4.0 Environmental and Sustainability Concerns Related to Phosphorus Fertilizer

Key Messages:

- Small amounts of P moving into surface water can have a large effect on water quality, so losses of P that are not agronomically significant can be environmentally damaging, particularly with respect to algae growth in freshwater (eutrophication).
    - Most of the P loss on the Northern Great Plains is driven by movement of dissolved P during the snowmelt period.
    - Phosphorus runoff is a function of the concentration of P in soil and vegetation at the soil surface and the amount of runoff that occurs, so management should focus on reducing the concentration of P at the soil surface during runoff periods.
    - While very high P concentrations at the soil surface are most frequently caused by excessive applications of manure P, fertilizer P can also be a contributor, especially if the fertilizer is broadcast.
- Soil fertility may be impaired through nutrient depletion if P removed in the harvested crop is not replaced.
- Accumulation of cadmium (Cd) in the soil from long-term application of Cd-containing P fertilizer may be a concern for human and soil health.
- Banding P fertilizer under the soil surface, near the seed-row during seeding at rates based on an effective soil test and an accurate prediction of crop requirements will reduce the risk of excess P in runoff, P depletion and excess Cd accumulation in soils and crops.

Summary

Small amounts of P moving into surface water can have a large effect on water quality, so losses of P that are not agronomically significant can be environmentally damaging. Phosphorus is an essential nutrient for the growth of aquatic plants and algae. Small increases in plant and algae growth can be beneficial by increasing the food supply for fish. But, as P concentrations in the water increase, dense algal blooms can occur and degrade the water quality for fisheries, recreation, drinking and industrial uses. Excessive plant growth and decomposition can use up the oxygen from the water, leading to fish kills. Lakes and other surface water bodies on the Northern Great Plains are often at risk for eutrophication because they are commonly shallow and fed by large, fertile agricultural watersheds that can supply high amounts of nutrients.

Phosphorus loss from a field is a function of the amount of P in the surface soil and the degree of transport (Figure 1). Risk of water contamination by P from agricultural land will be high in areas where soil test P is high, the ability of the soil to retain P is low, susceptibility to runoff is high, soil erosion risk is high, and water from the field can easily move offsite to sensitive waters through natural or artificial drainage. Most of the P risk indicators that have been developed worldwide concentrate on risk of loss from fields where the main mechanism for P loss is rainfall-induced erosion, which carries particulate P from sloping land into water bodies. Such indicators do not work well in the Northern Great Plans, where P losses are mainly from spring snowmelt runoff over relatively level landscapes and across frozen ground. Under these conditions in the Northern Great Plain there is very little erosion-driven loss of particulate P. However, soluble P in the soil or crop residues at the soil surface is easily dissolved in the melting snow and moved with the runoff. Since approximately 80% of annual runoff in the Northern Great Plains occurs during snowmelt, the dissolved P in snowmelt runoff is a major source of P movement into water bodies in this region.

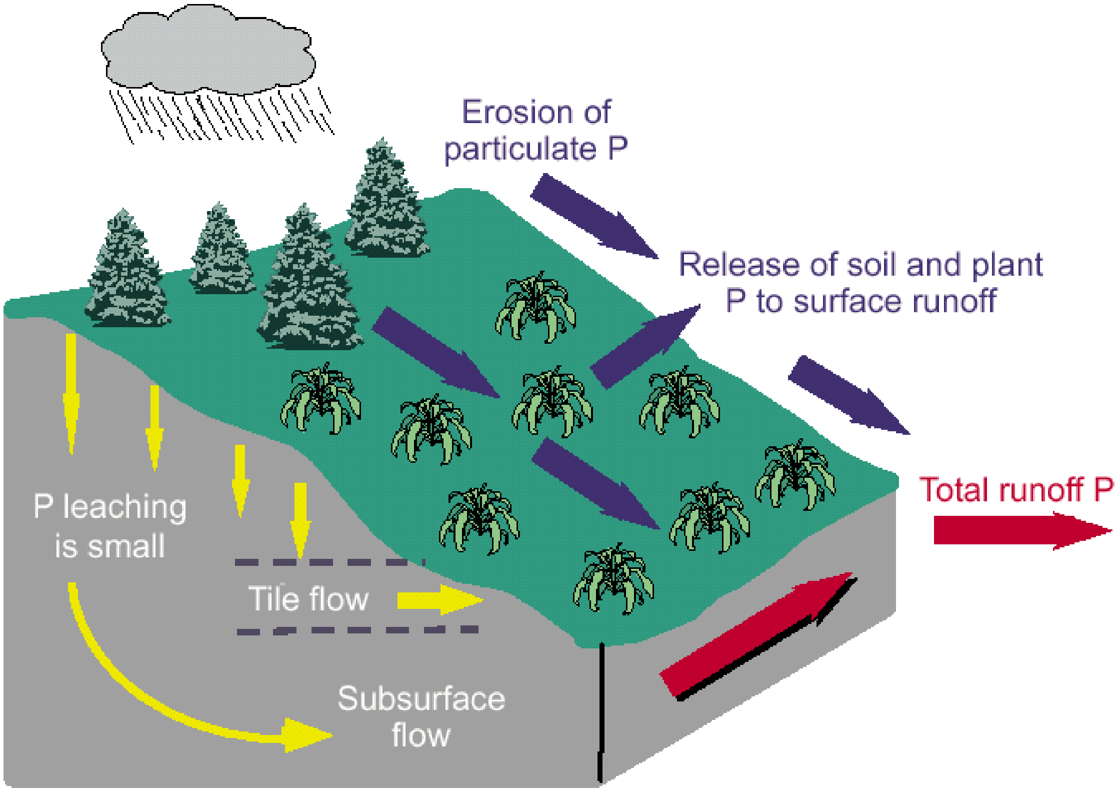


Figure 1. Processes that transport phosphorus to water from agricultural land (Sharpley, A. N., Daniel, T., Sims, T., Lemunyon, J., Stevens, R., and Parry, R. 2003. Agricultural phosphorus and eutrophication. ARS-149, USDA-ARS. https://www.ars.usda.gov/oc/np/phoseutro2/phoseutrointro2ed/

Many of the beneficial management practices (BMPs) to reduce P movement to waterways have been developed to reduce nutrient loss from erosion. Erosion-focused BMPs concentrate on practices such as vegetative buffer strips to trap eroded particles before they enter water bodies, maintenance of vegetative cover in place of bare soils, and reduction in tillage or the adoption of no-till to reduce the movement of soil particles. On gently sloping landscapes on the Northern Great Plains, where most nutrient transport is during snowmelt and in the dissolved form, vegetation is less effective in trapping nutrients and may contribute nutrients to snowmelt runoff. Living plant material contains high concentrations of soluble P that can be released during freezing and thawing. In addition, crop residues left on the soil surface under no-till management also contain soluble P, although the concentration is lower than in living plant material. Slow snowmelt leaves the water in contact with the residues and the surface P for a long time, allowing the soluble P to leach out of the residues and into the surface water, especially when soils are frozen and impermeable.

Effective 4R nutrient stewardship practices to reduce P runoff on the Northern Great Plains must focus on reducing the concentration of various sources of P in contact with the snowmelt runoff water. Research in Alberta and Manitoba demonstrates that the amount of dissolved P in runoff water increases as the soil test P concentration at the soil surface increases, just as it does elsewhere. However, those relationships are consistently linear, with no obvious “change point” to indicate substantial increases in runoff losses of P above a specific concentration of soil test P. Phosphorus fertilizer rates that are closely matched to crop demand should be used to reduce accumulation of P at the soil surface.

Broadcast P applications, particularly if not incorporated, will increase the amount of soluble P near the soil surface and can increase the risk of P movement in runoff. In-soil banding of P will reduce the risk of P loss by placing the P below the soil surface, where it is not in contact with the runoff water. Placing the P in a concentrated band near the seed-row can also increase fertilizer use efficiency and reduce the amount of P required for optimum crop yield.

Large P losses can occur where rainfall or runoff in general follows quickly after surface P application, before the soluble P fertilizer has reacted with the soil to reduce its availability. Since the risk of P loss is greatest immediately after application, P fertilization, especially broadcast applications, should be timed to avoid periods of high runoff. Fall broadcast P applications should be avoided because the fertilizer can remain near the surface over the winter in a soluble form that can move with the spring runoff. Applying fertilizer after snowmelt, just prior to or during seeding can avoid movement in spring runoff and reduce the risk of P loss.

Therefore, optimum 4R nutrient stewardship practices to reduce P runoff in the Northern Great Plains should concentrate on matching P application rates to crop demand, ensuring that soil test P concentrations in the surface soil are managed to avoid excess accumulation, placing P fertilizers below the soil surface and timing applications to avoid P fertilizer remaining at the soil surface during the snowmelt period or prior to rainfall events. It is also important to consider that most of the P loss will occur from a small area of the watershed and practices that reduce risk of P movement is those sites will probably have the greatest benefit on water quality.

Excess accumulation of P in the soil, especially near the soil surface, can increase the risk of P movement to water bodies. However, P depletion should also be avoided as it can reduce the productivity of the soil, because crops on very low testing soils may not be able to attain optimum yields even with high rates of fertilizer P. Accumulation or depletion of P in the soil will reflect the balance between P applied in fertilizers or other soil amendments and P that is removed in the harvested crop. As a result, depletion of soil P may be particularly problematic in organic production systems where synthetic fertilizer inputs are not permitted. A long-term sustainability approach to P fertilizer management is desirable, where fertilizer is managed through the rotation to maintain reasonable concentrations of available soil P to optimize soil productivity while avoiding increased risk of P movement to water.

