

## Options for managing soil phosphorus supply

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**Abstract.** *This paper considers potential agronomic strategies to assist in sustainable management of the soil phosphorus resource in Australian farming systems, with an emphasis on material relevant to northern New South Wales pastures. The option most likely to ensure that soluble phosphorus is not a limitation in the system is the import of phosphorus as mineral fertiliser. However, as fertiliser prices rise there is increasing interest in other options, such as composts and biosolids, which can provide some readily available phosphorus as well as organic phosphorus for improving the 'cycling' of phosphorus within the system. Agronomic management to maximise quantity and quality of pasture and crop plant residues also facilitates phosphorus cycling since it builds soil organic matter, but is more effective if there is sufficient and reliable rainfall to drive high dry matter production. Improving the phosphorus-use efficiency of the system by incorporating species into rotation or intercropping systems that are able to access phosphorus from less soluble sources has been successful in other parts of the world, but there is scarce information for such systems in Australia. A long-shot is the seed and soil microbial inoculants to facilitate improved phosphorus uptake that are currently being field tested in Australia. Progress, in selection and breeding for cereal genotypes that are agronomically more phosphorus-efficient, and other plant genotypes that can access less labile phosphorus sources, is gaining momentum but also still remains a long term prospect.*

### Introduction

Maintenance of available phosphorus (P) in soil is a problem faced by all growers. This paper discusses potential agronomic strategies to assist in sustainable management of the soil P resource in Australian farming systems, with an emphasis on material relevant to northern New South Wales (NSW) pasture-based systems. Firstly some background information about the P cycle is provided and the role of soil organic matter and microbes is highlighted. Three broad options for P management are considered; (i) importing P as fertilisers, either mineral or organic, (ii) practices for increasing soil P cycling to facilitate release and synchronous uptake of plant-available P, and (iii) approaches for maximising the P use-efficiency of crops and pasture species in the system.

### P cycle, soil organic matter, microbes and mycorrhizae

Phosphorus can exist in many different forms in soil (Figure 1), from readily plant-available sources such as mineral phosphate and easily converted labile organic P compounds; to highly insoluble forms including P in some complex organic matter compounds and P 'fixed' by minerals. The soil type (texture and pH in particular) and the organic matter content influence how P behaves in the soil, the pathways it follows and where it ends up. Ultimately the goal of the grower is to maximise P uptake into the plant.

Soil organic matter (SOM) is important for a number of physical, chemical and biological functions. It changes relatively slowly over time but can be increased as long as inputs are greater than outputs ie. more carbon going in as roots and residues than is coming out as respiration. Soil microbes are part of the SOM. A major question concerns how can growers manipulate this tiny but very important 'pool' that contributes to the overall 'health' of the soil, and more specifically is the 'eye of the needle' through which organic matter has to pass in order to produce plant available nutrients such as phosphate (Figure 1).

Another soil microorganism, the mycorrhizae, can contribute to uptake of P by plants, although the process is very complex and the details of the processes involved are still the subject of much research. A range of direct and less direct mechanisms has been suggested including: increased physical exploration of the soil; increased P movement into mycorrhizal hyphae, modification of the root environment; efficient transfer of P to plant roots; increased storage of absorbed P; and efficient utilisation of P within the plant. However, in Australian systems, or at least for crops, it seems that a high level of infection with mycorrhizal fungi does not confer yield benefits and sometimes causes a yield penalty (Ryan et al. 2002; Ryan et al. 2004; Ryan et al. 2005), despite certainly contributing to P uptake (Li et al. 2005; Li et al. 2006; Thompson 1990).

