

Soil testing for different phosphorus pools in cropland soils of the Great Plains

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ABSTRACT: Knowledge of soil phosphorus (P) pools and their measurements is important in nutrient cycling studies. An overview of the P cycle, with emphasis on calcareous cropland soils of the Great Plains, was prepared to meet this objective. Phosphorus pools can broadly be placed into four main groups: primary P minerals, secondary P minerals, occluded P minerals, and organic P. The dominant groups and their amounts in the soil are highly dependent upon soil pH, weathering intensity, P fertilization, cropping history, and crop-residue management. Chemical procedures for the first three groups are usually based upon the ability of the extractant to separate P from the dominant cations, such as calcium, iron, and aluminum, or from reactive clay surfaces. Generally, the first three groups exist in inorganic forms, and the fourth as part of the soil organic matter. These pools require combustion or oxidation to orthophosphate before analysis. The primary and secondary P minerals, through equilibrium with the soil solution P, contribute to the plant available P, and consequently to the extractable P in a soil test. The organic P requires mineralization to orthophosphate first before it becomes a part of the available P, and the occluded P requires dissolution of an outer protective coating. Areas of similar soil mineralogy and pH (acid soils, calcareous soils, etc.) usually use the same soil test or P-availability index. Thus, in arid western states, the sodium bicarbonate (Olsen) procedure is used, and in areas of greater rainfall where acid soils exist, the Bray-1 procedure is used. More universal methods include the Mehlich 3 procedure, which is acceptable for both acid and basic soils. Other P procedures exist, but regardless of the procedure used, all have to show good correlation with soil P levels and P uptake and crop yields. Thus, categories (low, medium, high) are established for soil-test values based upon the probability of response of a crop to added fertilizer P. Knowledge of the cycling and fate of this nutrient, the second-most-important soil element for plant growth, is essential for good soil management and productivity.

Keywords: Available P, Bray-1, calcareous soils, organic P, phosphorous, phosphorus pools, threshold soil P

Phosphorus plays a crucial role in both plant nutrition and environmental water quality (Ozanne 1980, Cooke and Williams 1973, Sharpley et al. 1994).

Unlike nitrogen (N) and sulfur (S), which can exist in gaseous forms, P quantity and fate are completely associated with the terrestrial ecosystem (Smeck 1985). It is required by crops in major amounts, along with N and potassium (K), for adequate yield production (Engelsted and Terman 1980) but can cause serious eutrophication problems when sufficient amounts are dissolved in surface waters (Daniel et al. 1998). Because of these two important but contrasting roles, knowledge of

the different P pools, their transformations, and their measurements is vital for a better understanding of P cycling and its ultimate fate as a useful plant nutrient or a water pollutant.

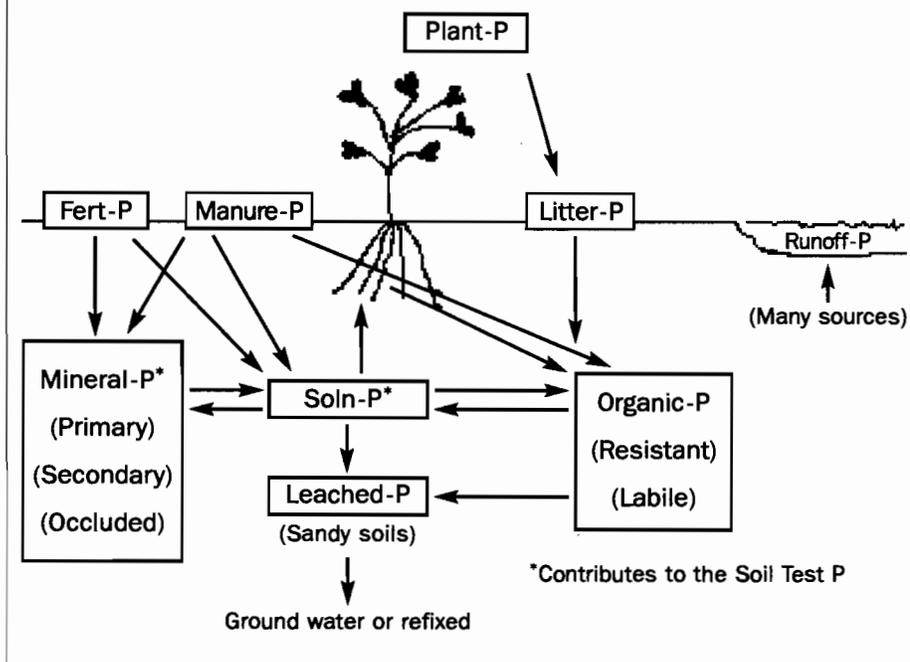
All P comes initially from sedimentary and, to a lesser extent, igneous rocks in the primary mineral apatite (calcium phosphate enriched) and its many forms, depending upon chemical inclusions such as fluoride (F) for fluorapatite (major component of phosphate rock [PR]) and hydroxide (OH) for hydroxyapatite (major component of P fertilizer end product) (Lindsay et al. 1962). Phosphate rock exists in abundant quantities