Another environmental concern related to P fertilizer management is the accumulation of cadmium (Cd) in the soil over time. Long-term consumption of large amounts of Cd in the human diet, particularly in subsistence diets low in zinc and iron, has been linked to chronic toxicity and adverse health effects. Soil organisms may also be negatively affected by excess Cd exposure, affecting soil ecology and health. Therefore, it is desirable to ensure that concentrations of Cd in soils remain low enough to avoid adverse effects on soil or crop quality. The amount of Cd added to soils from P fertilizer application is a function of the rate of application, the frequency of application and the concentration of Cd in the fertilizer material. Cadmium is removed from the soil primarily through crop harvest, with erosion, bioturbation and leaching also being minor potential pathways of loss. Therefore, over the long-term, changes in Cd concentration in soils reflects the balance between Cd input and removal. However, because addition of Cd in phosphate fertilizer at normal agronomic rates of application is low relative to background concentrations, major changes is soil background concentrations will take many years to develop. In Canada, the concentrations in the soil after 100 years of application at current rates are not predicted to represent an increased risk relative to the current soil quality guidelines. Nevertheless, accumulations of Cd in the soil can be minimized by avoiding excess applications of P fertilizer and by using fertilizer BMPs that optimize fertilizer use efficiency.

On the Northern Great Plains, in-soil banding near the seed-row during seeding at rates based on an effective soil test and predicted crop requirements are BMPs for optimum P use efficiency that will reduce the risk of excess Cd accumulation in soils.

Detailed Information

Phosphorus is an essential nutrient for plant growth and an adequate supply of P is important to ensure optimum crop production. However, P in runoff can lead to eutrophication of surface water. A more long-term issue may be the accumulation of potentially toxic trace elements such as cadmium in the soil from repeated applications of fertilizers containing trace element contaminants. Indirectly, greenhouse gas emission from transport and application of fertilizer is of concern. Soil degradation including organic matter loss and P depletion can occur if inputs of crop residue and P are inadequate to compensate for losses and removal over time. Effective 4R nutrient stewardship practices must be designed to address these types of environmental concerns to ensure long-term sustainability of the land and water resources that support both agriculture and society.

4.1. Phosphorus loss to surface water and eutrophication

The largest environmental issue related to P in the Northern Great Plains region is eutrophication of fresh water caused by nutrient loading (Chambers et al. 2001; Salvano et al. 2009). Eutrophication refers to the enrichment of water with dissolved nutrients that stimulate plant and algal growth. Some stimulation of growth may be beneficial, by increasing the food supply for fish and increasing the productivity of the lake. However, eutrophic lakes can develop dense algal blooms that reduce the water quality for fisheries, recreation, drinking and industrial uses (Lewtas et al. 2015). Excessive plant growth and decomposition can lead to depletion of oxygen from the water, resulting in fish kills.

In freshwater bodies, P is the most commonly limiting nutrient, so increasing the P concentration in the water will increase plant growth and can potentially lead to eutrophication (Chambers et al. 2001; Jeppesen et al. 2007; Schindler et al. 2008b; Wilander and Persson 2001). Lakes are classified according to their nutrient loading status and the risk of algal growth. Oligotrophic lakes are low in nutrients, containing less than 4 to 10 µg P L^{-1} so that algal growth is nutrient-limited and water is usually clear (Table 1). Mesotrophic lakes are moderate in nutrient content, with concentrations of 10 to 20 µg P L^{-1}. As P concentration increases above 20 to 35 µg P L^{-1}, the lakes become eutrophic and are green with algae through most of the ice-free season. Hyper-eutrophic lakes have extremely high nutrient concentration and excessive algal growth. If P concentration is above 100 µg P L^{-1}, algal growth is limited by factors other than P, such as N, micronutrients or light.

Table 1. Total phosphorus trophic thresholds for Canadian lakes and rivers (http://ceqg-rcqe.ccme.ca/download/en/205/?redir=1555081609, accessed April 12, 2019)

Trophic Status	Total phosphorus (ppb, µg/Litre)
Ultra-oligotrophic	< 4
Oligotrophic	4-10
Mesotrophic	10-20
Meso-eutrophic	20-35
Eutrophic	35-100
Hyper-eutrophic	> 100

Lakes and other surface water bodies on the Northern Great Plains are at high risk for eutrophication because they are commonly shallow and fed by large, fertile agricultural watersheds that can supply large amounts of nutrients. Many of the lakes in the region are naturally eutrophic, as this is part of the aging process of lakes located in fertile areas with nutrient-rich soils (Lewtas et al. 2015). However, P and sediment loading from agricultural activity is a major contributor to enhanced eutrophication of lakes in the Northern Great Plains. For example, the increased eutrophication and deterioration of water quality in Lake Winnipeg, the 10th largest freshwater lake in the world, has been attributed in part to nutrient loading from agricultural activity (Schindler et al. 2012).

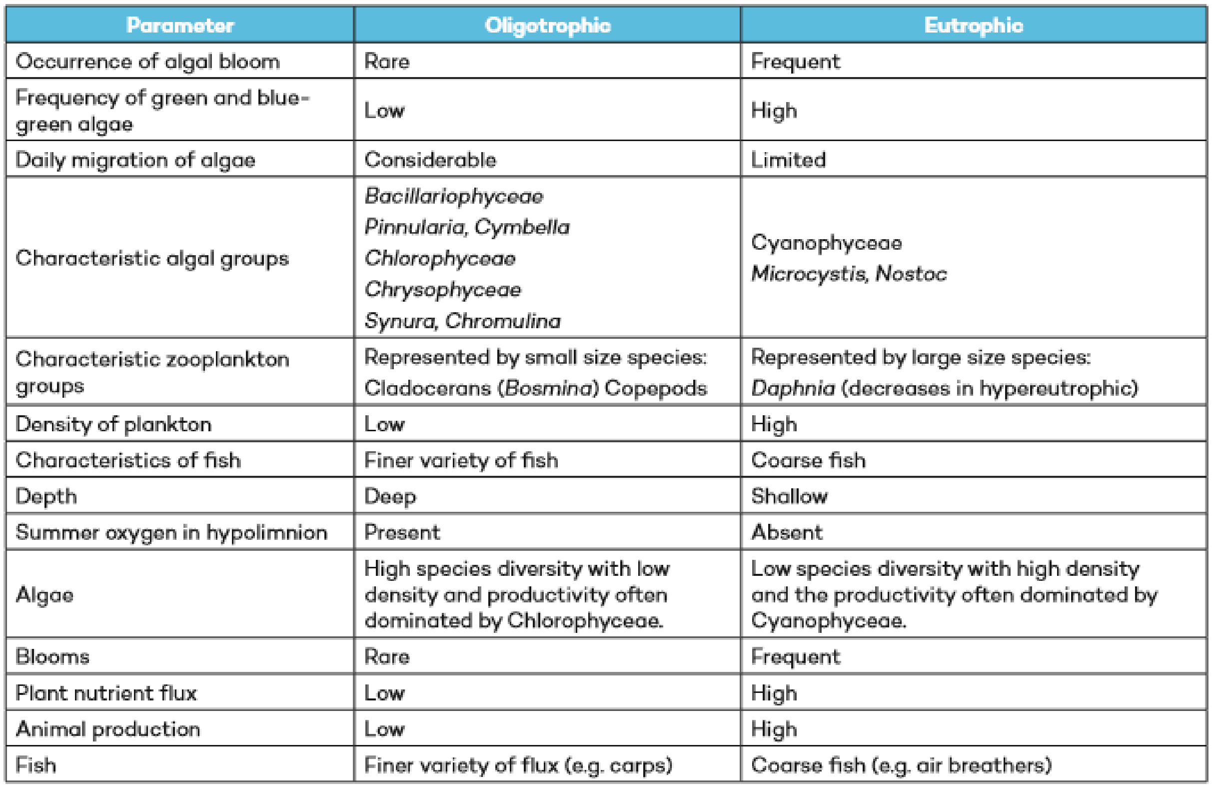
Phosphorus enters water bodies in local runoff water and regional inlet streams and is lost through outlet streams and by incorporation into the sediments. Some of the soluble P in the lake binds with soil particles and minerals in the water and sediment and becomes less available to bacteria and algae. However, some of the compounds that retain P are sensitive to redox conditions. Therefore, if water at the bottom of the lake becomes oxygen-depleted, the top few cm of sediment, which is usually aerobic, will become anaerobic, releasing soluble P to the water. The plant-available P will move towards the surface water and increase the amount of P that is available for algal growth. In shallow lakes, long-term P accumulation may lead to the release of P from bottom sediments even when the water is oxygenated (Schindler et al. 2008a). Release of P from sediments can lead to continued P problems even after external inputs of P have been remediated.

The amount and rate of turnover of dissolved P has a great effect on the amount of algal growth (Chambers et al. 2001). As P is the primary limiting factor for algal growth in freshwater lakes on the Northern Great Plains, the growth of algae will largely depend on the concentration of P in the lake water, which will be a function of climatic conditions such as rainfall and temperature, the amount, timing and bioavailability of the nutrient load, the rate of input of nutrient-rich water compared to the volume and output of the lake (flushing rate) and the depth of the lake. If a lake is rapidly flushed, its concentration will reflect the concentration in the in-flowing waters, while a slowly flushing lake will have a P concentration that is more controlled by sedimentation. Even if a lake has a low overall P concentration, there may still be problems in specific areas near the shoreline where channels, streams and rivers discharge nutrients and dilution is limited.

