

Technical Bulletin:

Phosphorus fertilizer use efficiency in soils

EXECUTIVE SUMMARY

- » Fertilizer phosphorus (P) use efficiency (recovery of fertilizer P) depends on factors related to the fertilizer itself, the crop grown, but mainly to the soil environment.
- » Recovery of fertilizer P by plants in the first year after application to low fertility soils is generally low.
- » The conversion of available P to less available forms in soil is the reason for the low initial efficiency of P fertilizers.
- » The orthophosphate anion, the predominant form of available P in soils, is strongly retained by soil mineral surfaces – a process termed adsorption – and also forms a range of insoluble compounds with soil cations (principally aluminium, calcium and iron) – a process termed precipitation.
- » In soils where adsorption is the dominant P retention mechanism (acidic and neutral soils), as the P status of soils is increased by fertilization, plants take up P from the fertilizer P added each year, as well as having variable access to residual P in the soil from fertilization in previous years, so that apparent P efficiency (or the P balance efficiency) increases. This is not the case in soils where precipitation reactions dominate P retention (alkaline calcareous soils) where P retention may not be diminished by previous fertilizer P applications.
- » Significant increases in fertilizer P use efficiency can be achieved by different fertilizer formulations, altering timing of application, altering placement in the soil or changing the rate of P applied and choosing crop species or varieties efficient at scavenging P from soils.

BACKGROUND

Soil phosphorus (P) deficiency is one of the major factors limiting crop yields worldwide. Although required by plants in a smaller quantity compared with other primary macronutrients (e.g. nitrogen and potassium) the inadequate supply of P results in severe limitations to plant growth.

In order to adequately supply P to crops, the addition of fertilizer P (or other sources) becomes necessary in most agricultural soils, especially in highly weathered tropical acidic soils. However, due to the complex behavior of P in soils, it is well known that only a small fraction of added P fertilizer is taken up by plants when soils are initially fertilized with P (McLaughlin *et al.* 2011). For this reason, P fertilizer recommendations for initially low P soils far exceed actual crop removal. As the P status of soils is increased by fertilization, plants take up P from the fertilizer P added each year, as well as having variable access to residual P in the soil from fertilization in previous years, so that apparent P efficiency (or the P balance efficiency) increases.

This factsheet describes how P use efficiency can be measured, what factors affect it, and management options to increase it.

HOW TO EVALUATE THE P USE EFFICIENCY?

Phosphorus use efficiency is defined in several ways. The traditional way of calculating the

recovery by crops of fertilizer P applied is using the difference method, according to the following equation:

$$P \text{ recovery (\%)} = \frac{P \text{ taken up by crop (fertilized soil)} - P \text{ taken up by crop (unfertilized soil)}}{\text{Amount of P applied}} \times 100$$

This method may overestimate P use efficiency if added P improves the access of the plant to P already present in the soil. A more accurate method to measure P use efficiency is the direct method by labelling a given fertilizer with an isotope (³²P or ³³P) and measuring recovery of the isotope by the crop.

Recently, (Syers *et al.* 2008) proposed that the balance method be used to assess fertilizer P efficiency. The balance method is described mathematically as:

$$P \text{ use efficiency (\%)} = \frac{P \text{ taken up by crop (fertilized soil)}}{\text{Amount of P applied}} \times 100$$

The “efficiency” obtained by the balance method is always higher than that by the difference method; and it may even exceed 100%, which indicates that soil P reserves are being mined. This is due to calculation artefacts from not taking into account an experimental plot without added P (Chien *et al.* 2012).

Thus, when you see P use efficiency figures quoted, it is worth checking how they were calculated.

The fate of added P in soil

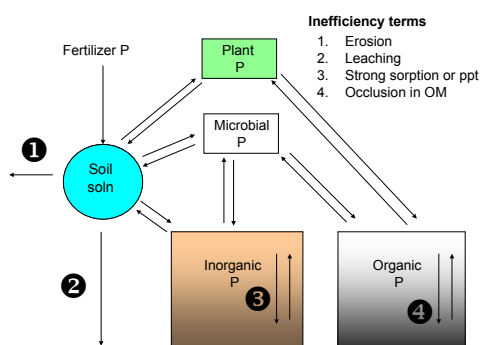


Figure 1. The fate of fertilizer P in soils and the processes that lead to inefficiency. Processes marked * only lead to inefficiency in the build-up phase of soil P fertility (strong retention) or when organic matter (OM) is accruing in soil over time (occlusion in OM).

PROCESSES THAT LEAD TO LOW FERTILIZER P USE EFFICIENCY

Conceptually, soil P is considered lost from the soil only when it is removed by crops, moved away in runoff or even leached under some specific instances (Figure 1).

