Am I wasting phosphorus?
A Literature Review by Glenn Bailey, Rural Solutions SA
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Key Points

- Phosphorus fertilisers are expected to get more expensive as demand overtakes supply.
- Fertiliser applied phosphorus can be lost rapidly on some sandy soils. There are some simple tests that can be done to indicate the risk of this happening.
- In other soils, phosphorus is fairly immobile and won’t be lost to leaching.
- Building up the soil reserves of phosphorus will make P more plant-available, regardless of how or when it is applied.
- The total phosphorus in the soil has value to you, not just the more readily available phosphorus.
- Generally if you maintain a balanced phosphorus regime, you will use everything that you apply in the long run.
- Phosphorus is fixed by most soils. This is a generally a good thing as it prevents leaching losses, so unless you have ‘high risk soils’, don’t be concerned about “lockup”.
- Don’t buy into alternatives to phosphorus fertilisers that claim to improve access to phosphorus stored in the soil.

Recommendations for managing phosphorus

Phosphorus inputs can be managed by balancing fertiliser inputs with removals in plant or animal materials. Plant removal can be determined accurately by tissue analysis of the crop\(^7\). There are also a number of established removal figures available for crop and livestock production.*

Your soil reserves should be monitored through a soil sampling program using the Colwell and Total Phosphorus tests.

If you have a sandy soil, know your risk of leaching losses using the “reactive” aluminium and iron tests and the phosphorus buffer index test.

On alkaline soils, testing for free lime (carbonate percentage) can also be useful to determine if there is a risk of excessive phosphorus lock-up.

Manage your soils for a healthy pH (i.e. Between 6 and 7 by applying lime at a rate that matches your farming systems acidification rate). Improve soil physical condition through the minimisation of traffic from stock and vehicles when soils are wet. Both of these activities will improve plant access to soil phosphorus.

As a general rule; a long term history of applying phosphorus fertilisers in excess of crop removal will build a soil reserve of phosphorus that can be drawn upon in years to come. The longer the fertiliser history, the more uniform the distribution of nutrients will be within the soil, which will enhance the growth of newly emerged crops. Once a critical threshold of phosphorus content in the soil has been passed, new applications of phosphorus will be used with close to 100% efficiency, giving phosphorus the potential to be one of the most efficient nutrients to manage.

You just need to understand how phosphorus behaves in the soil.
To do this…. Read on!!
Phosphorus is one of the most common elements found in plants, usually ranking 8th after carbon, oxygen, hydrogen (which combined make up around 95% of plant dry matter), nitrogen, potassium, silicon and calcium.

Unlike these other 7 elements, phosphorus is almost universally deficient in unfertilised soils from the South-East region of SA.

Phosphorus behaves differently to most of the other major nutrients, and its ability to have residual effects, sometimes for decades after being placed on paddocks, means that it is often misunderstood and mis-managed.

This fact sheet aims to explain why phosphorus fertilisers are important, how they enter and are stored in the soil, and how farmers can get the most efficient use out of P applications.

**Introduction**

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**Global status of phosphorus**

Phosphorus fertilisers are not only a key ingredient for successful farming, they are of critical importance for feeding our expanding global population. Modern food production could not occur at current levels without the use of processed mineral fertiliser. In Australia, many agricultural regions were only able to be developed for this use after single superphosphate became available.

The reserves of mineral rock phosphate used in almost all modern fertilisers were formed 10-15 million years ago. Some studies have indicated that the reserves known today have an estimated life of another 50-100 years, with production peaking in 20 years (Figure 1). However, others are more optimistic suggesting world reserves, including those currently undiscovered or unviable, will sustain us for another 400 years (20 generations).

While time frames may be disputed, general agreement is that quality is decreasing and cost of production is increasing. It is probably more an issue of demand outstripping supply, resulting in an increase in prices. In the years 2007-2008, fertiliser P demand exceeded supply, resulting in a price increase of 700% over a 14 month period. This price hike took most of the world’s farmers by surprise.