Many blue-green algae (Cyanobacteria) species can fix atmospheric N_2, so in waters with low N concentrations they will often out-compete other algae if sufficient amounts of P are available. The higher the P loading and concentration, the more common excessive algal blooms dominated by cyanobacteria become (Table 2) (Lewtas et al. 2015). Cyanobacterial blooms are particularly undesirable because they produce surface scums, noxious tastes and odours and may produce toxins than can be harmful to humans, livestock, wildlife and other aquatic organisms. The toxicity is most harmful to the nervous system or the liver and can lead to derangement, staggering, tremors, abdominal pain and death in almost any mammal, bird or fish (Chambers et al. 2001). Human deaths from drinking water contaminated by blue-green algae are rare because people usually avoid algae-contaminated drinking water, but pet and livestock illness and death can occur. During the summer, sloughs in the prairie pothole region can be prone to this problem because of the prevalence of shallow water bodies, nutrient enrichment and warm conditions.

Excess plant and algal populations can also deplete oxygen concentrations in lake water. While plants are net producers of oxygen because they release oxygen during photosynthesis they will use oxygen during night, depleting the oxygen concentration in the water and stressing fish populations (Chambers et al. 2001). Decomposition of large amounts of organic matter left after algal blooms can also deplete oxygen concentrations, leading to fish kills.

Table 2. Typical characteristics of the trophic state of a lake (Ghosh and Mondal 2012).



Parameter	Oligotrophic	Eutrophic
Occurrence of algal bloom	Rare	Frequent
Frequency of green and blue-green algae	Low	High
Daily migration of algae	Considerable	Limited
Characteristic algal groups	*Bacillariophyceae* *Pinnularia, Cymbella* *Chlorophyceae* *Chrysophyceae* *Synura, Chromulina*	Cyanophyceae *Microcystis, Nostoc*
Characteristic zooplankton groups	Represented by small size species: Cladocerans (*Bosmina*) Copepods	Represented by large size species: *Daphnia* (decreases in hypereutrophic)
Density of plankton	Low	High
Characteristics of fish	Finer variety of fish	Coarse fish
Depth	Deep	Shallow
Summer oxygen in hypolimnion	Present	Absent
Algae	High species diversity with low density and productivity often dominated by Chlorophyceae.	Low species diversity with high density and the productivity often dominated by Cyanophyceae.
Blooms	Rare	Frequent
Plant nutrient flux	Low	High
Animal production	Low	High
Fish	Finer variety of flux (e.g. carps)	Coarse fish (e.g. air breathers)

4.1.1 Reducing P losses from agricultural soils

The amount of P that will move from the field is a function of the P concentration near the soil surface and the degree of transport (McDowell et al. 2001b; Sharpley 1995). Risk of water contamination by P from agricultural land will be high in areas where soil test P is high, the ability of the soil to retain P is low, susceptibility to runoff is high, soil erosion is high, and water from the field can easily move offsite to sensitive waters through natural or artificial drainage (Van Bochove et al. 2006). Leaching of P is not normally an issue but may occur on soils with very low P sorption capacity, on soils where there is a large amount of macropore flow, or if soil test P is very high from application of organic wastes to sandy soils or acid organic soils. Labile organic forms of P are more prone to leaching than are inorganic P forms (Campbell and Racz 1975). If conditions conducive to leaching occur in tile-drained land, the risk of subsurface drainage losses of P into surface water may be high (King et al. 2015).

Phosphorus risk indicators have been developed to estimate the risk of P transfer from field to surface waters by numerical ratings that integrate P transport factors such as erosion, runoff class, and distance to water with P source factors such as soil test P and application of fertilizers and manures (Salvano et al. 2009; Sharpley et al. 2012; Van Bochove et al. 2006). Most indicators have been developed to assess the risk of P loss from fields where rainfall-induced erosion carries particulate P from sloping landscapes into water bodies. The erosion-based risk differs from the situation on much of the Northern Great Plains where P losses are largely driven by snowmelt-driven runoff over relatively level landscapes and frozen soils (Salvano et al. 2009). In studies conducted in Saskatchewan, spring snowmelt runoff represented about 80% of annual runoff (Nicholaichuk 1967; Nicholaichuk 1984; Nicholaichuk and Read 1978). In paired watersheds in Manitoba, snowmelt runoff accounted for 80 to 90% of total annual runoff, although snowfall accounted for only 25% of total annual precipitation during the study period (Tiessen et al. 2010).

The dominating effect of snowmelt on runoff in the Northern Great Plains leads to a dominating effect of snowmelt runoff on P transport. In a three-year study in the Red River basin in Manitoba, 62% of the annual P load was delivered during the 12-18 day snowmelt period (Rattan et al. 2017). The method of P movement will differ between snowmelt-driven runoff and rainfall-driven runoff. Snowmelt usually occurs over a few days to weeks, and so is slower than rainfall events than occur over minutes to hours. During snowmelt, the frozen soil is resistant to particle detachments, so snowmelt is not as erosive as rainfall events. As a result, there is normally far less suspended particulate P moving in snowmelt as compared to rainfall runoff, so a higher proportion of P is in the dissolved rather than the particulate form. In paired watershed studies in Manitoba, average concentrations of dissolved nutrients in runoff were higher during snowmelt than rainfall events (Tiessen et al. 2010). The concentration of suspended sediment and particulate P were greater during rainfall events than snowfall runoff events, but losses of dissolved P were much greater (about 5x) than particulate P both in snowmelt and rainfall events (Li et al. 2011). Similarly, in studies in Saskatchewan, the P in snowmelt was primarily in the dissolved rather than the particulate form and the particulate P that was measured in runoff appeared to be associated with organic matter rather than soil mineral matter (Cade-Menun et al. 2013). Because snowmelt in the Northern Great Plains leads to much greater runoff than rainfall events, most P movement occurs during snowmelt as dissolved P (Cade-Menun et al. 2013; Li et al. 2011; Tiessen et al. 2010). Snowfall accumulation and hence the duration and intensity of snowmelt runoff is greater in the black and gray than the brown and dark brown soil zones, likely increasing the relative risk of P movement in runoff. In addition, seasonal variations in precipitation and pattern of snowmelt can influence runoff amount and intensity and hence P movement (Clearwater et al. 2016).

Phosphorus present in snowmelt runoff may originate from residual P from manure or fertilizers that remain at the soil surface, or from P leaching from vegetation (Elliott 2013; Tiessen et al. 2010). Plant material such as cover crops, buffer strips, forages, weeds or winter annuals may release soluble P from cells that are lysed by freezing and thawing, increasing the P concentration in runoff. In field studies in Ontario, water-extractable P was higher in cover crops than in wheat residue and increased with plant decomposition (Lozier et al. 2017). In a comparison of P losses in simulated snowmelt from a range of plant materials, the release of P was strongly related to plant P concentration (Elliott 2013). Juvenile winter wheat had higher P concentration than mature spring wheat straw and about 50 times more P was released from the juvenile winter wheat than from the mature spring wheat residue (Elliott 2013). Most of the P from the winter wheat was released as dissolved P while most from the loss from spring wheat residue was as particulate P. Potential release of P from winter wheat was about 1.3 lb/acre (3.0 lb P_2O_5/acre), more than enough to be of environmental concern. When residue was combined with soil to simulate an active layer, loss was much less than for the soil and plant residues individually, indicating that soil performs an important role in intercepting the P released from vegetative residues during snowmelt.

In the Northern Great Plains, where P loss is dominated by snowmelt runoff events, beneficial management practices (BMPs) for control of P movement should concentrate on reducing the movement of dissolved P during early spring. Movement of dissolved P will be a function of the concentration of P in the runoff water and the volume of runoff that occurs. Many of the BMPs to reduce P movement to waterways have been developed to reduce nutrient loss from erosion (Cade-Menun et al. 2013). Erosion-focused BMPs concentrate on practices such as vegetative buffer strips to trap eroded particles before they enter water bodies, or reduction of bare soil and tillage to reduce erosion. In areas where erosion is a major factor in nutrient transport, practices that use vegetation to prevent erosion or intercept nutrients have effectively reduced nutrient loads. However, in the dry climate and gently sloping landscapes of the Northern Great Plains, where most nutrient transport is during snowmelt and in the dissolved form, vegetation is less effective in trapping nutrients and may actually contribute nutrients to snowmelt runoff (Elliott 2013; Sheppard et al. 2006). Long, slow snowmelt leaves the water in contact with the thawing residues and the surface P for a long time, allowing time for meltwater to extract and transport the soluble P.

Similarly, conservation tillage is a recommended practice to reduce erosion losses and hence reduce the risk of P loss when the dominant form of transport is through particulate movement. In areas where rainfall-induced erosion dominates P loss, use of conservation tillage to increase infiltration and reduce runoff can reduce the total quantity of P losses from the field. However, where the dominant path of loss is through movement of dissolved P in snowmelt, conservation tillage practices are not as effective (Tiessen et al. 2010). In a paired watershed study in south-eastern Manitoba, converting to no-till resulted in a small decrease in loss of particulate P but a greater loss of dissolved P. Since dissolved P during snowmelt was by far the dominant form of P loss from the watersheds, total P loss increased with the adoption of conservation tillage (Tiessen et al. 2010). Total P loss was minor from an agronomic viewpoint (1.33 lb P_2O_5/acre/year) but this small amount is environmentally significant and can contribute to eutrophication.