in places such as Morocco, South Africa, the United States, the former Soviet Union, and China, but it must be strip-mined to recover the apatite mineral (Cathcart 1980). Phosphate rock (usually fluorapatite), a very insoluble form of phosphate, must be concentrated and converted to the available orthophosphate form through thermal or, more often, acidulation processes (Robinson 1980). Acidulation with concentrated sulfuric acid eliminates the fluoride and gives rise to phosphoric acid and, through manufacturing, to the superphosphates (0-18-0, ordinary; 0-45-0, triple). The addition of ammonium to phosphoric and sulfuric acids produces the ammonium phosphate fertilizers, monoammonium phosphate (MAP, $\text{NH}_4\text{H}_2\text{PO}_4$, 11-48-0, 11-55-0), and diammonium phosphate (DAP, $[\text{NH}_4]_2\text{HPO}_4$, 18-46-0). Also, with the addition of anhydrous ammonia, orthophosphoric acid can be combined and concentrated by the removal of a water molecule to produce the liquid, high-grade, ammonium polyphosphate ($\text{P}_2\text{O}_7^{4-}$) P fertilizer (10-34-0).

Native and fertilizer soil P undergo many changes with time. Chemical and physical weathering, along with a reduction in soil pH from the leaching of basic cations, give rise to the many forms of P secondary minerals, such as the Fe-enriched strengite and the Al-enriched variscite (Lindsay 1979). Dissolved and reprecipitated P can also become enveloped by compounds such as iron oxides (Fe_2O_3) and calcium carbonate (CaCO_3) and can become occluded and physically protected for long periods of time (Walker and Syers 1976, Bowman et al. 1998). With more time and the introduction of agriculture, soluble inorganic P becomes "fixed" by the soil reactive surfaces, or—through plant uptake—it becomes a part of the surface crop residue and roots and, ultimately, a part of the organic P in the soil organic matter (Bowman and Halvorson 1997). In some instances where large amounts of P are continually applied as fertilizer or animal manures, the surface P could become dislodged with the soil particle or in the manure, or even as water-soluble P, and carried away through erosion into runways, streams, and rivers (Sharpley and Smith 1990). Not only does this constitute a loss of

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Figure 1
P Cycle



the valuable P fertilizer resource but also a potential pollutant resulting in destruction of aquatic life forms when these bodies of water become nutrient-enriched and oxygen-deficient (Parry 1998).

Objectives. Our objectives were twofold. First, we wished to present an overview of different soil P pools (Figure 1) and discuss how these pools are generally determined, how they cycle, and how they relate to P soil testing, availability indices, and potential pollution. A secondary objective was to present data obtained from soils in the central Great Plains to show quantities of these pools and their relationships to existing soil properties, as well as to offer brief definitions of some of

the P terms used in this report. For more through overviews of P forms and methods, the following reviews and research papers (although far from inclusive) are suggested: Kuo 1996, Larsen 1967, Stevenson 1986, Tiessen and Stewart 1987, Sharpley and Smith 1985, Sharpley 1993, Selles et al. 1995, O'Halloran et al. 1987, Weil et al. 1988, Pote et al. 1996, Tiessen et al. 1984, Daniel et al. 1998).