When soluble P is added to soil, it strongly partitions to the solid phase in soils and onto the surface of clay-sized minerals. This is termed adsorption. Generally, the greater the clay content in soils, and the greater the proportion of clays dominated by aluminium and iron oxides, the stronger the retention of P. This is why the deep red soils (rich in iron oxides) often require large additions of P fertilizer when first brought into agricultural production. The retention of soluble P by adsorption to solid phases in soils is not irreversible (Figure 1) and adsorbed P can be desorbed to move back into the soil solution. When a soil is first fertilized with P, adsorption (movement of soluble P to soil surfaces) dominates, and P fertilizer efficiency is therefore low (often <20%, Equation 1) – some term this “fixation”, but the P is not irreversibly fixed. As more and more P is added to soil, the forward reaction weakens, and the reverse reaction (desorption of P back into soil solution) becomes faster, so that efficiency of added P fertilizer rises. At equilibrium, the adsorption and desorption reactions are equally fast. When the soil has reached a high P fertility status, amounts of P fertilizer added can be reduced (often to a level which just replaces P removed in produce) as efficiency is now high (approaching 100%), and the soil P fertility is now said to be at “maintenance” phase.

In highly calcareous soils, retention of soluble P is predominantly by a different process of moving P from soil solution to solid phases in soil, known as precipitation. Soluble P readily forms insoluble minerals with calcium (Ca) at high pH. While precipitation is also reversible (a process termed

dissolution), in highly calcareous soils there is enough available Ca to precipitate very large quantities of P, so that in these soils “P fixation” is indeed a problem (Bertrand *et al.* 2003).

Retention of P in organic matter is also only an inefficiency process when organic matter is accruing in soil. This may occur when low fertility soils are first fertilized, plant production increases and organic matter contents in soil increase (Williams and Donald 1957). It may also occur when cultivation of arable soils is reduced over an extended period in minimum till situations. As organic matter accumulates, so too does P in that organic matter, at a rate of ~20 kg P per ton carbon (Kirkby *et al.* 2011). Like the reactions with soil minerals, immobilization is reversible, and P can be mineralized from the organic matter if soils are cultivated or if other limitations to microbial processes are removed (e.g. liming of very acidic soils) (Haynes 1982).

REACTIONS OF P FERTILIZERS IN SOILS

When a fertilizer granule comes into contact with soil, water slowly moves toward the granule, dissolving it. Concentrations of P are high immediately around the granule, so that initially, precipitation reactions take place (Figure 2).



Figure 2. Precipitation of P binds soils around a fertilizer granule in a calcareous soil.

As phosphate ions in solution slowly migrate away from the fertilizer granule, P concentrations in soil solution reduce and adsorption is the dominant reaction reducing both P solubility and availability (Figure 3). These are

some of the reasons why P does not move far from the point of application (no more than a few cm). As P diffuses away from the granule, the precipitates will slowly dissolve, except in highly calcareous soils where Ca-phosphates may remain.

SOIL FACTORS THAT AFFECT P USE EFFICIENCY

Soil pH

Soil pH is a major determinant of P use efficiency in soils for two reasons. Firstly, extremes of pH can markedly limit plant growth e.g. in low pH soils aluminium and manganese toxicity can restrict root growth and in high pH soils micronutrient deficiencies can limit crop growth. Secondly, soil pH markedly affects P chemistry in soils through its effect on P adsorption, and through interactions that affect precipitation of P into solid forms in soil (Figure 4).

Soil mineralogy

Both the amount and the type of clay present in soil strongly affect P adsorption as these are the main components active in P retention. Soils with high clay content, especially those dominated by aluminium and iron oxide minerals, retain P most strongly. Conversely, highly sandy soils do not retain P and leaching may be problematic in those soils.

Soil water status

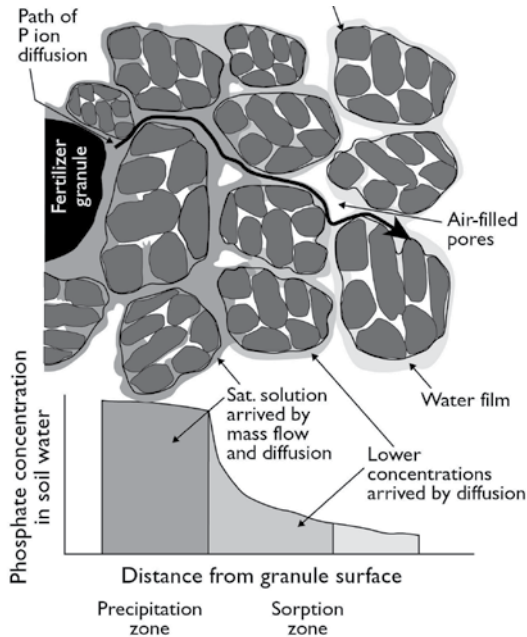


Figure 3. Diagram representing the movement of phosphate out of granules into soils (Hedley and McLaughlin 2005).

