

contribute to a wide range of water-related problems including summer fish kills, unpalatability of drinking water, and formation of trihalomethane during water chlorination (Kotak et al. 1994, Palmstrom et al. 1988). Consumption of cyanobacterial blooms or water-soluble neuro- and hepatoxins released when these blooms die can kill animals and may pose a serious health hazard to humans (Lawton and Codd 1991, Martin and Cooke 1994).

Because of these problems with drinking water treatment, some areas, such as New York State, have done a “U turn” in strategic planning for nutrient management and water quality impacts. It is now cheaper to treat the cause of eutrophication rather than its effects. In the early 1990s, New York City decided it would be more cost-effective to identify and remediate the sources of P in its water supply watersheds rather than build a new water treatment facility. Since then, a variety of programs were established to control nutrient loadings for point and nonpoint sources (NPSs) in the New York City watershed. Because their concern was freshwater quality, P was the main nutrient of consideration.

Recent outbreaks of the dinoflagellate *Pfiesteria piscicida* in the eastern United States may also be influenced by nutrient enrichment (Burkholder and Glasgow 1997). Although the direct cause of these outbreaks is unclear, the scientific consensus is that excessive nutrient loading helps create an environment rich in microbial prey and organic matter that *Pfiesteria* and menhaden (target fish) use as a food supply. In the long term, decreases in nutrient loading will reduce eutrophication and will likely lower the risk of toxic outbreaks of *Pfiesteria*-like dinoflagellates and other harmful algal blooms. This has dramatically increased public awareness of eutrophication and the need for solutions.

The sources of P and N to lakes and rivers consist of point sources, such as discharges from factories and sewage treatment plants, and NPSs, such as suburban lawns and agricultural lands. On a practical basis, point sources are readily identified and measured, while NPSs are diffuse and difficult to identify and measure. The main NPSs contributing to the P load of water bodies are summarized in Table 34-2. Runoff from uncultivated or pristine land is considered the natural background loading, which cannot be reduced. This source determines the natural trophic status of a lake or river and can be sufficient to cause eutrophication.

In this lesson, P is referred to in its elemental form rather than as P_2O_5 , commonly used in fertilizer analysis. The conversion factor from P to P_2O_5 is 2.29. When plant-available forms of soil P (as determined by soil testing laboratories) are discussed, they will be referred to as soil test P (ppm or mg/kg) and in each case the specific method of analysis used will be identified. Based on a six-inch soil depth containing 2 million pounds of soil, the conversion factor from ppm to lbs P/acre is 2.0. For more detailed information on the methods used for soil P testing, how they were developed, and why they vary among regions, see the following articles: Fixen and Grove (1990), Sharpley et al. (1994 and 1996), and Sims (1998).

The Forms and Reactivity of P in Soil

Soil P exists in inorganic and organic forms (Figure 34-2). Each form consists of a continuum of many P compounds, existing in equilibrium with each other and ranging from solution P (taken up by plants) to very stable or unavailable compounds (the most typical). In most soils, 50% to 75% of the P is inorganic.

...P is the primary agent in freshwater eutrophication...

Added P is rapidly fixed by Al, Fe, and Ca compounds in soil...

Table 34-2. Nonpoint sources of phosphorus.

Terrestrial	
Runoff from pristine land ¹	<ul style="list-style-type: none"> • soil erosion • animal excreta • plant residues
Runoff from cultivated land ¹	<ul style="list-style-type: none"> • soil erosion • fertilizer loss • animal excreta • plant residues • sewage sludge
Runoff from urban land ¹	<ul style="list-style-type: none"> • soil erosion • septic tanks • domestic waste
Atmosphere (cultural ² ; natural ¹)	<ul style="list-style-type: none"> • wet precipitation • dry precipitation
Aquatic	
Lake sediments ²	<ul style="list-style-type: none"> • bottom sediments • resuspended sediments
Biological ¹	<ul style="list-style-type: none"> • fauna and flora

¹ Impossible to control.

² Difficult to control.