Methods and Materials

Three very different Colorado soils relative to their physical and chemical properties were used to conduct the various soil P tests. These were an Ascalon loamy sand

(Aridic Argiustoll), a Platner silt loam (Aridic Paleustoll), and a Weld silt loam (eroded phase) (Aridic Paleustoll). Air-dried, 2 mm (0.0788 in), screened samples were used for all analyses. Phosphorus methods and references or synopsis of procedures are given in Table 1. Adsorption isotherms (Olsen and Watanabe 1957, Syers et al. 1972) were also determined on the three soils. To construct these isotherms, 16-hour equilibrations were carried out with 5 g (17.6 oz) soil to 50 mL (1.69 fl oz) 0.01 M CaCl₂. From these isotherms, the adsorption maximum and the phosphate buffering capacity (PBC) can be calculated or approximated. The latter parameter is obtained from the slope of the line relating the change in the quantity of P adsorbed to the change in the concentration of P in solution, and the former when the slope of that line is zero or when no more P is adsorbed.

Although references are given for most of these methods, a brief description of those not fully shown will be given here. All determinations for inorganic P (Pi) are based on the removal of an aliquot from an extract or digest. The source of extract or digest is based upon the pool or form of P to be determined. For example, total organic P method uses a hot (90°C, or 194°F) basic EDTA extraction (Bowman and Moir 1993), while the Olsen P method uses NaHCO₃, and acid-extractable P method, dilute H₂SO₄. The extract is then neutralized to obtain the appropriate pH for optimal colorimetry at 882 nM (8820 Å) wavelength after the addition of the ascorbic acid-molybdate-blue reagent (Watanabe and Olsen 1965). The colorimetric reading, which requires some time for full color development, is then converted to P concentration or quantity from a calibrated P standard curve. For organic P (Po) determination, the same aliquot or an appropriate-size aliquot is oxidized or digested to convert the organic P to its inorganic (Pi) form. This digestion is usually accomplished with the addition of an oxidizer such as potassium persulfate (K₂S₂O₈) in 5.5 M H₂SO₄ at a temperature of about 200°C (392°F) (Bowman and Moir 1993) for about 30 minutes. (Water is boiled away.) Note that neutralization of the acidic digest will be required. Some soil testing institutions determine P by inductively coupled plasma spectroscopy. Because of the high temperature (1,000°C) (1,832°F) generated by this procedure, total P (Pi plus Po) is obtained

Table 1. List of selected P methods and references.

P methods	References and procedures
NaHCO ₃	Olsen et al. 1954, Olsen and Sommers 1982, Kuo 1996
Bray 1	Bray and Kurtz (1945) as modified by Soil Analysis Handbook of Reference Methods, Soil and Plant analysis Council Inc. 1999.
Anion-exchange strips	Commercial membranes cut into strips (Tiessen and Moir 1993)
Water-soluble	5 g soil to 50 mL water shaken 1 hr (requires centrifugation)
CaCl ₂ -soluble	Same as water-soluble but extracted with 0.01 M CaCl ₂
Total organic	Bowman and Moir (1993), Olsen and Sommers (1982)
Acid-extractable	1 g soil extracted (shaken) with 100 mL 0.5 N H ₂ SO ₄ for 1 hr
Occluded	Bowman et al. (1998)
Total	Bowman (1988), Olsen and Sommers (1982)
Sequential extractions	Tiessen and Moir 1993, Hedley et al. 1982, Kuo 1996

from the extract. For both Pi and Po determinations, one should always run appropriate blanks to account for potential interferences.

