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Phosphorus in the Calcareous Soils of Southern Idaho:

A Literature Review with Implications for Crop Production, Manure Management and Water Quality

by ANNA CAREY, AMBER MOORE, and APRIL LEYTEM

INTRODUCTION

In an agricultural area like southern Idaho, managing agricultural phosphorus (P) is essential to the area's economic and environmental sustainability. Phosphorus is an essential plant nutrient, and low available P can limit crop production. This has led to the addition of P as manures and fertilizers. However, excess P can increase P in runoff and degrade water resources.

Substantial research has been done in Idaho and elsewhere on the chemistry and movement of agricultural P. Southern Idaho's situation is unique, however, both because of the region's calcareous soils and because the region's dairy industry produces a large supply of manure that is used as a fertilizer in crop production. This publication summarizes the research relevant to southern Idaho and gives implications for crop production, manure management, and water quality.

PHOSPHORUS LOSSES AND ENVIRONMENTAL IMPACTS

Phosphorus is lost from a cropping system primarily through overland runoff and soil erosion. In extreme cases, P can be also lost through leaching. Through non-point sources of pollution like these, P can end up in Idaho waterways and water bodies, where it contributes to eutrophication—nutrient enrichment and accelerated growth of algae and larger plants. If levels of P in the water are excessive, algae and plant growth may also be excessive, resulting in low dissolved oxygen levels when the plants decay and eventually the death of other aquatic organisms (Bjorneberg et al. 2006). Algae blooms also decrease water clarity, aesthetic value, and recreational use (Shock and Pratt, 2003).

Relatively low levels of P in the soil can cause concentrations of P in water bodies that are considered eutrophic (Hart et al., 2004). Inorganic P in soil solution at levels of 0.2 to 0.3 mg/L can be critical for plant growth, whereas eutrophication of a lake can be triggered at P levels as low as 0.02 mg/L (USDA, 2003). Because of this, agencies like the Idaho Department of Environmental Quality (DEQ) along with the U.S. Environmental Protection Agency (EPA) have worked together to set total maximum daily loads (TMDL) of P for water bodies or watersheds throughout Idaho (Idaho DEQ, 2010). The TMDL set by the DEQ for total P in the Mid Snake River is 0.075 mg/L, which is considered the maximum level for the river to remain of "beneficial use" (Buhidar, 2005).

Erosion

Phosphorus is often bound tightly to soil particles; therefore, soil erosion is a very common way of losing P to the surrounding environment. As soil losses increase, P losses increase as well. In southern Idaho, a field can lose up to 63 tons of soil per acre per year when soil particles are carried away by a furrow irrigation system (Sojka et al., 2007). Phosphorus bound to sediment makes up the majority of total P (TP) lost through erosion or runoff in situations where soil erosion by water is high, as with highly tilled, low-residue, furrow-irrigated systems (Bennett, 2001) Total P consists of all forms of P: dissolved in water, in particulate form, and bound to sediment. Transporting P to surface water bodies in Idaho not only decreases productivity of the farm but also causes eutrophication.

The Natural Resources Conservation Service (NRCS) has established a soil test benchmark for helping producers to minimize P losses. The Idaho phosphorus threshold (IDPTH) for soils where surface water is the primary resource concern (i.e., the soil has a high potential for runoff) is 40 ppm Olsen P (60 ppm Bray-1 P) (NRCS, 2007). The NRCS recommends that landowners keep their soil test P values under this threshold to protect water quality. Olsen P is the preferred soil test for approximating the P available for plants in alkaline and calcareous soils.

Leaching

Phosphorus leaching is less of a concern in southern Idaho soils than in soils from other areas for two reasons. First, the region's soils have high levels of calcium (Ca) that can bind to P. Second, the high water-holding capacity of the area's predominantly silt loam soils slows the downward movement of water. However, leaching can occur when there is more P than can be sorbed by soil (P saturation).