If conservation tillage is combined with broadcast application of P, the risk of P loss is increased (Janssen et al. 2000; Jarvie et al. 2017; Wiens 2017). The lack of soil inversion with conservation tillage can result in accumulation, or stratification, of nutrients at the soil surface, including those in crop residue and those added as fertilizers or manures. This stratification can increase the concentration of dissolved nutrients in runoff. In studies in Minnesota under corn, reduced tillage practices of ridge till or chisel plowing led to higher loss of soluble, particulate and total P than moldboard plowing (Hansen et al. 2000). Most P was lost as soluble P, averaging 75% of the total P loss. Where fall tillage was eliminated, there was more loss of soluble P in snowmelt because of P accumulation at the soil surface in the absence of tillage, P leaching from the crop residue, and more runoff because of the smooth soil surface.

4.1.2 4R nutrient stewardship practices that reduce P movement to water

Fertilizer applications can be a major source of P input into farming systems and a large potential source for P movement into water systems (Yates et al. 2012). However, the amount of P lost from the system will not necessarily relate directly to the amount applied because a large proportion of the P will be retained in the field through adsorption or precipitation or be utilized for crop uptake. Proper 4R fertilizer management practices that increase the amount of P taken up by the crop or retained within the field will be important in ensuring that losses from the field to water bodies are minimized.

Selection of fertilizer application rates that are closely matched to crop demand should be used to minimize the risk of P runoff. In simulated runoff studies on soils collected from a no-till field trial in Saskatchewan, P loss increased with the rate of broadcast P application (Wiens 2017). The largest amounts of total P exported in snowmelt runoff (0.45 lb total P per acre or 1.03 lb P_2O_5/acre) were for the treatment with the high application rate (72 lb P_2O_5/acre) combined with surface broadcast placement, with half or less of this amount for the unfertilized and 18 lb P_2O_5/acre treatments. The high rate and broadcast treatment also had the highest proportion of total P as dissolved reactive P.

Rates of P application matched to crop uptake will help to reduce accumulation of plant-available P in the surface soils. Runoff simulation studies with soils in Alberta and Manitoba have demonstrated that loss of P from the soil is linearly related to the concentration of soluble P present in the surface soil that interacts with moving water (Figure 2) (Sawka 2009; Wright et al. 2006). As the soil test P concentration (STP) increases, the concentration of P in the runoff water increases, as well. Therefore, as in studies conducted elsewhere, increasing the P concentration at the soil surface will increase the risk of P loss (McDowell et al. 2001a; Sharpley et al. 1994). However, contrary to those other studies, P loss relationships with soil test P in the Canadian Prairies have been consistently linear, with no obvious “change point” to indicate substantial increases in runoff losses of P above a specific concentration of soil test P.

In studies on eight field-scale microwatersheds in Alberta that included a range of tillage systems, there was a strong linear relationship between the site mean STP concentration and the P in the runoff water (Little et al. 2007). The relation between runoff P and the soil test measurements in the surface 2.5 cm and the surface 15 cm were similar, indicating that an agronomic sampling depth of 15 cm would be suitable for prediction of runoff risk. The study by Little et al. (2007) included sites that had a long-term history of manure application resulting in very high STP values and sites that had only received agronomic rates of P fertilizer and were low in soil test P. The relationship between runoff P and STP was strongly driven by the very high STP values in the manured plots and the relationship was no longer apparent when only the small range of STP values in the unmanured plots were included. Similar results were measured in watershed studies in Manitoba, where the soil test P concentrations were not related to runoff P, due to a narrow range of soil test P at this single study site, which had received recommended annual rates of P fertilizer rather than large, intermittent applications of P as fertilizer or manure (Liu et al. 2013). In addition, the majority of snowmelt runoff occurred on frozen soil when the soil-runoff interaction was minimal and when the influence of other sources of P, such as thawing vegetation, played a large role.

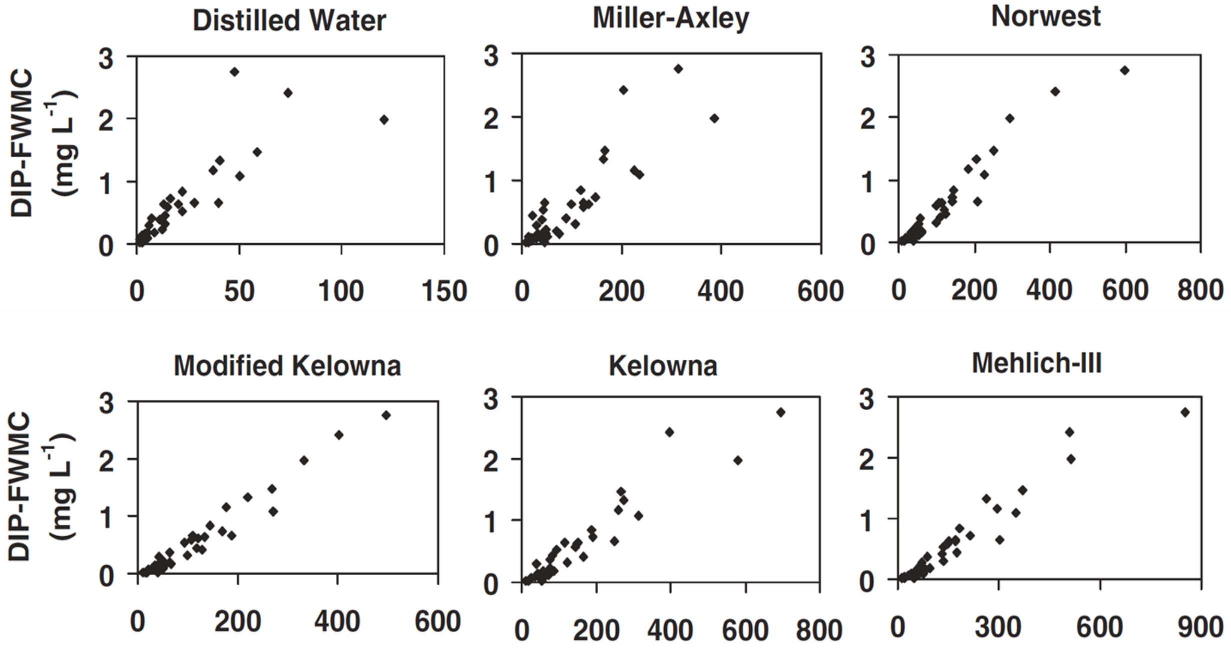


Figure 2. Relationships of soil test P and dissolved inorganic P–flow-weighted mean concentration (DIP–FWMC) for six soil test extraction methods for the first 30 min of simulated runoff in 38 Alberta soils (Wright et al., 2006).

Nevertheless, practices that significantly increase the STP values at the soil surface are likely to increase the risk of P runoff. Managing P concentrations with fertilizer applications closely related to agronomic optimum concentrations based on soil tests can help to avoid excessive concentrations of STP and reduce the risk of P loss. Therefore, once optimum agronomic concentrations of soil test P are achieved, P fertilizer rate should be matched to crop removal to avoid further accumulation of P in the soil over time.

In addition, increasing the rate of P fertilization above agronomic optimum concentrations can lead to luxury consumption of P by the crop, increasing the concentration of P in the crop tissue. Higher P concentration in the vegetative material in contact with runoff water can increase the amount of P leached and the amount of P movement. Again, matching P applications with crop demand can reduce the risk.

While the majority of P losses from agricultural fields are by runoff, P can also be lost by leaching and subsurface flow (King et al. 2015; McDowell et al. 2001b). As discussed previously, P will move more readily in labile organic forms than in inorganic forms. Risk of P leaching can occur with water movement through sandy, light-textured soils, soils with a low P retention capacity, waterlogged soils where reducing conditions mobilize P, organic soils or soils with high manure loading, and soils where there are preferential flow paths, such as root channels, earthworm channels, or cracks in the soil structure. With tile-drained systems on soils that are prone to P leaching, the risk of subsurface drainage losses of P may be high (King et al. 2015). These conditions are relatively rare on the Northern Great Plains, but where they occur, management practices that reduce P concentration in the soil will reduce the risk of P leaching.

To be agronomically effective, most P fertilizer sources are water-soluble, so will be initially available for movement in runoff. In studies on pasture soils in New Zealand, runoff losses of P were smaller with dissolved superphosphate than with granular superphosphate (Sharpley and Syers 1983). The liquid fertilizer may have infiltrated more easily into the soil, reducing the contact between the runoff water and the fertilizer. In addition, moving deeper into the soil may generate more soil-fertilizer contact, increasing the P retention. Use of less soluble fertilizers also can reduce the risk of dissolved P loss (Smith et al. 2016). Broadcast single superphosphate led to less loss of P than the other, more soluble granular fertilizers in studies using runoff boxes. Less soluble forms of P such as bone meal and rock phosphate had soluble P loss that did not differ from the unfertilized control. In rainfall simulation studies in grass and no-till fields in Pennsylvania, P losses were higher for 21 days after application from surface broadcast triple superphosphate fertilizer (TSP) and a low grade single superphosphate than from a rock phosphate source or the unfertilized control (Shigaki et al. 2006). Concentration of P in the runoff was directly related to the water-soluble P in the fertilizer material. The greatest amount of P loss was in the rainfall event that occurred one day after fertilizer application. Contribution of the soluble fertilizers to runoff decreased over time while the less soluble fertilizers continued to gradually release P for 42 days after application. However, as mentioned previously, to be agronomically effective, P fertilizers need to dissolve in soil solution, to become plant-available. Therefore, although use of sparingly soluble fertilizer forms may reduce the risk of environmental fertilizer loss, it will also reduce the agronomic benefit of the fertilizers. Use of higher application rates to compensate for lower fertilizer availability can lead to long-term accumulation of P in the soil and greater long-term risk of P loss. Combining timing and placement selections that reduce the concentration of soluble P at the soil surface during runoff events can allow soluble P sources to be used to optimize agronomic benefits while reducing the risk of P runoff.

