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A Soil Phosphorus Primer for Hawaiian Soils

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Phosphorus (P) is a macronutrient essential for many plant processes, such as DNA structure, energy production, stimulating healthy root growth, and signaling flower and fruit development. Low soil-P levels may lead to stunted plants, poor fruit development, and overall poor yields. Adding too much P to soils wastes fertilizer; can cause excess soil-P build-up, leading to potential contamination of surface water resources; and may inhibit the availability of other plant nutrients like iron and zinc (Havlin et al. 2005, Silva et al. 2000). This publication will describe the primary soil factors that affect P availability after it is added as a fertilizer and provide simple guidelines for P management in Hawai'i's diverse soils.

I. P Status of Hawaiian Soils

Clay mineralogy and soil pH are primary drivers of P availability in soils. In Hawai'i, soils can be divided into three general categories based upon their mineralogy and pH.

1 **High-activity clay[1] soils:** Formed under alternating wet and dry climates or as stream deposits on valley plains. Swell when wet, shrink/crack when dry. Near-neutral pH and high in nutrients. Examples: Wai'anae, Kahuku (O'ahu); central Maui; and Leeward Kaua'i.

2 **Low-activity clay[2] soils:** Rich in iron and aluminum oxide clay minerals that formed over millennia in wet climates undergoing intense weathering. Red in color and often acidic. Low in nutrients (e.g., calcium, magnesium, potassium). Common to windward Kaua'i and O'ahu, parts of west Maui, and upland forest lands.

3 **Volcanic ash-derived soils:** Soils formed in volcanic ash deposits characterized by non-crystalline clays with very high surface area. In areas with a wet climate (e.g., Hāmākua and Hāna), these soils are acidic and low in plant nutrients. In areas with seasonal rainfall, these soils are very fertile with near-neutral pH. Examples: mid-elevation Kona to Waimea (Hawai'i Island); Kula (Maui).

II. Processes Affecting P Availability

Synthetic fertilizers release P relatively quickly into the soil solution as orthophosphate ($H_2PO_4^-$, HPO_4^{2-}) that is readily available for plant uptake. Organic inputs must first be decomposed or mineralized by soil microbes to release orthophosphate into solution. Once in solution, P is quickly subject to transformations and processes driven by various soil factors, namely soil pH, clay mineralogy, and organic matter.

[1] High-activity clays include the following clay minerals: montmorillonite, hydrated halloysite, and vermiculite. These clay minerals have high nutrient retention per mass of mineral and have significant shrink–swell response under wetting and drying cycles.

[2] Low-activity clays include the following clay minerals: kaolinite and iron and aluminum oxides (i.e., hematite, goethite, gibbsite). These clay minerals have low nutrient retention per mass of mineral and do not shrink or swell under wetting and drying cycles.

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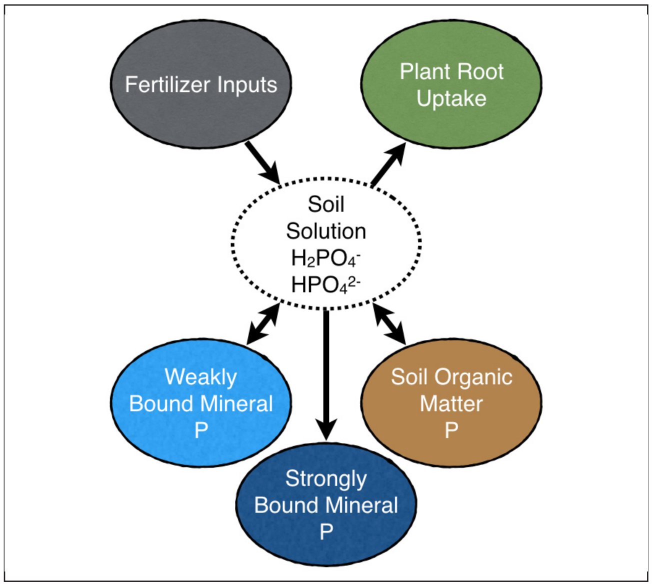


Figure 1. Fertilizer P dissolves into the soil solution, where it can follow four potential pathways that are in competition with each other: 1) plant roots uptake soil P; 2) soil P becomes temporarily weakly bound in various mineral forms and to clay surfaces; 3) soil P becomes strongly and permanently bound to mineral and clay surfaces; or 4) solution P is taken up by soil microbes into organic forms, which can later be released back into solution after decomposition.