For areas where groundwater is the primary resource concern (i.e., high potential for infiltration of water), the IDPTH is 20 ppm Olsen P for water tables less than 5 feet and 30 ppm Olsen P for areas where the water table is more than 5 feet below the soil surface (NRCS, 2007; Moore and Ippolito, 2009).

Research from the USDA Agricultural Research Service (ARS) in Kimberly, Idaho, shows that P leaching can occur in Idaho soils. In one study, P leaching occurred on a sandy soil in soil columns at P application rates as low as 149 lb/acre. Leaching of P was highest in soil that had been treated with liquid dairy manure (Figure 1) (Tarkalson and Leytem, 2009). These findings suggest that P leaching can be an Idaho concern, especially on sandy soils receiving lagoon water applications.

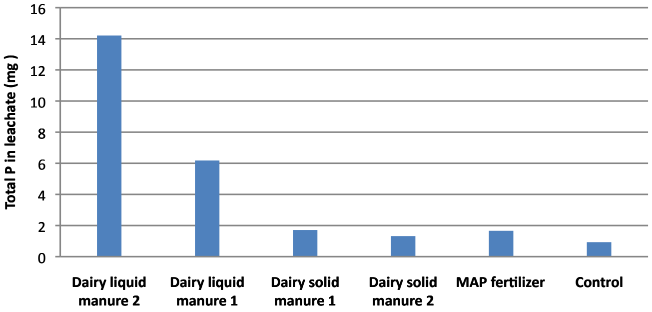

Figure 1. Total P in the leachates (P washed downward out of soil column) from columns of soil treated with different sources of P at the same P rate and subjected to an irrigation simulation. Total P in the leachates from the liquid manure treatments were significantly higher than total P in the leachates from the solid manure, fertilizer, and control treatments. (Adapted from Tarkalson and Leytem, 2009.)

In another ARS study, yearly applications of chemical P fertilizer, dairy compost, and dairy manure solids were compared on a three-year crop rotation of potatoes-barley-dry beans on a silt loam soil (Leytem and Bjorneberg, 2009). At a depth of 6-12 inches, researchers found significantly more P in the plots treated with manure, compost, and P fertilizer than in plots not receiving any P, despite tillage of P amendments only to a 3-inch depth. The P movement was attributed to leaching and was significantly higher in plots receiving manure than receiving compost or P fertilizer. Both this field study and the soil column study show the potential for downward P movement/leaching in Idaho soils and the differences in mobility of different P sources.

FACTORS CONTROLLING P SOLUBILITY IN SOUTHERN IDAHO SOILS

Many soils in southern Idaho are alkaline, meaning they have a soil pH above 7.5 (Leytem and Mikkelson, 2005). Calcareous soils, which are alkaline soils that contain a significant amount of calcium carbonate and have a typical pH range of 8.0-8.5, are also prevalent in southern Idaho. Phosphorus is highly reactive with the calcium carbonates (i.e., lime) in alkaline and calcareous soils (Lindsay, 1979). A series of reactions between Ca and P reduces P solubility and its resulting availability to plants. In addition to Ca, other elements in alkaline soils including iron (Fe), aluminum (Al), and magnesium (Mg) can also react with P, reducing its solubility (Leytem and Mikkelson, 2005; Leytem, 2008a).

Calcium

Calcium reacts with P in the soil to form calcium phosphate ($CaPO_4$) precipitates. In alkaline and calcareous soils, this is generally the most controlling factor for tying up P and reducing its availability for crop uptake. More specifically, as lime content (Ca concentration) increases in the soil, P availability to plants decreases (Figure 2) (Westermann and Leytem, 2003). To provide a crop growing in southern Idaho's calcareous soils with a similar level of available P as occurs in a non-calcareous soil, a grower would have to increase application of P_2O_5 to the calcareous soil by 10 lb/acre for each percent of free lime in the soil (Figure 3) (Leytem and Mikkelsen, 2005; Moore et al., 2009).