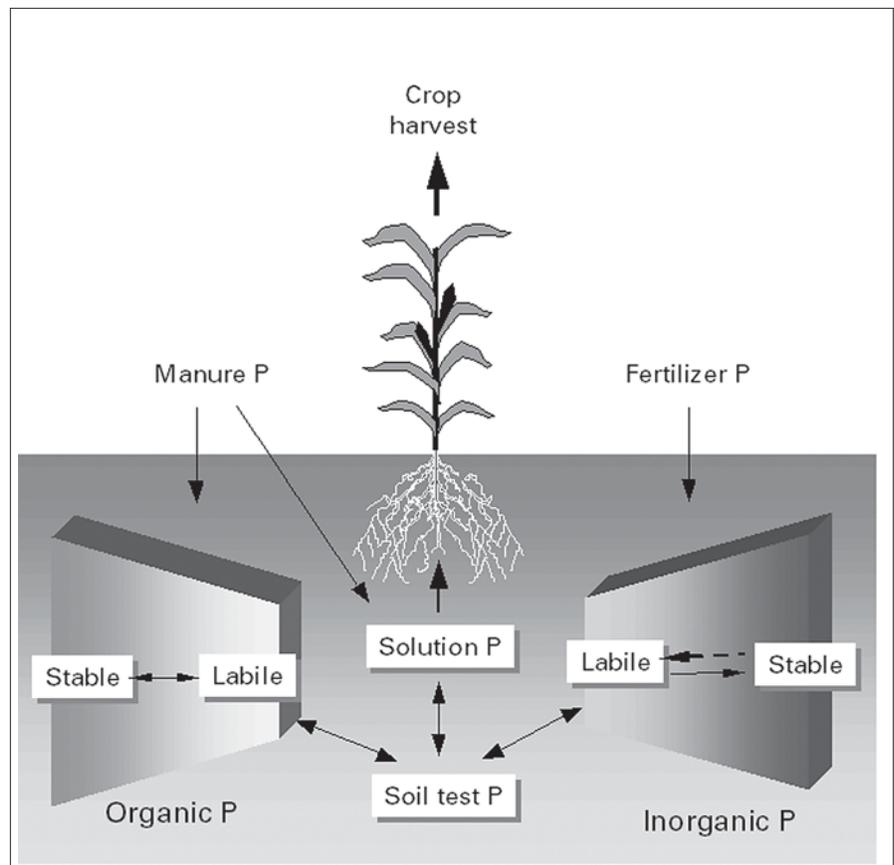


Figure 34-2. The P cycle in soil.

Inorganic P is usually associated with Al, Fe, and Ca compounds of varying solubility and availability to plants. Phosphorus has to be added to most soils so that there are adequate levels for optimum crop growth and yield. However, P can be rapidly fixed (also referred to as sorption) in forms unavailable to plants, depending on soil pH and type (Al, Fe, and Ca content). Conversion of unavailable to available forms of soil P usually occurs too slowly to meet crop P requirements (dashed line on Figure 34-2). As a result, soil P tests were developed to determine the amount of plant-available P in soil and from this how much P as fertilizer or manure should be added to meet desired crop yield goals. The estimated amount of plant-available soil P is subsequently referred to as soil test P.

Organic P compounds range from readily available undecomposed plant residues and microbes within the soil to stable compounds that have become part of soil organic matter. Biological processes in the soil, such as microbial activity, tend to control the mineralization and immobilization of organic P. Mineralization is the breakdown or conversion of readily available organic P to inorganic solution P. Although this occurs in most soils, it is usually too slow to provide enough P for crop growth. Immobilization is the formation of more stable organic P, which is resistant to breakdown.

In most soils, the P content of surface horizons is greater than subsoil (Figure 34-3). Except in special situations, added P tends to be fixed by the soil where it is applied, allowing for little movement down through the soil. In addition, P is cycled from roots to above ground parts of the plant and re-deposited in crop residues on the soil surface. This builds up organic material and stimulates biological activity in surface layers. Further, in reduced tillage systems, fertilizers and manures are surface applied with little or no mechanical incorporation, exacerbating P buildup in the top 2 to 5 inches of soil.

Phosphorus content and availability varies with soil parent material, texture, pH, as well as with management factors such as the rate of P

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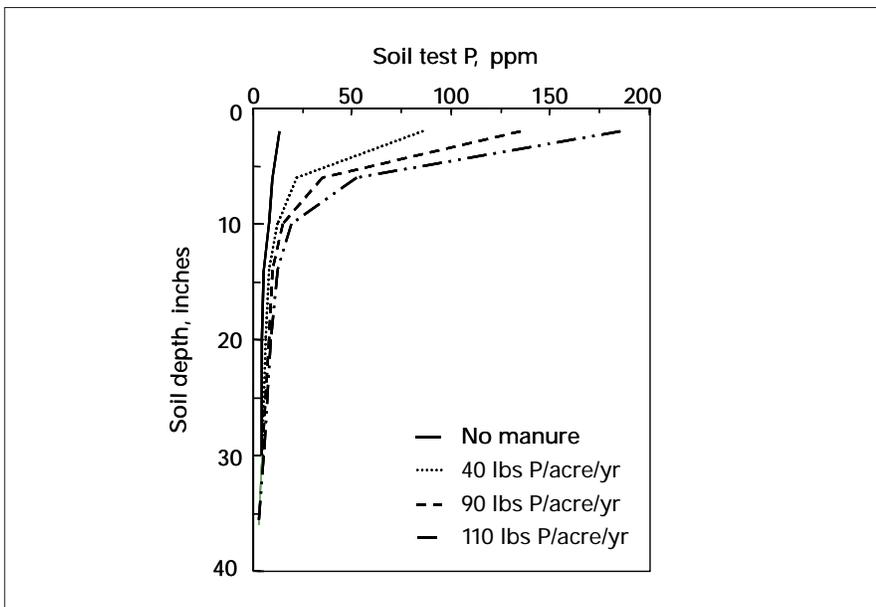


