and Food, Saskatoon, Saskatchewan.

**Sharpley, A.N. and S. Reikolainen. 1997.** Phosphorus in agriculture. Pages 1-53 *in* Phosphorus Loss from Soil to Water, H. Tunney, O.C Carton, P.C. Brookes and A.E. Johnston (eds.). CAB International, New York.

**Sharpley, A.N. and S.J. Smith. 1993.** Wheat tillage and water quality in the Southern Plains. *Soil Tillage Res.* **30**:33-48.

**Sharpley, A.N., S.J. Smith, O.R. Jones, W.A. Berg, and G.A. Coleman. 1992.** The transport of bioavailable phosphorus in agricultural runoff. *J. Environ. Qual.* **20**:30-35.

**Sharpley, A.N. and J.K. Syers. 1979.** Loss of nitrogen and phosphorus in tile drainage as influenced by urea applications and grazing animals. *New Zealand J. Agric. Res.* **22**:127-131.

**Sibbsen, E. and A.N. Sharpley. 1997.** Setting and justifying upper critical limits phosphorus in soils. Pages 151-176 *in* Phosphorus Loss from Soil to Water, H. Tunney, O.C Carton, P.C. Brookes and A.E. Johnston (eds.). CAB International, New York.

**Sims, J.T., R.R. Simard, and B.C. Joern. 1998.** Phosphorus loss in agricultural drainage: Historical perspective and current research. *J. Environ. Qual.* **27**:277-293

**Sonzogni, W.C., S.C. Chapra, D.E. Armstrong, and T.J. Logan. 1982.** Bioavailability of phosphorus inputs to lakes. *J. Environ. Qual.* **11**:555-563.

**Stamm, C., H. Fluhler, R. Gachter, J. Leuenberger, and H. Wunderli. 1998.** Preferential transport of phosphorus in drained grassland soils. *J. Environ. Qual.* **27**:515-521.

**Stewart, J.W.B. and R.B. McKercher. 1982.** Phosphorus cycle. Pages 221-238 *in* Experimental Microbial Ecology, R.G. Burns and J.H. Slater (eds.). Blackwell Scientific Publications, Oxford.

**Stewart, J.W.B. and A.N. Sharpley. 1987.** Controls on dynamics of soil and fertilizer phosphorus and sulfur. Pages 101-121 *in* Soil Fertility and Organic Matter as Critical Components of Production Systems, R.F. Follert, J.W.B. Stewart and C.V. Cole (eds.). SSSA Special Pub. No. 19, American Society of Agronomy, Madison Wisconsin.

**Stevens, R.G., T.M. Sobecki and, T.L. Spofford. 1993.** Using the phosphorus assessment tool in the field. *J. Prod. Agric.* **6**:487-492.

**Syers, J.K. and D. Curtin. 1988.** Inorganic reactions controlling phosphorus cycling. Pages 17-29 *in* Phosphorus Cycles in Terrestrial and Aquatic Ecosystems, H. Tiessen (ed.). UNDP, Saskatchewan Institute of Pedology, Saskatoon, Saskatchewan.

**Tiessen, H. and J.O. Moir. 1993.** Characterization of available P by sequential extraction. Pages 75-87 *in* Soil Sampling and Methods of Analysis, M.R. Carter (ed.). Canadian Soc. of Soil Science. Lewis Publishers, Boca Raton, Florida.

**Tinker, P.B. 1980.** Role of rhizosphere microorganisms in phosphorus uptake by plants. *In* The Role of Phosphorus in Agriculture, F.E. Khasawneh, E.C. Sample and E.J. Kamprath (eds.). American Soc. of Agron., Crop Sci. Soc. of Am. and Soil Sci. Soc. Am., Madison, Wisconsin. 910 pages.

**Tisdale, S.L., W.L. Nelson, and J.D. Beaton. 1985.** Soil fertility and fertilizers. Chapter 6. McMillan Publishing Co. New York. 755 pages.

- Uhlmann, D. and E. Albrecht. 1968.** Biogeochemische faktoren der eutrophierung van trinkwasser-talsperren. *Limnologica* (Berlin) **6**:225-245.
- USDA/USEPA. 1998.** Draft National Strategy for Animal Feeding Operations. United States Department of Agriculture, United States Environmental Protection Agency, September 11, 1998 draft. 47 pages.
- Vaughan, C.E. and M.B. Jones. 1980.** Soil phosphorus tests on California subclover-annual grass pastures. *Soil Sci.* **130**:307-313
- Withers, P.A., R.J. Unnein, J.P. Grylls, and R. Kane. 1994.** Effects of withholding phosphate and potash fertilizer on grain yield of cereals and on plant available phosphorus and potassium on calcareous soils. *Eur. J. Agron.* **3**:1-8.
- Xue, Y., M.B. David, L.E. Gentry, and D.A. Kovacic. 1998.** Kinetics and modelling of dissolved phosphorus export from a tile-drained agricultural watershed. *J. Environ. Qual.* **27**:917-922.