In calcareous soils with high P concentrations, P is more likely to be tied up in the form of Ca-P precipitates as opposed to other pathways, such as adsorbed to organic complexes or oxides. For 18 different soils in a laboratory study, precipitation with Ca dominated the P sorption process when P levels in the solution were between 49 and 619 mg P/L (Leytem and Westermann, 2003).

Timing also plays a major role in the formation of Ca-P precipitates in the soil. Research has shown that P becomes less plant available over time in Ca-rich soils (Sharpley et al., 1984). To account for this continual tie-up of P, it is important for growers to test their soils for P every year.

Mg, Fe, and Al oxides

Magnesium (Mg), iron (Fe) and aluminum (Al) in the soil combine with oxygen to form oxides that adsorb P to form Fe, Al, and Mg phosphates. Soil pH also has an effect on the amount of sorption that takes place between these oxides and P. For example, Ca and Mg in the soil normally increases with higher pH, becoming more dominant in P sorption. Aluminum and Fe are more dominant in P sorption tie-up as the pH decreases and soils become more acidic.

Organically complexed Mn, Mg, Al, and Fe

In addition to inorganic Mg, Al, and Fe oxides, Mn, Mg, Al, and Fe complexed with organic matter can tie up P (Leytem and Westermann, 2003).

Defining soluble, solution, sorption, and precipitation

The term "soluble" is used in soil P chemistry to describe P compounds that are dissolved in water. When P is not in solution, it can either adsorb to soil particles (being adsorbed, or sorption, refers to strong binding to soil particles) or it can form precipitates (solids) that are unavailable to plants. Precipitation is the process of dissolved chemicals binding to other dissolved chemicals to become solid. Sorption and precipitation are important processes to understand when determining the runoff and leaching potentials of P, as well as the availability of P for crop uptake.

Figure 2. Sudangrass growth with increasing lime concentrations. P uptake decreased from 53 mg P/plot to 32, 21, and 8 mg P/plot as the percentage of lime increased from 0% to 3, 9, and 15%, respectively. (Photo courtesy of D. T. Westermann and A. B. Leytem, from the USDA-ARS Kimberly, 2003.)

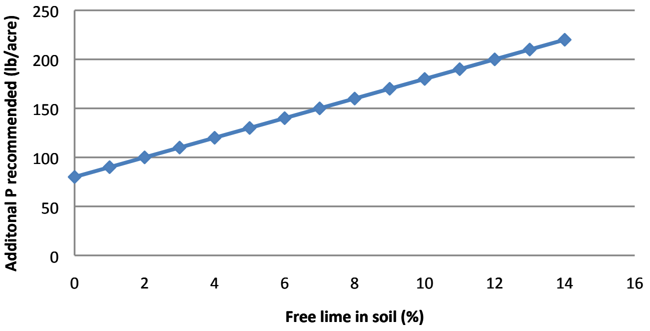

Figure 3. An example of increasing P fertilizer requirements for potatoes with increasing free lime content in the soil and a soil test P value of 20 ppm. (Adapted from Tindall and Stark, 1997.)

Results from a laboratory study on calcareous soils collected from throughout the Pacific Northwest showed that at lower concentrations of dissolved P, P sorption tended to be more related to organically complexed Fe and Mn than to Ca. At higher P solution concentrations (greater than 150 mg P/L), P sorption was influenced more by Ca content than by any other cation (Leytem and Westermann, 2006). Other researchers have also found that organically complexed Mn, Mg, Al, and Fe help to inhibit Ca-P precipitation by either (1) bonding with P directly or (2) coating the surfaces of the $CaCO_3$ and interfering with Ca-P precipitation (Halajnia et al., 2009). While Ca is the predominant element controlling P availability in fertilized calcareous soils, many other elements and complexes can react with or influence P availability.

FERTILIZER AND MANURES AS P SOURCES

Because P can limit production in a cropping system, P applications are common. Chemical P fertilizers are commonly used in southern Idaho, but manures are an increasingly common source of P due to an expanded dairy industry. As of 2009, Idaho had an estimated 545,000 dairy cows, with almost 75% concentrated in the central Snake River Valley. Those cows excreted an estimated 12,000 tons of P that year. This additional P has altered P use dynamics in Idaho, especially because manure is concentrated on a small land base.