Figure 34-3. Soil test P (as Mehlich-3 P) accumulates at the surface with repeated application of P for 10 years. Note that typical fertilizer P applications for a corn crop in Oklahoma with a medium soil test P (20-40 ppm Mehlich-3 P) is about 20 lbs P/acre.

Adapted from Sharpley et al. 1984.

...crop removal of inorganic P from soil is generally low. In the United States, an average 29% of P added in fertilizer and manure is removed by harvested crops...

...the rapid growth of the animal industry in certain areas of the United States ... [has created] regional and local imbalances in P inputs and outputs...

applications and tillage practice. Although P is relatively immobile in the soil, it is not non-mobile. It can move, especially where soils have become highly enriched with P.

Overall, soil pH is the main property controlling inorganic P forms, although Al, Fe, and Ca content determine the amounts of these forms (Figure 34-4). In acid soils, Al and Fe dominate fixation of P, while Ca compounds fix P in alkaline soils. As a result, P availability is greatest at soil pH between 6 and 7 (Figure 34-4). Immobilization of inorganic P by these processes renders a portion of the added P unavailable for plant uptake (Figure 34-5). Mehlich-3 soil P decreased with time after application of P to a clay and silt loam soil. At the same time, more inorganic P was fixed with Al and Fe (Figure 34-5). This illustrates why crop removal of inorganic P from soil is generally low. In the United States, an average 29% of P added in fertilizer and manure is removed by harvested crops, ranging from < 1% in Hawaii to 71% in Wyoming (National Research Council 1993). The low recovery reflects the predominance of high P-fixing soils in Hawaii.

The Evolution of Agriculture from P Sink to P Source

In many states, animal feeding operations (AFOs) are now the major source of agricultural income. However, the rapid growth of the animal industry in certain areas of the United States has been coupled with an intensification of operations. For example, during the last 10 years, cattle, pig, and poultry numbers have increased 10% to 30%, while the number of farms on which they were reared has decreased 40% to 70% (Gardner 1998).

This intensification has been driven by a greater demand for animal products and an improved profitability associated with economies of scale. Also, it has resulted in a major one-way transfer of P from grain-producing areas to animal-producing areas, creating regional and local imbalances in P inputs and outputs (Lanyon 2000, Sharpley et al. 1998, Sims 1997). On average, only 30% of the fertilizer and feed P input to farming systems is output in crops and animal produce.

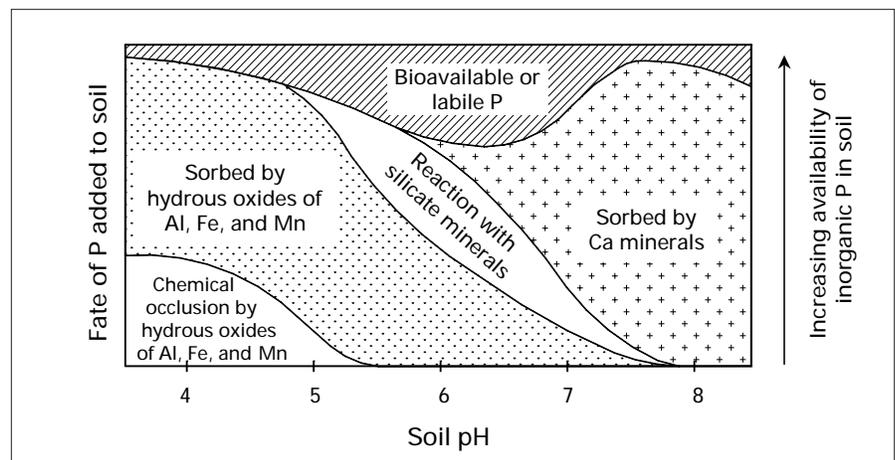


Figure 34-4. Approximate representation of the fate of P added to soil by sorption and occlusion in inorganic forms, as a function of soil pH.