Fertilizer placement that increases the concentration of P at the soil surface can increase the risk of P movement in runoff. In agricultural systems, the surface soil will tend to be enriched with P, particularly under no-till and/or with broadcast applications of P (Selles et al. 1999; Weiseth 2015). Because of its immobility, P tends to accumulate at the depth of application, especially under reduced tillage (Grant and Lafond 1994). Broadcast application without incorporation will leave the P fertilizer at the soil surface where it is at high risk of movement in runoff water. As mentioned previously, in a study on soil monoliths collected from a P study on a no-till field in Saskatchewan, broadcast application of 72 lb P_2O_5/acre led to large amounts of P loss in simulated runoff studies (Wiens 2017). Fertilizer P applications that are made by broadcasting without incorporation at rates above that which would normally be utilized by the crop in the year of application, such as the 72 lb P_2O_5/acre broadcast treatment, appeared to increase potential export of P in dissolved reactive forms. Studies with broadcast and in-soil applications of P on soybeans in Saskatchewan showed that broadcast P fertilizer led to higher concentrations of water-soluble P near the soil surface, which increased P export in simulated snowmelt runoff (Weiseth 2015).

Incorporation of broadcast fertilizer will reduce the risk of P movement, by reducing the concentration of P at the soil surface. It should be noted that different tillage equipment will provide different degrees of soil inversion and mixing, with moldboard plough and disc equipment generally providing more vertical mixing than chisel-type equipment (Chen et al. 2004; Mohler et al. 2006). Therefore, some forms of low disturbance tillage practiced on the Northern Great Plains may leave a substantial amount of broadcast P near the soil surface while other forms may be very effective at reducing surface P concentration. In field studies in Indiana, disking in diammonium phosphate fertilizer (DAP) reduced soluble P losses as compared to unincorporated DAP, but sediment loads were higher from disked DAP (Smith et al. 2017). Similarly in Kansas, incorporation of liquid P fertilizer through field cultivation prior to planting reduced P runoff (Janssen et al. 2000). Incorporation of P fertilizer will increase the contact between the fertilizer and the soil, increasing retention through precipitation and adsorption reactions and reducing the proportion of soluble P present that is subject to direct dissolution and movement in runoff water (Hansen et al. 2002). Phosphorus will react with the calcium and magnesium present in high pH soils to form sparingly soluble calcium and magnesium phosphate compounds (Sample et al. 1980). In acid soils, similar reactions occur with iron and aluminum oxides. Soils with a high capacity for P retention will be less at risk for P loss than soils with a low retention capacity. Due to the challenges of losing soluble fertilizer P when broadcast P is not incorporated or losing soil P by erosion when broadcast P is incorporated, P fertilizer should not be broadcast in areas that are prone to runoff.

In-soil banding of P below the surface will reduce the risk of P loss by placing the P in a position where it is protected from runoff. Phosphorus is relatively immobile in the soil and so remains near the site of fertilizer placement unless disrupted by tillage (Grant and Lafond 1994; Selles et al. 1999; Weiseth 2015). Banding will leave the P fertilizer in a zone that is not directly in contact with runoff water, reducing the risk of P movement. In studies that evaluated 30 minutes of runoff using runoff boxes, injecting the fertilizer even 1 cm below the soil surface reduced P losses from monoammonium phosphate fertilizer (MAP) by 98% as compared to broadcasting the fertilizer and leaving it at the soil surface (Smith et al. 2016).

Placing the P in a concentrated band near the seed-row can also increase fertilizer use efficiency and reduce the rate of P required for optimum crop yield. Band placement of P reduces contact with the soil and should result in less P retention than broadcast application, thus increasing fertilizer use efficiency (Tisdale et al. 1993). In P-deficient soils with a high P retention capacity, the optimal method of supplying P for early crop growth is generally by banding the fertilizer near or with the seed, during the seeding operation (i.e., use of “starter P”). The banded fertilizer is available to the crop early in the growing season and the residual P will be located below the surface where it will be protected from movement in runoff.

Timing of P application can also have a large effect on losses. Runoff occurring soon after application of broadcast P fertilizer can lead to large P losses. Studies at Swift Current where P was broadcast in the fall on summer fallow and left unincorporated, a situation that would encourage P runoff, led to losses of about 9.8% of the fertilizer applied (Nicholaichuk and Read 1978). In studies in Ontario, fall broadcast and shallow incorporation of P fertilizer increased the water-extractable P concentration at the surface, increasing the risk of P release to runoff events immediately after P application (Lozier et al. 2017). Large P losses can occur where rainfall or runoff in general follows quickly after surface P application. However, P enrichment of runoff from soluble P fertilizers rapidly declines with time after fertilizer application. Concentration of dissolved reactive P in simulated surface runoff from field runoff plots decreased from 90 mg L^{-1} the day after application TSP to 7.8 mg L^{-1} seven days after application and continued to decline until it was just under 2 mg L^{-1} 42 days after application (Shigaki et al. 2006). Therefore, application of P immediately prior to occurrence of runoff events should be avoided, particularly if P is broadcast. Furthermore, in areas such as the Northern Great Plains, where cold winters and frozen soils restrict the soil's capacity to retain fertilizer P, fertilizer P should not be applied in late fall, or on frozen soil.

When considering the range of BMPs for P fertilization, it is important to identify the major pathways for P movement at a given site, before recommending or adopting specific management practices to address the problem (Salvano et al. 2009; Sims et al. 1998; Flaten et al. 2019). Optimum 4R nutrient stewardship practices to reduce P runoff in the Northern Great Plains should concentrate on matching P application rates to crop demand, ensuring that STP concentrations in the surface soil are managed to avoid excess accumulation, placing P fertilizers below the soil surface and timing applications to avoid P fertilizer remaining at the soil surface during the snowmelt period or immediately prior to rainfall events. It is also important to consider that most of the P loss will generally occur from a small area of the watershed and practices that reduce risk of P movement in those sites are likely to have the greatest benefit on water quality (Sharpley et al. 2011). Within a field, P tends to accumulate in lower-slope and depressional areas where water movement is concentrated (Letkeman et al. 1996; Roberts et al. 1985; Wilson et al. 2016). Reducing or eliminating P application on those sites could reduce the risk of P movement off-field, without impairing crop yield potential.

4.2. Phosphorus Depletion in Soils

Excess accumulation of P in the soil, especially near the soil surface, is undesirable as it can increase the risk of P movement to water bodies. However, P depletion should also be avoided as it can reduce the productivity of the soil and the sustainability of crop production. In studies in Alberta, barley yields on soils with very low soil test P were lower than on higher-testing soils, even when very high rates of P fertilizer were applied (Nyborg et al. 1999). An adequate level of soil P fertility is required to satisfy plant requirements through the growing season for optimum crop yield.

Soil testing laboratories suggest a critical concentration of soil test P, using a soil test suited to the specific region, above which the plant will no longer respond to additional P applications.

Many of the soils in the Northern Great Plains contain soil P concentrations below suggested critical concentrations, indicating that P fertilizer is required to optimize crop yield (Figure 3). Between 2010 and 2015, the percentage of samples taken that were below critical concentrations increased in Manitoba and Alberta but decreased in many of the Northern Great Plains states and provinces (Figure 4). Some caution should be used when interpreting these data since there may be bias if an increasing number of soil samples are being submitted to develop manure management plans, as those samples would be taken on soils that may have been targeted for manure application and may not be representative of the general field situation. In addition, different soil test methods and critical concentrations are used by different testing laboratories, making comparison difficult.