Manure composition

Animal species, diet, and age as well as manure collection and storage methods create manures with unique physical and chemical properties (Figure 4) (Leytem, 2008a). Manures and composts predominantly contain orthophosphate P (orthoP), an inorganic form of P that is readily available for plant uptake.

Up to 10% of P in dairy manure is organic P (Leytem et al., 2006); most forms of organic P are not readily available for plant uptake (Hansen et al., 2004). Organic forms of P such as phytic acid are less plant available due to soil sorption (binding to the soil). Animal manures with 35-80% phytic acid contents contain less readily available P than manures (like dairy manures) with 0-8% phytic acid, because phytic acid is an organic form of P that needs to be converted by microbial activity before the P is available for plant uptake (Leytem, 2008a).

Because phytic acid and other forms of rapidly decomposable organic P are not measured as plant available forms of P by the Olsen soil test, we may be underestimating P available throughout the season on manured soils. To address this issue, growers may want to consider multiple samplings and analysis for Olsen P following manure applications.

In addition to animal species, animal diet has a significant impact on P losses in runoff. On average, there is over-supplementation of P in dairy cow diets in the U.S. One study showed that when manures from cows fed high- and low-P diets were applied at the same P rate, the high-P diet manure had four times the dissolved reactive P in runoff than the low-P diet manure, at least within a month of application (Ebeling et al., 2002). The P in grains used as animal feed is predominatly phytic acid. Because some animals like poultry and swine cannot digest this form of P, high concentrations of P can be released into the manures (Hansen et al. 2004).

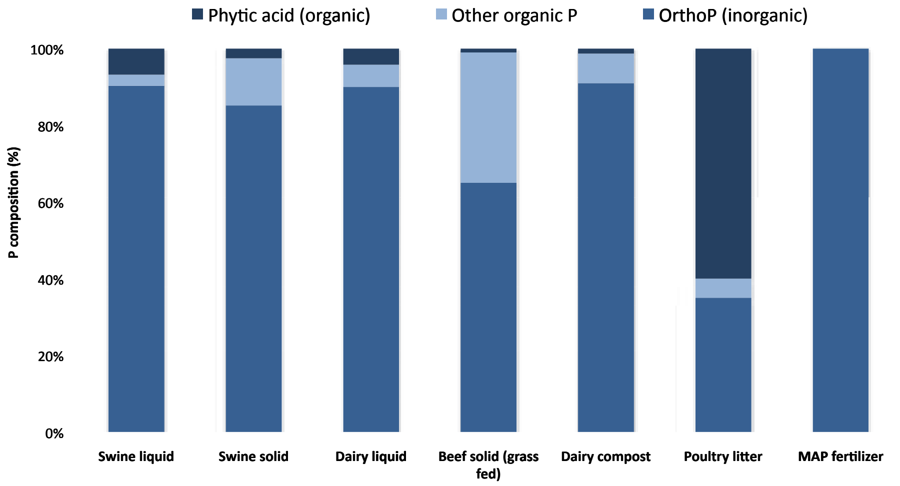

Figure 4. Breakdown of the composition of P in different types of manure and compost. Most of the P in manures is in the inorganic orthoP form, but manures differ widely in P composition compared to monoammonium phosphate fertilizer (MAP) (Adapted from Leytem, 2008b).

Adjusting animal diets can appreciably reduce the potential for P loss in runoff.

Carbon: phosphorus ratio

The C to P ratio is a major controlling factor in the availability of P from applied manures (Leytem et al., 2005). One reason availability of P decreases with increasing C:P ratio is the stimulation of soil microbial biomass. Microbes breaking down organic matter in the manure utilize nutrients such as nitrogen and P for growth, thereby immobilizing (tying up) these nutrients in their biomass (Leytem et al., 2005). With higher manure C:P ratios, microbes use more of the manure's soluble P for energy, and therefore more P is immobilized. One study showed that the addition of manures with less than 8% organic P (similar to dairy manure) caused plant available P to decrease and microbial biomass P to increase after several days of incubation (Leytem, 2008a; Leytem et al., 2005).