Four different sources of aged dried manures (beef, chicken, dairy, and swine) were also evaluated for P content by various organic and inorganic P methods. Manures were also ground to pass through a 2 mm (0.0788 in) screen. Ash content was determined from the content of residue remaining after combustion of samples at 550°C (1022°F) for two hours.

Data presented represent averages and standard deviations where appropriate. Analysis of variance for mean differences among the same pools for the three soils were conducted, and the LSD_{0.05} critical value is listed (Gomez and Gomez 1984).

Results and Discussion

When soluble fertilizer P is applied to soils, some is taken up by plants (Figure 1), but a large part interacts primarily with water and the Ca ion of the neutral and calcareous soils of the Great Plains to form compounds of lower P solubility (Lindsay et al. 1962). In acid soils, this interaction occurs with Fe and Al compounds. This precipitation, or P sorption reaction, where soluble P is lost from the soil solution, is collectively referred to as P fixation. It is the main reason high-availability fertilizer P is often applied in bands in neutral and calcareous soils and soluble plant-available P is generally low in soils. Alternatively, low-availability P (phosphate rock) can be broadcast in acid soils, because maximum fertilizer-soil mixture is ideal for P solubilization. The most soluble forms of P, monocalcium phosphate, MAP, and polyphosphates, with sufficient time, are converted to the low-solubility hydroxyapatite by way of dicalcium phosphate and tricalcium phosphate (Lindsay et al. 1962). The soluble P can also be fixed on the surface of calcium carbonate (alkaline soils) and oxides of Fe and Al (acid soils) (Sample et al. 1980).

The general reaction pathway in semiarid soils such as the Great Plains, is:

Fert-P (monocalcium phosphate) → Octocalcium phosphate → Hydroxyapatite (Most soluble) → (Least soluble)

In acid soils, P solubility is mostly controlled by the minerals strengite (FeSO₄.2H₂O) and variscite (AlPO₄.2H₂O).

Table 2. Comparison of Olsen and Bray-1 P soil tests, and their response to certain crops. Samples taken 0 to 15 cm (0 to 6 in) or 0 to 20 cm (0 to 8 in) deep; 10 to 15 cores/8 ha (20 ac).

Bray-1 Soil test levels	Olsen ug/g	Relative levels	Crop response [†]				
			Corn	Grain sorghum	Small grains	Soybean	Alfalfa
0-5	0-3	Very low	Hp	Hp	Hp	Hp Hp	
6-15	4-10	Low	Pr-Po	Pr-Po	Pr	Po-D	Pr
16-24	11-16	Medium	D	D	Po	D	D
25-30	17-20	High	D	D	D	D	D
> 30*	> 20*	Very high*	D	D	D	D	D

[†] Crop response: Hp = highly probable; Pr = probable; Po = possible; D = doubtful

* Potential exists for P environmental pollution.

While the fertilizer industry has specific ways of measuring P fertilizer solubility (water- and citrate-extractable), once the P fertilizer mixes with soil, a regional soil test is more appropriate for assessing its plant availability and its potential for pollution. The two most common tests in the Great Plains are the sodium bicarbonate (NaHCO₃-extractable P or Olsen-P test) and the Bray and Kurtz extractable P or Bray-1 P test (Olsen et al. 1954, Bray and Kurtz 1945, Kamprath and Watson 1980). The first test is used in neutral and calcareous soils, the latter in acid soils. A Mehlich 3 test (Mehlich 1984) is also commonly used in both acid and calcareous soils and has the added advantage, like the NH₄-HCO₃-micronutrient test (AB-DTPA) (Soltanpour and Schwab 1977), for alkaline soils to extract multi-elements.