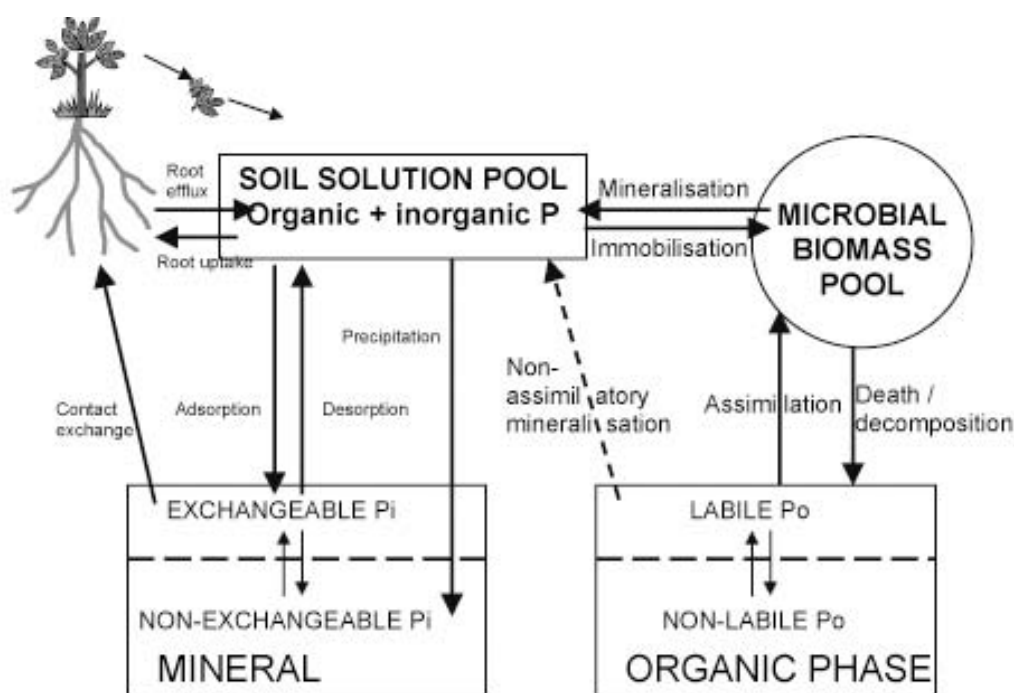


Figure 1. Soil P Cycle – pools and pathways. Modified from: McLaughlin *et al.* (1999).

#### Fertilisers, manures, composts and biosolids as sources of P

When soluble granular P fertilisers are applied to soil, a large proportion of the P quickly dissolves (within 24 h) but there are many fates for that dissolved P once it gets into the soil solution pool (Figure 1). The concentration of P around the fertiliser granule is high, and P may be lost from the soil solution pool by precipitation reactions, where soluble P combines with other elements in the soil (calcium, aluminium, iron) to produce new solid compounds (Figure 1). Some of these new compounds can eventually dissolve over time, or when a plant root reaches them, to release P into a soluble form again. However, some P compounds can remain very insoluble and are therefore ‘locked up’ in the non-exchangeable pool (Figure 1) and effectively unavailable for plant uptake. As P moves away from the granule through soil pores it binds to soil surfaces by a process called adsorption. This is where P is attracted to the clay mineral surfaces of soils – some of the P on the surface remains in a plant available form (ie. it can move back into the soil solution pool) but some may be very strongly bound and permanently removed from the plant available pool into the non-exchangeable pool (Figure 1). Crops derive their P from the soil solution that is in equilibrium with the adsorbed P in the soil (this process is called desorption – see Figure 1) and from P compounds that can readily dissolve.

Part of the dissolved P is also incorporated into the soil organic matter by the soil microbial biomass but can be later mineralised to soluble P by other microbial processes or exudates from plant roots (Figure 1). Soil microbes however compete with crop roots for soil solution P (McLaughlin and Alston 1986; McLaughlin *et al.* 1988c). Organic P in soil also exists in forms that

Table 1. Concentration of N, P and K on a dry weight basis in commonly applied wastes or residues [Modified from Gascho (2002) and Pittaway (2002)]

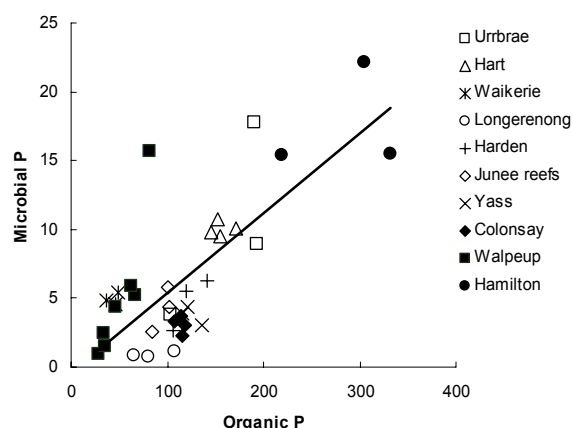
Waste	N (%)	P (%)	K (%)
Livestock manures	1–3	0.4–2	1–2.5
Poultry manures	0.3–5	1–3	1–2
Pig bedding litter	0.3–1	0.05–0.6	0.2–0.7
Plant Residues	1–7	0.1–1.7	0.1–9
cotton trash	1.3	0.45	0.36
peanut shells	0.8	0.15	0.5
cornstalks	0.8	–	0.8
wheat straw	0.3–0.5	0.15–0.26	0.6–1.02
Municipal biosolids	2–9	1.5–5	0.2–0.8
		Mg/L	
Municipal effluents	1.6–2.7	0.2–1.2	1.1–1.7