Todays phosphorus use does not reflect future requirements; global food production has been estimated to need to increase by around 70% by 2050 to meet demand, and the biofuel industries need for P fertilisers also contributes to increasing demand.

**Figure 1: Peak phosphorus 'Hubbert’ curve, indicating that production will eventually reach a maximum after which it will decline (Cordell and White, 2009).**
What do our soils supply naturally?

Most soils in the South-East that have a reasonable clay content within the root zone will supply adequate amounts of potassium, magnesium and calcium, and if a legume is being grown, nitrogen as well. The amounts of these nutrients in many soils is such that they are unlikely to become deficient for generations. In contrast, historical records of soil tests taken from a range of South East soils suggest that, even if all of the phosphorus present in the soil were entirely readily available to plants, this reserve would be used up within a few years to decades in most soils.

From fertiliser to soil—what are the “fixing” reactions

When a superphosphate granule dissolves, the zone immediately surrounding it is subjected to a very low pH (1.0–1.5). This causes iron, aluminium, calcium and manganese to dissolve and to react with the phosphorus, forming a precipitate of a solid compound.

In acid soils, the end products of precipitate reactions are often variscite (an aluminium phosphate) and strengite (an iron phosphate); calcareous soils are thought to result in the formation of apatites (calcium phosphates). These precipitates are 10 to 30 times less soluble than the original fertiliser granule.

Calcium dominated soils are the strongest “fixing” soils, followed by iron dominant and then aluminium dominant soils. (Acidic soils in the south-east region are often high in aluminium).

Precipitation reactions may be responsible for as much as half of the phosphorus that becomes less available in the soil.

The remaining phosphorus that moves into the soil solution reacts with the surfaces of clay minerals (adsorption). Adsorbed phosphorus is generally more available to plants, although some will form less soluble substances over time.

Phosphorus is initially adsorbed onto the most reactive sites that bind it most strongly. The most reactive sites become saturated as more phosphorus is added, with any additional phosphorus then bonding to sites that hold it less tightly, so every additional unit of phosphorus applied is more readily available than the last.

Phosphorus added to a site, even decades in the past, if not removed retains the capability to make any future phosphorus applied more available, potentially going from a plant available liquid to an unavailable solid within seconds of contacting reaction sites. The amount of phosphorus that goes back into solution largely depends on the type and amount of reaction sites present compared to the amount of phosphorus present. Soil chemical and physical factors also have an effect on this process.

What happens to superphosphate in the soil?

Superphosphate
Granule Dissolves

Area around the granule
becomes highly acidic
(pH 1.0–1.5)

Fe, Al, Ca, Mg dissolve and form precipitates around the granule

Remaining phosphorus goes into solution and adsorbs onto clay particles
In 1970 Syers et al. reported that phosphorus fixing was only partially reversible. Indeed, it is a common statement that the efficiency of phosphorus (P) fertiliser is low, with only 10-25% being accessed by plants in the year of application. However, by 2010, Syers et al. had modified that view to say that when an adequate time period is considered, the efficiency of phosphorus fertiliser is high. Based on a longer term view of phosphorus availability, it was proposed that the validity of phosphorus fixation (that is phosphorus lost from the usable soil reserve) was questionable, and that most fixation reactions were reversible over time. A number of longer term phosphorus balance experiments were cited that demonstrated recoveries frequently exceeding 60% and indeed up to and exceeding 80%. This would not be possible if phosphorus was irreversibly fixed in soils.

There are situations where soils do lock up phosphorus so that it becomes permanently unavailable in a practical sense. The main offenders are soils with very high surface free lime (calcium carbonate) that can rapidly immobilise phosphorus into a plant-unavailable form. In these instances, it can be justifiable to use liquid foliar applications to improve crop yields. Surface free lime over 15% of the soil mass is commonly viewed as problematic.