Clay reactive surfaces (calcium carbonate, hydrous oxides) can also fix P. As shown in Figure 1, the soluble P can be fixed, taken up by plants and microbes, leached in very sandy soils, or removed by erosion and become a

potential pollutant. The soluble P (sometimes called P intensity) is in dynamic equilibrium with the mineral P (primary mineral plus fixed or secondary P), which feeds into the soluble P pool once P is taken up by the plants. This process of replenishing P in solution is referred to as the P buffering capacity (PBC) and is a function of reactive surfaces (initial P intensity) and initial P quantity (all mineral P sources and P from labile organic P sources). The soil test P (Table 1) is a part of the above pools (mineral and soluble). Quantification of the soluble P is usually determined with water or dilute salts (CaCl₂ or KC1), which try to simulate the conditions (pH, ionic strength) of the soil solution.

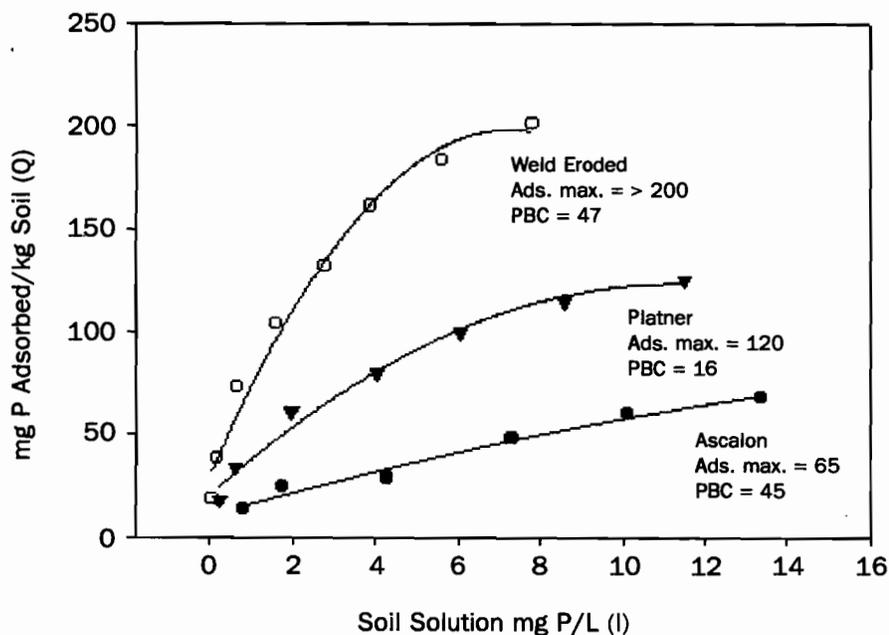
Once the soluble inorganic P is taken up by plants (or microbes), it is converted to organic P. Upon completion of the plant's life cycle, part of this P is transported into the grain (or fruits). Small grains can extract a sizable amount of P from the soil system (0.4% P in grain biomass). Part of the P in the crop is recycled with the stubble, stover, or

Table 3. Selected P pools in an acid Ascalon loamy sand, a neutral Platner loam, and a calcareous Weld silt loams. Pi is inorganic P; Po is organic P. Values represent means and standard deviations and critical values for comparison among means.

P parameter	Soils			LSD _{0.05}
	Ascalon l s	Platner l	Weld si l	
Olsen Pi (mg/kg)	17±2	23±3	9±2	4
Bray 1 Pi (mg/kg)	23±3	37±3	< 1.4	
AER (resin strips) Pi (mg/kg)	25±3	40±4	10±2	5
0.01 M CaCl ₂ -Pi (mg/L)	0.14±0.02	0.06±0.01	0.02±0.01	0.02
0.01 M CaCl ₂ -Po (mg/L)	0.16±0.02	0.19±0.02	0.15±0.02	0.04
Basic EDTA-Po (mg/kg)	42±4	137±9	119±7	11
Acid-Pi (mg/kg)	180±11	240±12	390±22	28
Total P (mg/kg)	220±10	360±15	475±15	24
soil pH	6.2	7.0	7.7	
Fines (silt + clay) (%)	18	67	70	
Soil organic C (%)	0.47	0.90	0.84	
CaCO ₃ (%)	0	0	2.0	

Figure 2

Adsorption isotherms relating adsorbed P (Q) to solution P (I).



dead leaves and ultimately into plant litter and soil organic matter. This soil organic P pool can contain resistant (slow-decomposing) or labile (fast-decomposing) organic P. Like the mineral P, the organic pool can also replenish the soluble plant-available P pool. This pool on the surface or near the surface may be subjected to wind and water erosion and transfer to sensitive water bodies (Parry 1998).