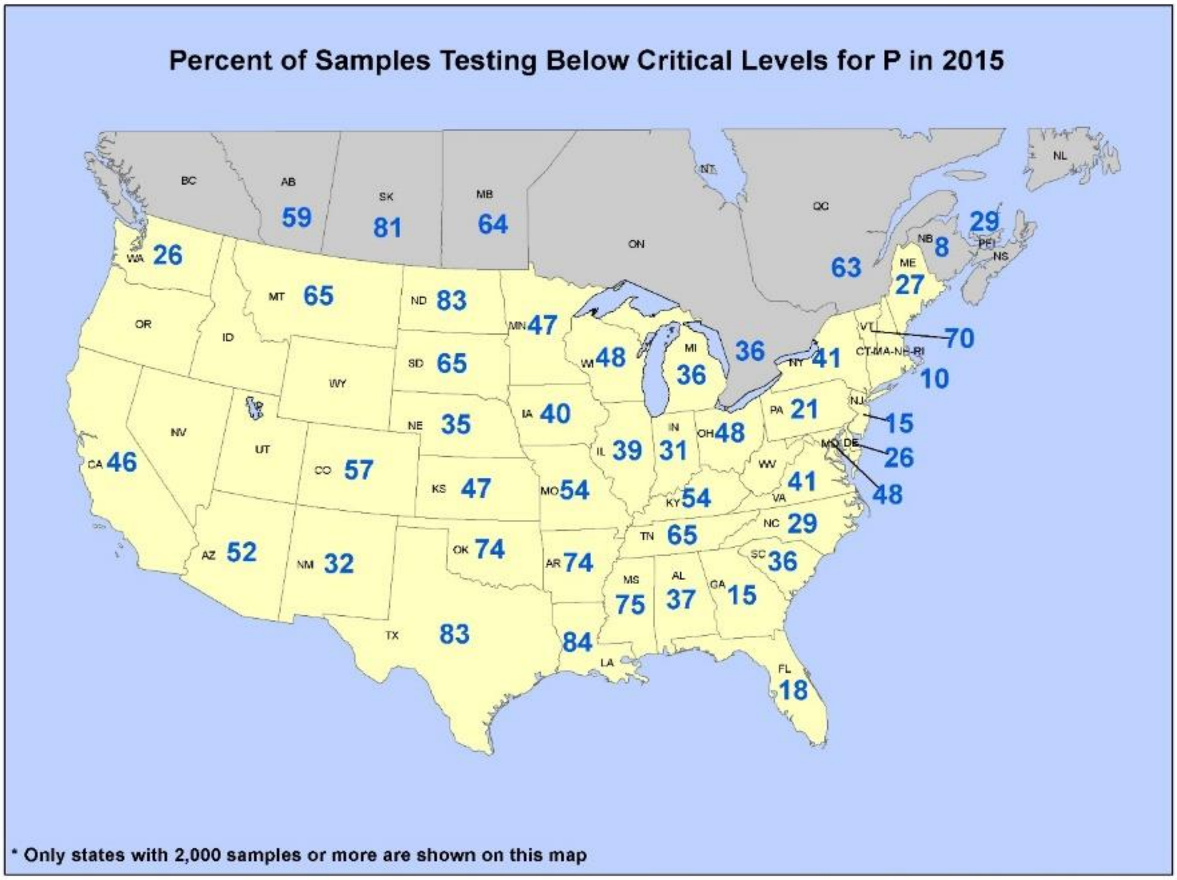
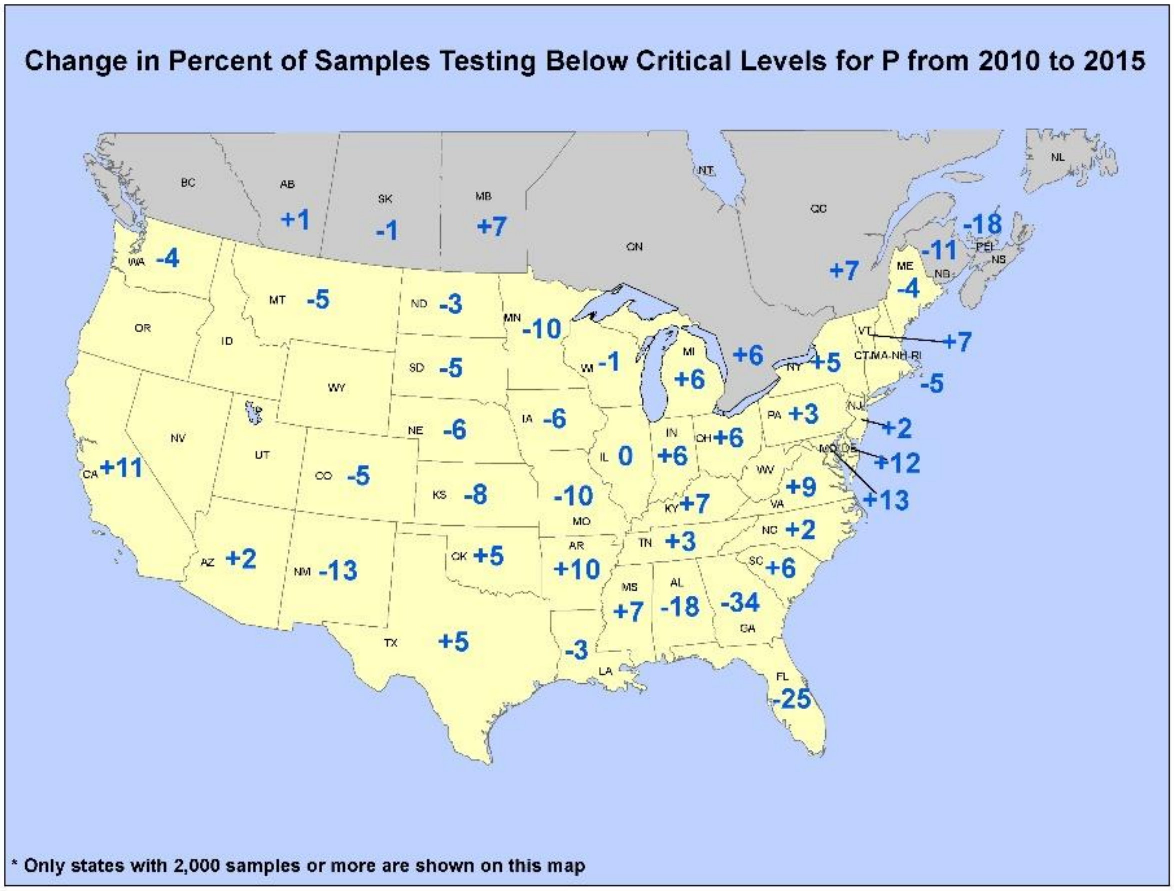


Figure 3. Frequency of soils testing below critical values of P in North America, by state or province (http://soiltest.ipni.net/maps/Percent_Change%20 accessed October 16, 2018)

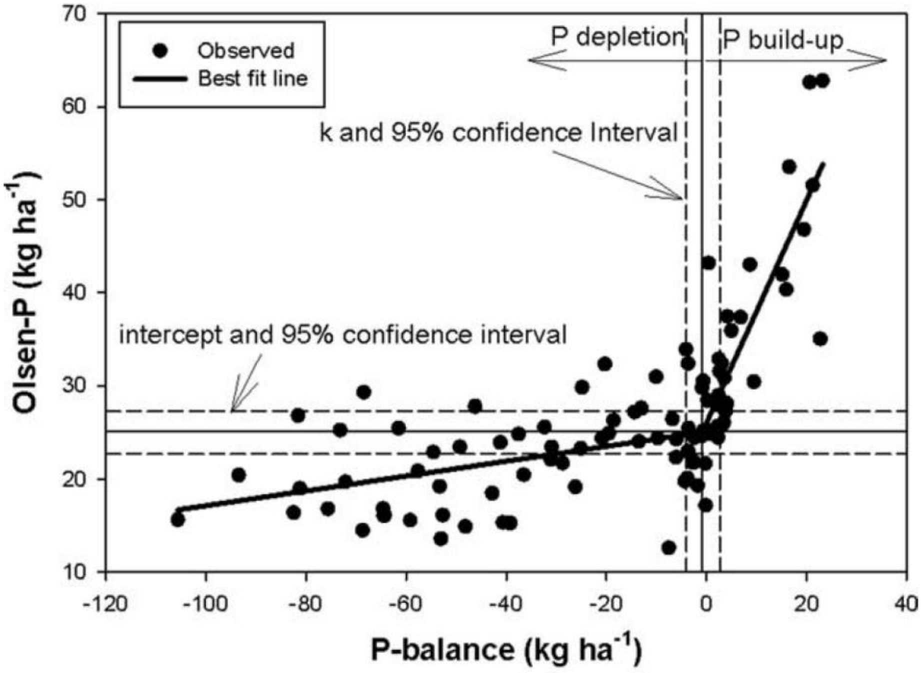
There is some concern that concentrations of soil test P may be declining in areas that are not being treated with manures, as was seen in the Manitoba sampling. Declining soil P could relate to shifts in cropping patterns, where crops such as wheat that have a high tolerance for seed-placed P are being replaced in the rotation with crops such as canola or soybean that have lower tolerance. Where producers rely on only starter P placed in the seed-row, limiting application to only the safe rate of seed-placed P means that less P is applied than is removed by these oilseed crops. For example, in Manitoba, inputs of phosphate fertilizer and removal of P in the plant were historically relatively well-balanced, because shortfalls in P input during production of canola were compensated by surplus additions of P in the cereal years. However, cropping patterns in Manitoba are changing, with more acres of canola and soybean and fewer acres of cereal crops. Also, crop yields and, therefore, crop removal of P have increased dramatically in recent years. Therefore, the risk of P depletion has increased in many areas of the Northern Great Plains.


Change in Percent of Samples Testing Below Critical Levels for P from 2010 to 2015

* Only states with 2,000 samples or more are shown on this map

Figure 4. Change in percentage of samples testing below critical concentrations for P from 2010 to 2015 (http://soiltest.ipni.net/maps/Percent_Change%20 accessed October 16, 2018)

Several studies in the Northern Great Plains have illustrated the effect of deficits or surpluses between P applied and P removed on soil test P. Long-term studies conducted at Swift Current, SK showed a good relationship between Olsen-P soil phosphorus concentrations and the balance between P applied and P removed in the crop, with P depletion occurring where P deficits occurred (Figure 5).



$$y = 25 + 0.08 * Pbal$$

$$y = 25 + 0.08 * Pbal + 1.1 * (Pbal - k)$$

Figure 5. Soil test P values in the top six inches of the soil reflect the balance between P input and P removal in the crop in long-term studies at Swift Current, SK (Selles et al. 2011).

Similar results were found in studies across the prairies that evaluated the effect on Olsen P of annual inputs of approximately 0, 40, 80 and 160 lb of P_2O_5 per acre from 2002 to 2010, in a durum wheat-flax cropping sequence (Figure 6). In these studies, withholding P fertilizer led to a large depletion in soil test P while applications of 80 lb P_2O_5 per acre or above led to a large increase. Application of 40 lb P_2O_5 per acre produced minor changes in soil-test P. However, the change in soil test P with P input varied widely with soil type. For example the rate of surplus P (P applied as fertilizer minus P removed by crop harvest) to raise Olsen P by 1 ppm varied from approximately 20 lb P_2O_5/acre on coarse-textured soil near Carman to 37 lbs P_2O_5/acre on clay loam soil near Brandon. In this study, similar rates of P were applied to both crops in the rotation, even though the flax crop tends to remove lower amounts of P. In rotations with canola, that removes greater amounts of P than are normally applied, the depletion would be greater than observed with flax.