Soil type is one of the primary factors determining the solubility of soil phosphorus. This relates to the abundance and type of iron, aluminium and calcium compounds in the soil. A simple test called the phosphorus buffer index (PBI) has been developed to define a soil based on its ability to buffer phosphorus availability as new phosphorus is added to the soil. Table 2 provides an example of how soils may be characterised using this test. The higher the PBI value, the more phosphorus is needed in order to see a change in the availability of phosphorus. Conversely, strongly buffered soils also take longer for phosphorus availability to decrease as phosphorus is removed in plant products.

### Table 2: Example of using PBI to classify soil based on phosphorus relationship (Burkitt and Gourley 2003)

<table>
<thead>
<tr>
<th>PBI Class</th>
<th>PBI Value</th>
<th>Critical Colwell Extractable P (mg/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very low</td>
<td>0-50</td>
<td>&lt;20</td>
</tr>
<tr>
<td>Low</td>
<td>50-100</td>
<td>&lt;30</td>
</tr>
<tr>
<td>Moderate</td>
<td>100-200</td>
<td>&lt;40</td>
</tr>
<tr>
<td>High</td>
<td>200-300</td>
<td>&lt;60</td>
</tr>
<tr>
<td>Very high</td>
<td>300-600</td>
<td>&lt;90</td>
</tr>
<tr>
<td>Extremely high</td>
<td>600+</td>
<td>&gt;90</td>
</tr>
</tbody>
</table>

Figure 2: Extract from Moody (2007), with PBI using the method developed by Burkitt et al. (2002).
Available phosphorus

Calcium, aluminum and iron that is present in the soil ensures that concentrations of plant available phosphorus (i.e. dissolved phosphates) are less than 1ppm\textsuperscript{11}.

Critical levels of solution phosphorus vary between crop type and soils, however 0.003 to 0.3ppm are common phosphorus concentrations in many soils\textsuperscript{12,8,2}.

The most important factor in maximising plant growth is the rate at which this volume of soluble phosphate is replaced by the soil reserves.

Soil tests such as the Colwell P test don’t measure plant available phosphorus; instead they provide an indicator of when the rate of supply from the greater phosphorus pool becomes unlimiting\textsuperscript{13}.

Soil Reserves

A long history of adequate phosphorus fertiliser usage generally results in phosphorus being distributed through a greater volume of soil than can be achieved through a single phosphorus application, and subsequently increases a plants opportunity to grow roots near a high phosphorus concentration zone in the soil\textsuperscript{6}. Plant roots will access significant proportions of their phosphorus requirements from the sub-surface soil if it is there. This may protect plants from phosphorus deficiencies when the soil surface dries out\textsuperscript{14}.

Phosphorus stored in the soil reserve is less available in dry years due to the low availability of soil moisture to dissolve it, and the fact that plant roots can’t develop in dry soil\textsuperscript{2}.

The phosphorus held by the soil, the undissolved phosphorus in the old fertiliser granule, and the phosphorus that becomes organic matter all provide a reserve of phosphorus for uptake by crops and pastures in future years. Bunemann (2006)\textsuperscript{15} found that almost all the phosphorus accumulated after a 24year cropping period could be found as inorganic phosphorus.

Organic phosphorus can be considered unavailable in the short term\textsuperscript{16}, and the accumulation of organic phosphorus is unimportant in farming systems where there is little long-term change in the organic matter content of the soil\textsuperscript{6}. For this reason organic phosphorus is usually a very minor contributor in the overall phosphorus budget.

Low input farming systems will generally mine soil phosphorus already in the soil, either as “native” phosphorus or as phosphorus that has accumulated under a past fertiliser regime. Negative balances may continue for many years\textsuperscript{16}. If phosphorus is not limiting, this may not result in any initial yield declines, however most Australian soils will reach a point of phosphorus deficiency within a short number of years.

Increased access to phosphorus already in the soil

Sites of fixed phosphorus in the soil are surrounded by a small amount of available (dissolved) phosphorus. Plant uptake of the available phosphorus will cause more of the fixed phosphorus to dissolve. This happens over very small distances in the soil, so the ability of fine root hairs to explore the soil will help determine how effectively phosphorus is sourced by the plant\textsuperscript{2}.