The Olsen test (0.5 M NaHCO₃) is used in calcareous soils (pH > 7.2) because the bicarbonate in the extract precipitates Ca as calcium carbonate and renders the P more soluble (Olsen et al. 1954). Modifications of

this test include the Colwell Procedure (1963), and the AB-DTPA procedure, developed at Colorado State University, which usually extracts one-half the amount of plant-available P compared with the Olsen test. The procedure is also adequate for slightly acidic and neutral soils. The Bray 1 test (0.03 M NH₄F+0.02 M HCl) is used in acid soils, because fluoride in the extract precipitates Al and renders the P more soluble (Bray and Kurtz 1945).

Table 2 shows a comparison of the Olsen and Bray tests (availability indexes) and their response to certain crops. These indexes have been developed by state agencies in Nebraska

and Colorado and are being used extensively in the Great Plains. Note, with the exception of small grains, a medium soil test level may be adequate for most crops. Some fertility experts, though, still advocate application of P for medium levels, especially as a starter to overcome low temperatures in the spring or against soil compaction. From the list of crops, soybean (*Glycine max*) appears to be the least sensitive to P needs. Where high levels of manures are regularly applied, soil test P values may exceed the very high level and create a potential for P pollution. Other extractants for areas outside the Great Plains include those developed by Mehlich (No. 1 and No. 3), and Morgan (Soil Analysis Handbook 1999).

Selected P pools for the three soils are shown in Table 3. Total soil P (sum of all organic and inorganic P pools) varied from 0.022% for the sandy soil to 0.048% for the calcareous silt loam. This procedure requires strong acids and peroxide to convert all forms of P to the inorganic (Bowman 1988, Olsen and Sommers 1982). From Tables 1 and 3, only the calcareous Weld soil would require P fertilization. Note the lack of P extractability with the Bray test for this soil. The acidity in the extractant is too low to appreciably dissolve calcium carbonate, and essentially no chelation of Ca occurred. Note, though, that the resin-strip desorption procedure worked well with all three soils; note also the high acid extractability of the calcareous Weld soil where CaCO₃ is being dissolved to release inorganic P. The acid-extractable P pool is usually measured as part of sequential extractions to arrive at the Ca-associated pools (Tiessen and Moir 1993). Resin strips or its modifications have also been used to determine biologically available P in pollution studies (Menon et al. 1991, Thien and Myers 1992).

After many years of weathering and mineral dissolution, part of the re-formed secondary P can become enveloped by ferric oxide in acid soils and by calcium carbonate in alkaline soils. This physically protected P is referred to as occluded P, and its availability, especially in acid soils, can be extremely low. Measurements of this pool are rarely needed but essentially require removal of the ferric oxide envelope with dithionite, or the calcium carbonate with dilute acid before the P can be analyzed (Bowman et al. 1998).

At times, especially in natural systems and high-residue input systems, the organic P provides a significant part of the plant-avail-

Table 4. Extractable P by different methods for four manure sources. Values represent means and standard deviations.