Most of the P taken up by plants arrives at the root surface by diffusion (A higher concentration in the soil solution and a low concentration at the root surface) through the soil. Diffusion of P is severely limited in dry soils as there are less water-filled pores and the diffusion pathway is much more tortuous. Hence drought can severely limit P use efficiency. On the other hand, flooding of soils can reduce the oxygen status of soils to such an extent that iron and manganese oxides, that are active in retention, are reduced (and solubilized) thus releasing the P that they held (Willett and Higgins 1978).

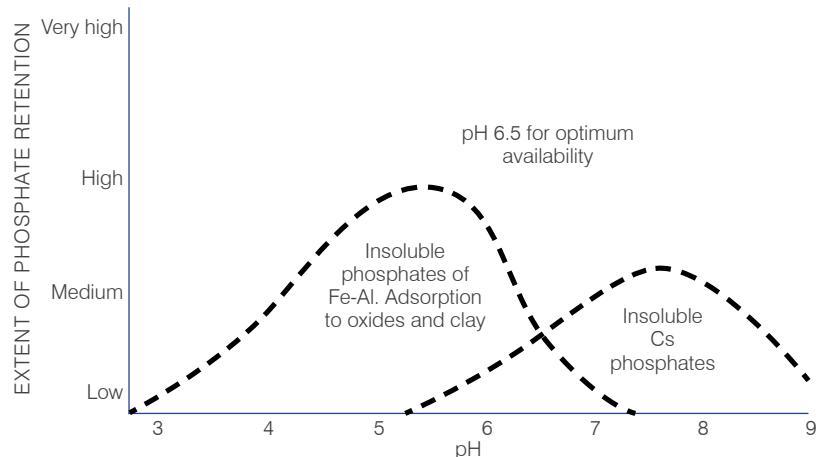


Figure 4. Soil P availability as affected by soil pH (Havlin et al., 1993).

MANAGEMENT FACTORS THAT AFFECT P USE EFFICIENCY

Crop species/variety

Increases in P use efficiency may be achieved through plant breeding programs to identify and select genotypes/species more efficient in taking up P from soils. Generally, this is closely linked to genotypes with efficient and extensive root systems or those with effective associations with mycorrhizal fungi, in order to access a greater soil volume (as P is diffusion limited in most soils) (Lynch 2007).

Fertilizer placement

In soils with high P retention due to adsorption reactions, band placement of P is the best management practice for soluble P fertilizers as this reduces the amount of soil:fertilizer contact and limits strong adsorption. On the other hand, broadcast application is best for sparingly soluble fertilizers such as reactive rock phosphates as this promotes dissolution in the soil.

Fertilizer formulation

Generally most soluble P fertilizers (MAP, DAP, TSP) have similar P use efficiency in most soils, provided there are no other limitations to crop growth (e.g.



N deficiency which will favor ammoniated products (MAP, DAP) over TSP, or Ca deficiency which will favor TSP). Less soluble products which have an alkaline reaction in soil (e.g. rock phosphates, struvite) will generally be less effective than soluble P sources except in very acidic soils, or soils prone to P leaching. Where acidification of soil improves P use efficiency (e.g. in alkaline soils) acidifying fertilizers will have advantages over those alkaline in reaction.

Of the numerous additives and microbial inoculants claimed to improve P use efficiency, none have been proven to date to consistently provide significant benefits (Chien *et al.* 2009).

Timing and rate of fertilizer application

Improvements in efficiency of fertilizer P can be achieved by varying the timing or rate of P applied.

Timing can make a big difference to P use efficiency e.g. in soils with high P retention capacities. Fertilizer must not be applied too long before planting, and is best applied at sowing, as increasing the time of contact with soil reduces P availability quickly in those soils. In highly sandy soils, P may need to be managed like nitrogen, by splitting applications and applying small amounts at sowing and topdressing later in the crop growth cycle.

Rate of application is important, as adding P to soils that already have sufficient amounts of plant-available P is wasteful and could lead to P losses to water bodies. Soil testing is the only way to determine the correct rate of P fertilizer to apply, along with consideration of other agronomic and risk considerations (e.g. potential yield, financial risk, etc).

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Further information

The Fertiliser Technology Research Centre was established in 2007 via a partnership between The University of Adelaide and The Mosaic Company. The scope of the centre was further expanded in 2009 via a partnership between The Mosaic Company and Australian Grains Research and Development Corporation (GRDC). The centre has expertise in soil chemistry, fertiliser technology and plant nutrition. Specifically, in developing novel fertiliser formulations, advanced isotopic and spectroscopic investigations of fertiliser efficiency, and field scale agronomy trials.

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