Another study showed that when cattle manure and P fertilizers were applied together, the recovery of P was greater than when fertilizer P was applied alone, most likely due to added C (Halajnia et al., 2009). Regardless of how P recovery happens, it is important for growers to understand the C: P ratio in manure can directly impact P solubility in the soil.

Increasing C in soil, whether from manure or other sources, can also increase P availability. Organic matter is made up of a variety of carbon compounds that can coat reactive surfaces that tie up P, such as soil particles and calcium carbonates, therefore making applied P more plant available. Adding humic and fulvic acids (organic matter compounds) with P fertilizers may help improve P availability (Leytem, 2008b; Delgado et al., 2002).

Nitrogen: phosphorus ratio

It is common to apply manure based on the nitrogen (N) requirements of the crop (Bary et al., 2000), which often leads to an overapplication of P, often by three to six times (Leytem et al., 2005; Tarkalson and Leytem, 2009; Moore and Ippolito, 2009). In Idaho, nitrogen-based applications can occur when the soil test P is below the P threshold values or where soil test results show a need for P (NRCS, 2007).

The N:P ratios of specific manure types differ depending on the animal and the diet fed. Dairy manure N:P ratios are often 2:1, whereas desired ratios are often closer to 5:1 for common crops like corn, barley, and potatoes grown in the western United States (Leytem et al., 2005; Leytem, 2008b). Increasing applications of swine manure on an N basis directly increased Olsen P and water-soluble P in soils, simply due to the increased tonnage of manure being applied (Figure 5). Applications of P in excess of plant needs are left to accumulate in the soil, thus potentially contributing to P movement into sensitive waterways.

MANAGING P FERTILITY AND CROP PRODUCTION

Plant uptake of P

Plants take up most P in the form of inorganic orthoP, as well as a few low-molecular-weight organic P compounds like nucleic acid and phytin (Havlin et al., 2005). The amount of P that is plant available is usually less than 20% of the total P in the soil (Schachtman et al., 1998).

Adding higher levels of manure P than required by the crop has been shown in several studies to not significantly increase P consumption by corn, potatoes, and other crops (Curless et al., 2004; Moore et al., 2010). In contrast, Brown and Griggs (2009) reported P tissue concentrations increased in forage triticale grown on manured fields as Olsen P increased up to 120 ppm. These findings suggest that the

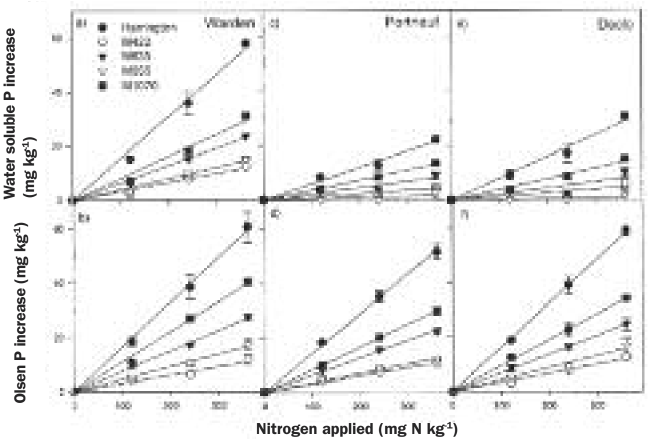

Figure 5. Increases in Olsen P and water-soluble P in three different soils (Warden, Portneuf, Declo) treated with five different swine manures containing three different levels of nitrogen. This graph shows that as more manure is applied on an N basis, the more P is applied. It also shows that the P increases vary with soil type and manure type but follow a similar trend. (Leytem et al., 2005)

P uptake potential of plants with increasing soil test P varies from crop to crop.