P methods	Manure sources			
	Beef	Chicken	Dairy	Swine
	mg P/ kg			
Resin strip 1 hr	1070±60	3000±160	1980±90	3740±200
16 hr	4700±210	7950±350	4790±240	9010±430
Water 1 hr	2450±120	5620±270	4300±230	6820±320
0.01 M CaCl ₂	570±35	2350±120	505±30	4420±220
Leached (water)	1040±50	3790±190	2450±120	5680±230
Bray 1	2750±130	6980±290	3580±170	8970±370
Olsen	3350±160	6110±250	4830±230	7950±320
Total Po	1120±80	6650±350	2220±160	2050±140
Total P	7750±310	22100±1000	6020±280	12810±600
Ash content (%)	44	60	86	44

able P. High organic matter soils and no-till systems where more residue remains than is oxidized will contribute P from the organic P to plants (Figure 1). These soils are usually fine-textured with a great capacity for nutrient release. The loamy sand Ascalon soil contained very little total soil organic P as measured by the basic EDTA method (Table 3), but high amounts of CaCl_2 -soluble inorganic P relative to the two other soils. Note also higher levels of organic P (Po) than inorganic P (Pi) in the CaCl_2 -soluble extract. Phosphorus usually moves in the soil in this organic form (Hannapel et al. 1964). The higher total organic P in the finer-textured soils correlates well with the soil organic carbon content. The organic P extracted in the Olsen procedure has also been regarded as labile and readily mineralizable for plant use (Bowman and Cole 1978). Plant residues and litter can contribute about 0.05 % of their biomass to P recycling.

Sequential extractions are used to measure various forms of chemical P in a soil because of differences in soil type, climate, and management (Tiessen and Moir 1993, Chang and Jackson 1957). In the Tiessen and Moir procedure, resin strips and bicarbonate are presumed to extract a more labile and plant-available form of P, dilute base; the P associated with Fe oxides, dilute acid; the Ca phosphates; and, lastly, the resistant P forms remain in the soil residue. This procedure estimates the progression and cycling of fertilizer P through the soil-plant system. Use of radioactive P (P-32) can serve a similar purpose (Morel et al. 1994) and was originally used to determine the labile (L-value) or exchangeable P (E-value) pool (Larsen 1967).

While the soil test is instructive in giving the relative seasonal amount of plant-available P, it tells nothing about the soil's tendency to supply P (P buffering capacity, or PBC), and the maximum amount of P the soil can hold when P is added through fertilizers and manures (adsorption maximum). For instance, the Ascalon soil has a higher CaCl_2 -soluble Pi level but a lower soil test P level than the Platner soil. The P adsorption isotherms (Figure 2) incorporate these two factors of soil solution solubility, P intensity and P quantity (soil test P, resin P, etc.). Thus, although the Ascalon soil has a relatively high CaCl_2 -soluble P level, its PBC (the slope of the P quantity to P solution) is relatively low, which means that this soil would not be able to supply P to the plants for a long time, and,

after a while, its intensity or available P would drop to deficiency levels. Note differences in PBC and adsorption maximum (P ads. max.), and its relationships to soil properties from Table 3. The calcareous soil can fix a lot more P than the sandy soil, and this is also reflected in the low soil test and the soluble P. After the adsorption maximum has been reached, the soil becomes very prone to P loss and potential pollution. This P adsorption maximum can be correlated to soil test P for soils with the same or similar properties. Because the soil test P is routinely determined and is easier to conduct than the adsorption isotherms, it is the analysis of choice also for monitoring P pollution potential (Table 3).

Manures can serve as a fertilizer and, if excessively applied, as a P pollutant during runoff events. Thus the quantity of P (source and application method), and the distance to sensitive bodies of water and the concomitant conducting properties of the soil (transport) are crucial components in determining pollution potential. A phosphorus index based on the above factors is being or has been developed by each state to address this potential problem. Table 4 shows values for extractable P in beef, chicken, dairy, and swine manures. These values are not corrected for ash content and would, therefore, be higher on an ash-free basis. Unscreened manure was much more variable than that which was passed through the 2 mm (0.0788 in) screen. Note that manures contribute both inorganic (Pi) and organic P (Po). Chicken and swine manures, with their litter, contained the highest amounts of total P and cattle manure the least. Note that in these instances, the organic P in manures varied from 27% (dairy with litter) to 6% (swine with litter). The basic EDTA procedure gave the greatest estimation of both the total inorganic and organic P, but other procedures with acid extractions were just as efficient for the inorganic P with the organic P released being about 80% of the basic EDTA procedure.