A number of processes have been suggested to try and enhance the utilisation of phosphorus stored in the soil, and so reduce the ratio between total soil phosphorus and that of readily available phosphorus. These have included: plant selection for phosphorus scavenging plants and plants with more abundant root systems, growing plants that release organic anions, increasing phosphatase (enzyme) activity, and promoting microbiological activity\textsuperscript{17,6}.

Mycorrhizal associations may be able to reduce the total amount of phosphorus in the soil reserve by enhancing root exploration of...
Increased access to P already in the soil (cont.)

the soil. However, in most situations where there are few losses to erosion, leaching or long term fixation, these efficiencies have little real effect\(^\text{20}\). Also, if mycorrhizal fungi supply no nutritional benefits they can then act as a parasite and can reduce plant yield\(^\text{4}\). Hosseini et al\(^\text{13}\) showed some “beneficial” bacterial inoculants could actually have a negative effect on phosphorus uptake and yield.

What about the claims that organic and biological farming can improve the utilisation of phosphorus from the soil reserve? There is little evidence that organic or low-input farming systems naturally increase the numbers and diversity of soil organisms. Also, the research from Australia indicates that phosphorus nutrition is not improved by these systems\(^\text{26,26}\).

Experiments show that all plants draw their phosphorus from the same labile (readily available) pool, i.e. there are no plants that have advantageous access to a more “fixed” form of phosphorus. The only way to mobilise non-labile phosphorus is to deplete the labile phosphorus, thus shifting the soil equilibrium\(^\text{27}\).

The iron and aluminium phosphates have an increasing solubility with increasing pH. Manage soil pH to 6-7 for maximum availability of phosphorus. As a consequence, liming acid soils often increases the availability of soil phosphorus\(^\text{12,8,28,29}\). Phosphorus uptake from soil can be increased through the use of nitrogen fertilisers\(^\text{11}\).

Reducing soil compaction will improve root abundance within the soil, allowing the plants to access a greater area of the soil and the soil nutrient pool. Note that soil conditions in the immediate vicinity of plant roots are considerably different from the surrounding soil, including phosphorus depletion activity, pH and root exudates\(^\text{12}\).

Regardless of initial phosphorus status, or if fixed phosphorus can be made more available, eventually phosphorus depletion of the soil will occur and replacement will need to take place. At best, methods may improve access to soil phosphorus merely delaying the inevitable need for phosphorus fertiliser applications.

Fertiliser formulations and timings

The water solubility of fertilisers need not be as high as that of superphosphate in order to achieve maximum yields, and lower solubility fertilisers (e.g. rock phosphate) may in some instances provide better residual effects under certain conditions.

Improved residual effects can be due to the lower occurrence of precipitation reactions resulting from very low pH and the avoidance of stronger sorption reactions related to a very high soil water phosphate concentration\(^\text{5}\).

Reactive rock phosphates are best used in acid soils when soil phosphorus is already above the critical level, and high solubility fertilisers (such as superphosphate) will provide better results when soil reserves are low\(^\text{7}\).

Once the soil P reserve has been built up, method and timing of applications of phosphorus cease to be critical\(^\text{19}\). There is little difference in long term efficiency of phosphorus usage between infrequent large doses, and frequent small doses, except at the extremes of soil buffering capacities (i.e. leaching soils or calcareous or ironstone soils)\(^\text{19}\).

NB/ The acidity of superphosphate is often overstated, as very little residual acid is left over following the production process. For example, to neutralise the acid in 1000Kg of superphosphate only about 12kg of lime is required\(^\text{7}\).
Plant Requirements

Annual crops require a high concentration of soil phosphorus at germination due to the plants initial small and inefficient root system, and the need to ensure early vigour and plant yield potential. Phosphorus is the least mobile of the major nutrients. As a result, around 95% of phosphorus uptake comes from plant roots growing into a source of soil solution phosphorus, as opposed to phosphorus moving to the root hair via soil water movement. Phosphorus is usually not available to a plant until it is less than 0.1mm from a root hair. This means young plants with few roots that are growing in very coarsely structured soils can struggle to access adequate phosphorus even when good soil reserves are present.