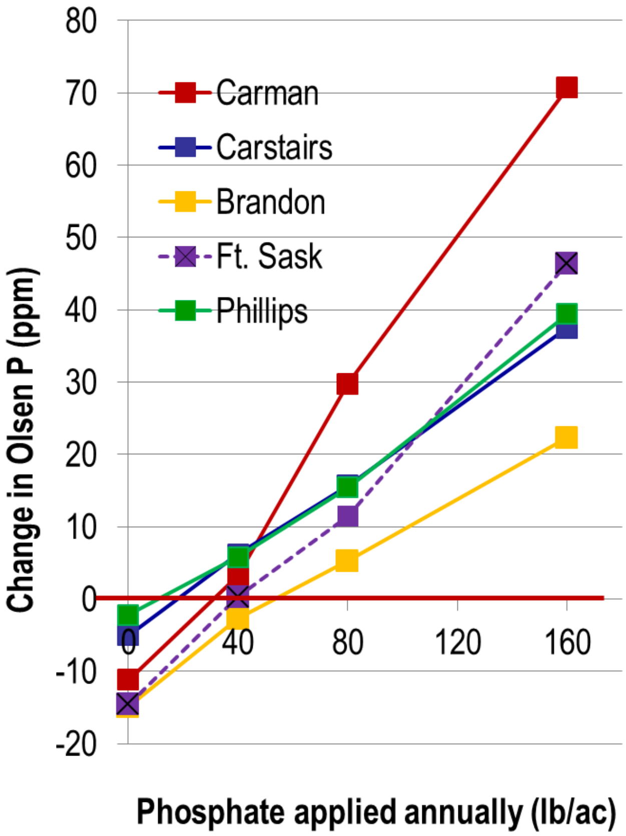


Figure 6. Change in Olsen P values with annual P application after 8 years of cropping following a durum wheat-flax cropping sequence on five soils in Western Canada (Grant 2012).

Depletion of soil P may be a major issue on organic farms due to the restrictions placed on the type of P inputs that may be used (Entz et al. 2001). A survey of organic farms in Manitoba showed soil P concentrations were lower than normally found in conventionally managed fields. The lowest available soil P concentrations were observed on farms with the longest history of organic management. In the University of Manitoba's long-term Glenlea organic rotation studies, soils in the high-yielding organic grain-forage rotations had lower concentrations of readily available P than conventional rotations after 13 years of cropping (Welsh et al. 2009). Regardless of whether a cropping system is organic or conventional, high yielding crop rotations that export significant amounts of P without replenishment will develop P deficiency over time.

Excessive depletion or accumulation of P in soils can cause problems. Excess P accumulation can increase the risk of P movement into water bodies, leading to eutrophication. Conversely, depletion of soil P can reduce the supply of P from the soil to the crop, potentially limiting yield, especially in situations where the P application is reduced to meet safe limits for seed-placement. A long-term sustainability approach to P fertilizer management is desirable, where fertilizer is managed through the rotation to maintain reasonable concentrations of available soil P and optimize soil productivity while avoiding increased risk of P movement to water.

4.3 Cadmium loading to soil

Cadmium (Cd) is a potentially toxic trace element that is naturally present in soils, but is also added from atmospheric deposition, industrial contamination, sewage sludge, irrigation water and agricultural inputs such as manures, fertilizers and soil amendments (Alloway and Steinnes 1999; Sheppard et al. 2009b). Agricultural crops can accumulate Cd from the soil, with the amount of uptake depending on factors including crop genetics, soil Cd concentration and Cd phytoavailability as affected by soil characteristics. Long-term consumption of large amounts of Cd in the human diet, particularly in populations with diets that are deficient in other trace elements, has been linked to chronic toxicity and adverse health effects including kidney tubule dysfunction and reduced bone density (Godt et al. 2006). Soil organisms may also be negatively affected by excess Cd exposure, affecting soil ecology and health (McGrath 1999). Therefore, it is desirable to ensure that concentrations of Cd in soils remain low enough to avoid adverse effects on soil or crop quality.

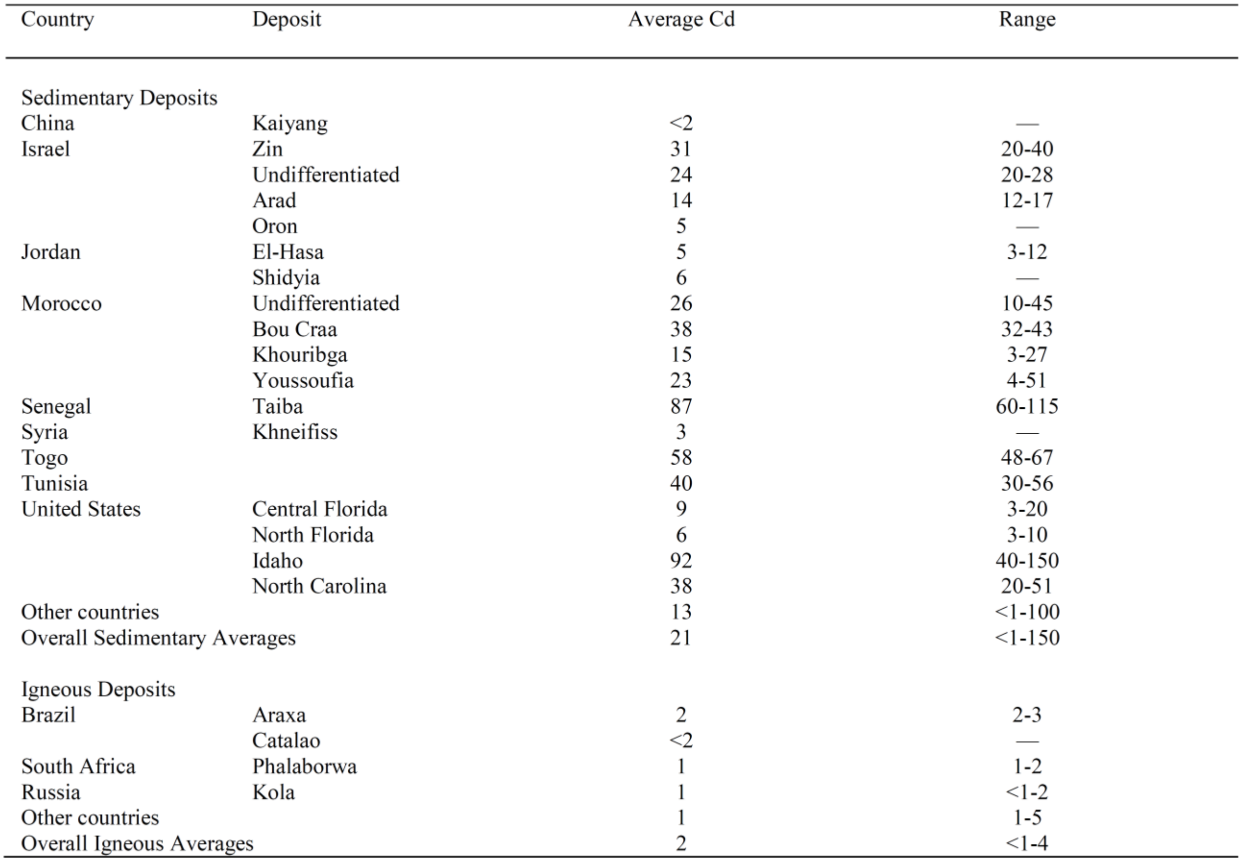
Phosphorus fertilizers are a major source of Cd input into the soil in agricultural systems (Sheppard et al. 2009a; Sheppard et al. 2009b). Phosphorus fertilizers contain Cd as a contaminant at concentrations varying from trace amounts to as much as 300 mg Cd kg^{-1} of dry product, depending on the concentration of Cd in the phosphate rock used for its manufacture (Table 3) (Syers et al. 1986). Cadmium concentrations in sedimentary rocks are normally higher than in igneous rocks, because Cd will coprecipitate as a substitute for Ca in the phosphate compounds during the geological formation of sedimentary rocks (Traina 1999). The Cd present in raw phosphate rock will be carried through during fertilizer production, so the resulting fertilizer produced will reflect the Cd concentration of the rock source (Chien et al. 2003; Chien et al. 2011; Molina et al. 2009; Syers et al. 1986). While Cd can be removed from P fertilizers during production, the process is costly and is not a priority for the industry (Syers 2001).

The amount of Cd added to soils from P fertilizer application is a function of the rate of application, the frequency of application and the concentration of Cd in the fertilizer material. Cadmium is removed from the soil primarily through crop harvest, with erosion, bioturbation and leaching also being minor potential pathways of loss (Sheppard et al. 2009b). The Cd concentration is most plants is very low, so the amount of Cd removed from the soil in the harvested crop is small. Although both input and removal of Cd tend to be low relative to the total amount of background Cd present in the soil, Cd will accumulate in the soil over time if input is greater than removal (Sheppard et al. 2009b). Total input and net Cd balance will vary widely depending on the fertilizer source, rate of application and the crops grown (Christensen and Huang 1999; Christensen and Tjell 1991; Sheppard et al. 2009b).