Soil pH and Mineralogy Control Weakly Bound Mineral P

Soil P is most available between pH 6 to 7. In this pH range, P has the highest potential to be in soil solution and available to plants. In acidic soils (pH <6), P precipitates with dissolved iron (Fe) and aluminum (Al) to form solid minerals. This is the case in highly weathered oxide and volcanic-ash soils, such as on eastern Kaua‘i, central O‘ahu, and the Hāmākua coast of Hawai‘i Island. On the other hand, in alkaline conditions (pH >7), dissolved calcium (Ca) reacts with P to form solid minerals, taking P out of solution. In Hawai‘i, alkaline soils occur on coastal plains like ‘Ewa (O‘ahu) or Central Maui that were formed over ancient coral beds and limestone. Fortunately, soil pH can usually be adjusted with lime or sulfur, which increases the availability of weakly bound mineral forms of P.

Clay Mineralogy Controls Strongly Bound Mineral P

Phosphorus in solution can become strongly bound or “fixed” to clay surfaces, after which it is generally unavailable for plant uptake (see Figure 2 for more detail). P-fixation is a characteristic problem of highly weathered soils rich in oxide clays and volcanic-ash soils containing non-crystalline clays. This is due to the high surface area and reactivity of these clay minerals. The ash soils of the Hāmākua and Hāna regions of the Big Island and Maui are often P deficient because of their extremely high P-fixation capacity, thus requiring high P inputs initially to meet plant P needs. Less-weathered high-activity clays (e.g., Wai‘anae) and young soils rich in organic matter (e.g., Puna) have a low P-fixation capacity requiring lower P inputs (Fox and Searle 1978).

Organic Matter Holds and Releases P and Increases Mineral P Availability

Typically, a large proportion of soil P exists in organic forms (30–65%), primarily because significant quantities are continuously added to soil in the form of plant and root residues, animal manures, and microbial detritus. Organic forms of P can make substantial contributions to the P nutrition of plants, but these contributions are difficult to quantify because the transformation of organic P to orthophosphate is controlled by soil biological and physical properties, environmental conditions (temperature and moisture), and land-use history. In simple terms, organic inputs with too much woody material (C:P ratio >300) will tie up soil-solution P and make it unavailable for plants until the material is more fully broken down. On the other hand, manure inputs with high concentrations of P contribute P to soil solution, and repeated applications can lead to excess P accumulation (Condron et al. 2005, Paul 2007).

Organic matter decomposition can increase P availability via 1) displacement of weakly bound P molecules by organic molecules and 2) coating of clay surfaces, which prevents P-fixation. Readily available sources of organic P include bone and fish meals and animal manures, which, when used in soils with high P-fixation capacity, can greatly improve P availability.

III. Managing Soil P

One of the first steps in proper management of P fertilizer is to know the mineralogy and current P status of your soil. The Hawai‘i Soil Atlas (http://gis.ctahr.hawaii.edu/SoilAtlas#map) provides soil taxonomic information, P-fixing capacity, and expected pH range. A soil test, however, is indispensable, as it will assess current

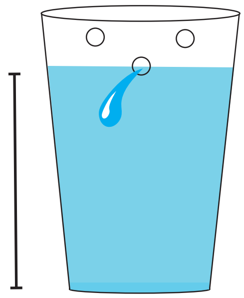
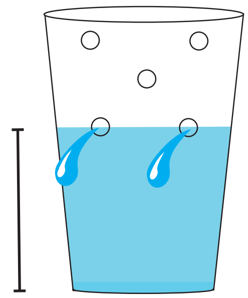
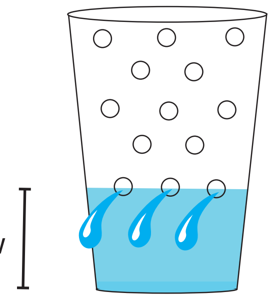
P-Fixation Capacities of Mineral Types and Soil Series			
P-Fixation Capacity	Very High 	High 	Low 
Clay Minerology Types	Non-crystalline clays (volcanic-ash derived)	Low-activity clays (e.g., Al/Fe oxides and kaolinite)	High-activity clays (e.g., halloysite, montmorillonite)
Soil Series Examples	Hilo, Honokaʻa, Hāna, Waimea, Kula	Kapaʻa, Wahiawā, Haʻikū, Leilehua	Lualualei, Waialua

Figure 2. P fixation in soils can be described in terms of a cup with holes in it. In the figure, the bottom part of the cup with no holes represents that soil's P-fixing capacity, while the blue water level is the amount of P fertilizer added to the soil. Water contained in the bottom of the cup represents fixed P that becomes permanently unavailable to plants. Water that leaks from the holes is weakly bound P that enters the soil solution and is available for plant uptake. In a low P-fixing soil, a small amount of P fertilizer will overcome the fixation capacity and meet plant nutrient requirements. Soils with "High" or "Very High" fixation capacities require much higher P inputs to overcome fixation and fully supply plant requirements. In soils with a long history of P application, "water levels" already can be quite high, allowing farmers to reduce P fertilizer application to the amount needed to resupply plant uptake of P.

pH and the concentration of available P in the soil. With these two pieces of information, a decision can be made on the need for liming and P fertilizer.