Leaching

It is because phosphorus reacts so quickly to form a solid that leaching losses are insignificant in most soils. This doesn’t apply to many of the sandy soils of the South-East where large phosphorus losses due to leaching can be expected. Some soils have been shown to be capable of losing a 32kg/ha application of phosphorus within a 5 month period. Measurements of over 30 sandy soils revealed that an average of 57% of the applied phosphorus was washed from the top 30cm of soil and was not used by the plant with some soils losing up to 100% of applied phosphorus during this period. Notably this result appeared to be independent of the rainfall received with some sites receiving as low as 168mm. A soils “reactive” iron and aluminium content was shown to be a significant predictor of its phosphorus leaching risk. Lewis et al (1987) investigated sand over clay soils within the SE region and determined that over a 25year period, no phosphorus accumulations could be observed within the top 7.5cm of the clay layer. They concluded that phosphorus that was leached from the topsoil was washing through the sandy surface horizons and then moving laterally above the clay to some low point in the landscape.

Total Phosphorus and Colwell Phosphorus relationship

Syers et al (2010) found that, similarly to the data presented in this document, long term experiments showed strong linear relationships between the increase in Total and Olsen Phosphorus, demonstrating that the rate of phosphorus availability was directly related to the total phosphorus stored in the soil. (Note: Both the Colwell and Olsen tests measure the P extracted from a soil using sodium bicarbonate, and results can be related to crop yield calibrations). Once a critical level of soil phosphorus is reached (and this level varies with soil type), the efficiency of additional phosphorus fertiliser is at or near 100%. As
“Farmers today are reaping the rewards of phosphorus investments made in the past, perhaps from up to 2 generations ago.”

Total Phosphorus and Colwell Phosphorus relationship (cont)....

Available phosphorus is used by plants, it is replaced by readily available phosphorus. As readily available phosphorus is depleted, less readily available phosphorus is released to replace it. These reactions are reversed as more phosphorus is applied as fertiliser. The long term soil trial at Rothamsted (England) showed that a plot that initially had a 45 year phosphorus fertiliser history, and then had no fertiliser for the next 50 years still yielded twice that of a never fertilised plot. In summary, farmers today are reaping the rewards of phosphorus investments made in the past, perhaps from up to 2 generations ago.

Total phosphorus is often dismissed as having little agronomic value. Figure 5 shows that where soil types are not taken into account, it is difficult to relate the total amount of phosphorus in the soil with indicators of plant availability, in this case the Colwell extractable phosphorus test. However, the soil types, particularly if they are from the same area, can show very strongly that increasing total phosphorus directly relates to increased plant availability. Figures 6 to 9 demonstrate this relationship, with each soil presenting quite a different availability for a given amount of total phosphorus. Farmers can make use of this relationship to better manage their phosphorus budget, to better assess their soils phosphorus storage capacity, and to better anticipate the timing of a phosphorus fertiliser program.

A soils buffering capacity and organic matter content were found to affect the shape and magnitude of the relationship between total phosphorus content and the Colwell phosphorus measurement.
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This publication has been written as a result of a literary review by Glenn Bailey, Rural Solutions SA.

It has been edited and published by the MacKillop Farm Management Group to improve grower understanding of how phosphorus fertiliser behaves in the soil.

The MacKillop Farm Management Group is a regionally based, independent, not for profit producer network that communicates and develops innovative and sustainable farming practices through research and extension for the benefit of primary producers and agribusiness in the south eastern region of South Australia and western Victoria.

This publication has been made possible due to funding from the South East Natural Resource Management Board under its “Innovation Grants” funding program.

**Additional Resources**

- Removal figures available for crop and livestock production available from various internet sources.
  Also available in the publication “Australian Soil Fertility Manual”, FIFA (2006)