For monogastric animals, much of the P can be in the form of undigested phytate-P from the original grain feed, but the use of the phytase enzymes may be able to release more available P to the animal and thus reduce the pollution potential from excreta (Sharpley et al. 2001). For a greater understanding of the role of manures in agriculture, the following references are suggested (Shreve et al. 1995, Moore et al. 2000, Mueller et al. 1984).

In the final analysis, the bulk of the P is used in production agriculture for food, feed, and fiber. Adequate P levels promote early root formation and growth, improve the quality of fruit, vegetable and grain crops, and are vital to seed formation. They also improve water-use efficiency and N-use efficiency, and they enhance winter hardiness and early grain maturity. Thus, P quantity, placement, and timing are crucial for good management. As a nutrient that comes exclusively from the soil, P's adequate use and recycling are important to long-term productivity, and sustainability.

Summary and Conclusions

Phosphorus serves as an important soil nutrient, but it must be managed correctly so it does not become a pollutant. Its solubility in soil is very low, and fertilizer sources quickly become fixed or unavailable through precipitation and adsorptive processes. As P is removed from solution by these processes and by plant and microbial uptake, mineral surface or labile P renews the solution P. The rate of renewal (buffering capacity) is a function of soil texture and the quantity of exchangeable solid phase P. The soil test P reflects this availability of seasonal P and is one of the most useful parameters in P studies. For pollution studies, the P index has been introduced. The P soil test and a P index serve as good indicators of both fertility and pollution potential. However, knowledge of the soil P reactive potential (buffering capacity, maximum sorption) would be complimentary to soil test data.

Brief Definition of P terms

For more complete definitions of some of these terms, one can refer to the glossary provided by the Soil Science Society of America (1996).

Adsorption: Bonding of soluble P forms to clay surfaces (usually a physical phenomenon).

Available P: P that can be used by plants in a growing season (labile P). Usually P from a fertility index, P extractable in water or dilute calcium chloride, P on anion-exchange resins, or P (31) exchangeable with radioactive P (P-32). Available P measurements should always be accompanied by the method of extraction.

Desorption: release of P from clay surfaces to the soil solution (inverse of adsorption).

Dissolution: release of inorganic P from the mineral compound.

Fixation: P is converted from a soluble or exchangeable form to one less soluble or to a nonexchangeable form. General term for all of the above.

Organic P: P in crop residue, litter, grains, manures, and soil organic matter that cannot be measured directly without oxidation or chemical digestion (nucleic acids, phytates). Can be measured as total or partial in a given extract (0.5 M NaHCO₃; 0.5 NaOH; 0.5 M or 18 M H₂SO₄).

P buffering capacity: measures the resistance of the soil system to changes in I (the slope of a Q and I relationship; ($\frac{Q}{I}$ or $\frac{dQ}{dI}$)).

P fertility index: Soil testing value for level of available P (low, medium, high) such as Olsen-P, and Bray-1 P.

P-indexing tool: tool by NRCS and other state planners to rank vulnerability of fields as sources of P loss in surface runoff. Contains a transport and a source component.

P intensity (I) or solution: amount of soluble P in the soil solution (very small pool) in equilibrium with solid phase. Measured as mg P/L.

P quantity (Q) or capacity: amount of exchangeable P on the soil solid phase in equilibrium with the soil solution P. Measured as mg P/kg soil.

Precipitation: Soluble P forming solid complexes as a function of pH, usually with Fe, Al, and Ca.

Resin-extractable P: anion-exchange resin beads or strip used as sink to fix P desorbed from a solid phase (soil, manure) into solution.

Soil P saturation: percent saturation of available P to maximum P fixation.

Sorption: Same as above but can be physical, chemical, or biological.

Threshold soil P: based on perceived soil P test levels above which could cause eutrophication from runoff.

Total soil P: P extracted with strong acids and strong oxidizing agents. May require fusion and hot digestion operations.

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