Choosing the Right Source

There are many types of synthetic P fertilizers in pelletized and liquid forms that deliver soluble P to the soil. They can be bought as single-P fertilizer materials such as triple super-phosphate (e.g., 0-45-0) or in a myriad of blended forms with nitrogen and potassium (e.g., 10-30-10). Organic sources of P include materials like bone meal (10–25% P) and fish meal (4–6% P). Although a mineral, rock phosphate (27-41% P) is a P-rich fertilizer, with certain products approved for use in organic cropping systems, but P availability from this source is typically low, except in acidic soils below pH 5.5 with low calcium levels (Nelson and Janke 2007, Silva 2000). Overall, organic sources release P more slowly—over several weeks or months—compared to synthetic fertilizers, which release most of their P within days. However, organic amendments allow for higher P availability in high-fixation soils and also build soil P over time. Regardless of type, when P levels are excessively high in soils, this means soil reserves are full and fertilizers low or absent in P should be utilized.

Determining the Right Rate

When making P fertilizer-rate decisions, three pieces of information at minimum are needed: 1) crop P requirement, 2) current soil P concentration from a soil test, and 3) the soil's P-fixation capacity (Hue and Fox 2010). In fields with a long history of P application, fixation is less limiting, as the clay surface bonding sites have already been filled with P. Once enough P fertilizer has been added to overcome P fixation and soil-test P levels are sufficient, P inputs can be decreased to merely replace the small amount that crops take up (see Figure 3). In areas that have accumulated excessive soil P, fertilizer

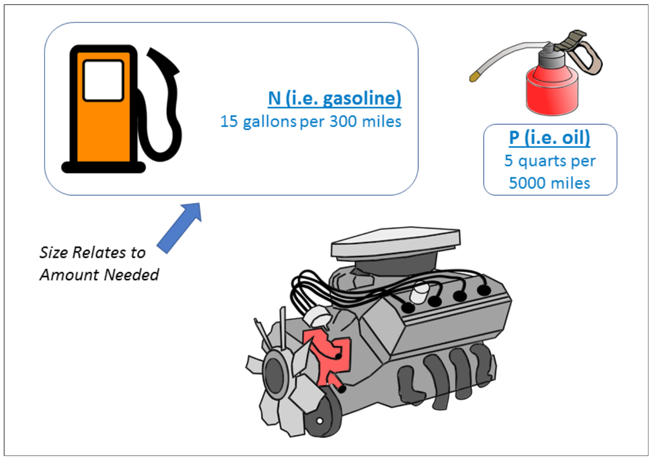


Figure 3. Soil P can be likened to the oil required by the engine. Initially, a large amount is needed to fill the oil tank, but thereafter, small amounts are needed to maintain optimum oil levels. Nitrogen, on the other hand, is like gasoline. It is used in relatively large amounts, quickly, and requires frequent replenishment.

schedules should switch to mixtures with little to no P (e.g., 46-0-0 or organic inputs such as feather meal (13-0-0) or leguminous sources of N).

Applying in the Right Place

When applying P fertilizers, applications should be placed close to where plant roots will grow, either by banding or strip tillage, rather than being broadcast over the entire soil surface. Banding P fertilizer increases efficiency by reducing contact between fertilizer and soil surfaces, which minimizes fixation, and by increasing solution-P concentration near plant roots to levels needed for optimum growth. Banding P fertilizer is especially beneficial in high P-fixing soils. The benefits of banding are highest in soils with low P concentrations, diminishing as solution-P concentrations reach high levels or with high P-fertilizer application rates (Uehara and Gillman 1981).

Erosion Is the Main Pathway of P Loss

As P is often held in or on soil particles and organic matter, the main way P is lost from a field is via wind and water erosion. In soils with high P, surface runoff can wash dissolved P into streams and water bodies. In sandy soils and soils with low P-fixation capacity that have a history of high manure application, downward leaching of P through the soil can occur. Losses of soil P can have negative impacts on water quality and aquatic life through algal blooms and fish die-off events (Mullins et al. 2005). To prevent erosion, soil-conservation practices such as contour and minimum tillage or buffer strips should be implemented on the landscape. Precise application and scheduling of P fertilizer as well as appropriate irrigation to match plant P and water requirements can minimize leaching of P into groundwater supplies.

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