Over the long-term, increases in concentrations of Cd occur in agricultural soils that have received high Cd inputs over time, but not on soils where Cd input is low (Schipper et al. 2011). Long-term trials in Sweden (Andersson 1977), Denmark (Christensen and Tjell 1991; Dam Kofoed and Sondergard-Klausen 1983), Norway (Baerug and Singh 1990), Britain (Jones et al. 1987; Nicholson and Jones 1994), Finland (Mäkelä-Kurtto et al. 1991) and the United States (Mulla et al. 1980) have shown increases in soil Cd concentration over time as a result of a surplus Cd balance. In pasture systems in Australia (Williams and David 1976) and New

Zealand (Andrewes et al. 1996; Gray et al. 1999; Loganathan et al. 2003; Loganathan et al. 1997; Loganathan et al. 1995; Roberts et al. 1994) applications of phosphate fertilizers that were estimated to contain in the range of 20 to 50 ppm Cd led to significant increases in the Cd concentration in the surface soils. In a pasture system in Ireland, 31 years of application of 60 lb P_2O_5/acre as triple superphosphate, containing approximately 39 ppm Cd significantly increased Cd concentration of Cd in the surface 10 cm of soil, but the increase was <0.1 ppm (McGrath and Tunney 2010). Trials conducted at seven sites across the Canadian prairie provinces showed that DTPA-extractable Cd in the soil increased with the amount of Cd added over time (François et al. 2009; Grant et al. 2014; Lambert et al. 2007). The change in Cd availability varied from soil to soil but was low with typical agronomic rates of P application.

Table 3. Cadmium concentrations (mg/kg) of sedimentary and igneous phosphate rocks (Van Kauwenberg 2001) as cited by Roberts (2014)



Country	Deposit	Average Cd	Range
Sedimentary Deposits			
China	Kaiyang	<2	—
Israel	Zin	31	20-40
	Undifferentiated	24	20-28
	Arad	14	12-17
	Oron	5	—
Jordan	El-Hasa	5	3-12
	Shidyia	6	—
Morocco	Undifferentiated	26	10-45
	Bou Craa	38	32-43
	Khouribga	15	3-27
	Youssoufia	23	4-51
Senegal	Taiba	87	60-115
Syria	Khneifiss	3	—
Togo		58	48-67
Tunisia		40	30-56
United States	Central Florida	9	3-20
	North Florida	6	3-10
	Idaho	92	40-150
	North Carolina	38	20-51
Other countries		13	<1-100
Overall Sedimentary Averages		21	<1-150
Igneous Deposits			
Brazil	Araxa	2	2-3
	Catalao	<2	—
South Africa	Phalaborwa	1	1-2
Russia	Kola	1	<1-2
Other countries		1	1-5
Overall Igneous Averages		2	<1-4

A number of assessments of Cd balance have shown that the P balance (input - removal) is positive in many agricultural systems, indicating the potential for accumulation of Cd in the soil over time (De Vries and McLaughlin 2013; Keller and Schulin 2003a; Keller and Schulin 2003b; Keller et al. 2001; McDowell et al. 2013; Sheppard et al. 2009b). In studies in European soils, Cd concentration was closely related to phosphate accumulation, indicating that soil Cd was enriched due to applications as a contaminant in P fertilizer (Pan et al. 2010). Mass balance studies in Europe from 1980 to 1995 indicated a positive mass balance for Cd and resulting increase in concentrations of Cd in soil (Six and Smolders 2014). Similarly, correlations between phosphate and Cd in agricultural soils indicate that Cd addition in phosphate fertilizers has been a major driver of increased Cd concentration in soils over time (De Vries and McLaughlin 2013; Jones et al. 1987; Roberts et al. 1994).

In Canada, an indicator of the risk of trace element accumulation in soils was developed that showed that Cd influx was dominated by fertilizer applications in 90% of the soil polygons (Sheppard et al. 2009b). However, because addition of Cd in phosphate fertilizer at normal agronomic rates of application is low relative to background concentrations, major changes is soil background concentrations will take many years to develop. In Canada, the concentrations in the soil after 100 years of application at current rates are not predicted to represent an increased risk relative to the current soil quality guidelines (Sheppard et al. 2009b).

Since the increase in soil Cd is proportional to the total Cd added over time, 4R nutrient stewardship practices to reduce Cd accumulation can include reducing the rate of P application and selecting a fertilizer source that is low in Cd (Sheppard et al. 2009b). Many countries currently have limits on the concentration of Cd that can be present in P fertilizers (Table 4). In 2003, limits on Cd in European fertilizers were proposed to ensure that there would be no long-term accumulation of Cd in agricultural soils, but the limits have not been adopted into EU-wide regulation (Six and Smolders 2014). A new proposed regulation would limit Cd to 60 mg/kg P_2O_5 initially, with discussions continuing about reducing the concentration to as low as 20 mg over time (Ulrich 2019). Low Cd fertilizers can be produced by using low-Cd rock as the phosphate source or by decadmiating the fertilizer during the production process, although strict restrictions on the Cd concentration in fertilizers could increase fertilizer cost or restrict the available supply.

As mentioned previously, increases in soil Cd are often a function of the phosphate application rate (Lambert et al. 2007; Sheppard et al. 2009b). Therefore, accumulation of Cd in the soil can be minimized by avoiding excess applications of P fertilizer. For example, in nine long-term soil fertility experiments in the United States, more than 50 years of application of recommended rates of P fertilizers containing an estimated 5 ppm Cd increased soil Cd concentration by between 0 and 0.5% per year (Mortvedt 1987). In a 15 year study in Sweden, application of 22 lb P_2O_5/acre increased soil Cd in 0 to 20 cm depth by 0.33 to 1.1% per year, a minor effect relative to variation caused by uncontrolled factors (Andersson and Hahlin 1981). In a 29-year barley trial in England, application of agronomic rates of P did not increase soil Cd concentration (Richards et al. 1998), while in a 70-year fertility study in Norway, neither total nor available Cd concentration in the soils was increased significantly by the Cd added in fertilizer (Jeng and Singh 1995).

Table 4. Limits for Cd in P fertilizers in several countries expressed as Cd:P ratio, Cd:P_2O_5 or concentration of Cd in the fertilizer product (Roberts 2014)

Country	Limits	mg Cd/kg P	mg Cd/kg P_2O_5	mg Cd/kg 45% P_2O_5 Product
Limits for Fertilizer-Cd				
USA-Washington	0.0889 kg Cd/ha/yr	2040	889	400
USA-Oregon	7.5 mg Cd/% P_2O_5	774	338	152
USA-California	4 mg Cd/% P_2O_5	412	180	81
Australia	300 mg Cd/kg P	300	131	59
Canada	0.0889 kg Cd/ha/yr	2040	889	400
Japan		340	148	67
Austria	75 mg Cd/kg P_2O_5	275	120	54
Belgium	90 mg Cd/kg P_2O_5	206	90	40.5
Denmark		110	48.0	21.6
Netherlands		40	17.5	7.9
Finland	21.5 mg Cd/kg P_2O_5	49	21.5	9.7
Sweden	43 mg Cd/kg P_2O_5	100	43.7	19.7
EU Proposal (2001)	20 mg Cd/kg P_2O_5	45.8	20	9
	40 mg Cd/kg P_2O_5	91.6	40	18
	60 mg Cd/kg P_2O_5	137	60	27

In Europe, recent estimates of Cd inputs with fertilizers, manure and atmospheric deposition, and outputs of Cd with removal of crop harvest indicate that the mass balance is close to steady state (Nziguheba and Smolders 2008; Smolders 2017). European atmospheric deposition of Cd has decreased because of emission controls and P fertilizer usage has declined by 40%, leading to a prediction that soil Cd in agricultural soils growing cereals and potatoes will decline by 15% over the next 100 years (Six and Smolders 2014). In studies on seven soils across western Canada, allocation of agronomic rates of 40 lb P_2O_5/acre over 9 years led to minimal increases in soil Cd on most sites, regardless of fertilizer source (Grant et al. 2013; Grant et al. 2014). Increasing application rates to higher than normal agronomic levels led to increases in soil Cd concentration proportional to the amount of Cd applied in the fertilizer over time. Rate of P application required to optimize crop growth can be minimized by using P management practices that improve fertilizer use efficiency. On the Northern Great Plains, banding P fertilizer under the soil surface, near the seed-row during seeding at rates based on an effective soil test and an accurate prediction of crop requirements are BMPs for optimum P use efficiency. These same practices will minimize the risk of excessive accumulation of Cd in soil or crops.

As mentioned earlier, the greatest concern for trace element accumulation due to phosphate fertilizer application is from Cd because of the human health risks associated with Cd accumulation in edible crops. However, a range of other trace elements are also present in phosphate fertilizer and can accumulate in soils over time (Sheppard et al. 2009a; Sheppard et al. 2009b). While some of these trace elements, such as Zn and Cu, have nutritional benefits, others such as As and Pb are not desirable but the concentrations present in fertilizers are not considered a significant risk to human or soil health (Jiao et al. 2012; Sheppard et al. 2009b). Nevertheless, management practices to reduce Cd input and excess application of P fertilizer would also serve to limit the input of other potentially harmful trace elements.

Gaps in Knowledge

More information is needed on:

- landform effects on P losses to surface water for relatively level landscapes, since most studies have concentrated on more variable landscapes. Questions remain on how much P is moving off the field in level landscapes. Research into the benefit of improved fertilizer management practices targeted to depressional portions of the field where most runoff flows would be beneficial, especially on more level landforms where minor changes in elevation can channel the runoff. This would help in quantification of the potential benefits of variable rate P management for reducing P movement off field.
- the interaction between fertilizer source and the time of application on snowmelt P runoff and crop yield response would be useful, since some retailers of sparingly soluble P products are suggesting that they are suitable for fall application.
- long-term changes in Cd and P availability on a wide range of soils, to determine the impact of Cd and P loading over time as affected by soil characteristics. This type of information for P across a range of soils would help our understanding of the influence of soil characteristics and environment on long-term P availability as a function of P fertilizer deficits or surpluses.

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