Too much soil P may also lead to problems for plant uptake of other nutrients. Moore et al. (2010) completed a survey of P and micronutrient concentrations in silage corn produced on primarily manured fields. They reported that Mg, Ca, and Mn plant tissue concentrations decreased with increasing soil test P, particularly on silt-textured soils. This effect of high P on plant uptake of other nutrients illustrates that, in addition to environmental issues, producers can compromise plant nutrient balance with excessive manure.

Fertilizer compared with manure

Many studies have shown that crop yields are higher for manure applications than for fertilizer applications at comparable non-limiting fertilizer rates (Robbins et. al., 1997; Sutton et al., 2009; Damodar et al., 1999; Curless et al., 2004). Factors other than nutrient content can increase yields following manure applications. Increased organic matter and microbial activity, in addition to other known and unknown factors, may be contributing to these yield increases. Other studies have not illustrated these significant yield differences (Lee and MacDonald, 1977; Warman and Harvard, 1996; Leytem and Bjorneberg, 2009). These findings illustrate the complexities of increasing yields with manure applications.

One study from southern Idaho showed that soil test P and plant tissue P responded differently to P fertilizer and manures. When P fertilizer, liquid manures, and manure solids were applied to barley at the same P rate, soil test P was generally higher with P fertilizer than with liquid manures. Soil test P was lowest with solid or composted manures (Leytem and Westermann, 2005). However, tissue P values followed a different pattern, with some solid and liquid manure treatments having higher tissue P than fertilizer P treatments and other solid and liquid manure treatments having lower tissue P than fertilizer P treatments. Differences in tissue P accumulated by barley were attributed in part to wide-ranging manure C:P ratios. These findings illustrate that soil test P may not be an effective predictor of available P from different P sources. For some liquid or solid manures, plant-available P may be greater than indicated by the soil test value. Further research is needed to determine the relationship between soil test P, P source, and P uptake by plants.

Incorporation and timing

Incorporating manures into the soil may reduce the movement of not only N but also of P. This would reduce P loss to waterways and increase the P in the soil that is available for plant uptake, as long as erosion is minimal. Studies across the U.S. on the incorporation of cattle manure, swine manure, and poultry litter into the soil have shown significant reductions of P losses through runoff (Couillard and Li, 1993; Ginting et al., 1998; Yoon et al., 1994; Tarkalson and Mikkelsen, 2004). One study on the incorporation of dairy manure shortly after broadcast application showed that the runoff contained up to 33% less sediment-sorbed P, 45% less soluble P, and 37% less total P (Osei et al., 2003).

When adding any nutrient amendment, the greatest P loss in runoff occurs immediately after the manure or fertilizers are applied, especially if the P source is left on the surface (Smith et al., 2007). If irrigation or rainfall can be avoided for the first week after application, the animal manures can provide an agronomic benefit of increased soil P with minimal risk for P runoff, thus minimizing water quality degradation.

SUMMARY

- Phosphorus applied to the land can be lost through runoff or leaching. This can degrade surface waters and reduce the amount of phosphorus available for crops.
- Southern Idaho calcareous soils require more phosphorus to produce a crop than others with less calcium, because calcium can tie up phosphorus. Other factors can also play a part in tying up P.
- The type and composition of manure can cause manure applications to differ significantly in properties affecting P movement, soil test P interpretation, and short-term P availability to crops.
- Knowing manure composition can help predict short-term P availability.
- Manures can be excellent P sources for crops but need to be managed to minimize risks to surface waters.

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ADDITIONAL RESOURCES

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THE AUTHORS

Anna Carey, Scientific Aide, Twin Falls Research and Extension Center, University of Idaho; **Amber Moore**, Extension Soils Specialist, Twin Falls Research and Extension Center, University of Idaho; and **April Leytem**, Research Soil Scientist, ARS Northwest Irrigation and Soils Research Laboratory, Kimberly, Idaho.

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