differ in how they react with the soil solution pool and these are commonly called labile and non-labile pools (Figure 1). When organic fertilisers such as composts, manures and biosolids are applied to soil they contribute P to both the soluble and organic pools, and they can contain considerable amounts of P (Table 1). Grazing animals will also contribute to P cycling via dung and urine, and may concentrate nutrients in ‘camp’ areas, but further discussion of this is outside the scope of this paper. Data for Australia demonstrates that biosolids can supply P to support crop yields equivalent to that obtained with inorganic P fertiliser (Weggler-Beaton *et al.* 2003) and that biosolids have a residual nutrient value, including P (Pritchard *et al.* 2006). Nevertheless, soluble P availability from organic fertilisers needs to be managed to avoid potential losses and negative environmental impacts (Bell *et al.* 2006).

**Increasing P cycling – residues and rotations**

Practices that increase organic matter in soil should, generally, increase the capacity to cycle P. Thus, at the Wagga Wagga long term trial site in south-eastern Australia, organic P increased over 24 years in the rotations with a mulched subterranean clover pasture component, especially with direct-drill (Table 2). Losses of organic P were largest (–42 kg P/ha) under continuous wheat with stubble burning and cultivation (Bunemann *et al.* 2006). As can be seen from Table 2, the pattern of changes in organic P in the Wagga Wagga trial caused by agricultural management was closely correlated to changes in organic matter carbon (C). This link between organic C and organic P was also evident in a survey of 10 sites across southern Australia with different land use, including three sites from NSW. The data showed that organic P was highest where organic C input was high, such as under trees or in grassland and pastures, and lowest in wheat-fallow situations particularly with stubble-burning and cultivation.

Concurrent with accumulation of organic P was an increase in P stored in the microbial biomass as shown by the positive correlation between organic P content and microbial P shown in Figure 2. Microbial P is one stage closer to being plant-available P than organic P, and so high microbial P content may reduce the P fertiliser requirements of a soil.



**Figure 2. The potential ability of the soil to cycle P (microbial P) increases as organic P increases (From: GRDC Project UA00095 Organic P in Australian Farming Systems, Australian Farm Journal July 2006).**

Laboratory studies on low P status alkaline soils from southern Australia (S. Iqbal – PhD thesis in preparation) have shown that addition of mature wheat, pea or canola shoot residues with a wide C:P ratio (from 870:1 to 1,860:1) to a soil low in organic C tends to build up microbial P but without any rapid release of plant-available P. Eventually, after six weeks incubation, there was slow release of available P for the following three months at a rate dependent on the amount and type of C, P and N in the added residue. Incorporation of young shoot material from peas and canola with narrow C:P ratio (from 133–253:1), as might occur where mulching or green-manuring are used, increased microbial P and plant-available P, and resulted in growth and P uptake of wheat similar to that obtained with moderate additions of P fertiliser (4 kg P/ha). Surprisingly, addition of mature canola root material to soil also caused rapid accumulation of plant-available P, highlighting that contributions from roots should not be ignored in P budgets. Further work, combining fertiliser and plant residue additions together, showed that although some P fertiliser is temporarily immobilised as microbial biomass in the presence of residues, there is a net gain in plant-available P compared to unamended soil and treatments with high C:P residues only. However, to obtain a target amount of plant-available P in soil

**Table 2. Change in organic P and C in 0–10 cm after 24 years of different rotation, stubble management and tillage treatments at Wagga Wagga**

Rotation	Stubble and tillage management	Change in organic P (kg P/ha)	Change in organic C (t C/ha)
Wheat-Lupin	Mulch, 3 cultivations	–13	–4
Wheat-Lupin	Burn, 3 cultivations	–43	–6.5
Wheat-Wheat	Burn, 3 cultivations	–42	–7
Wheat-Subclover	Mulch, direct-drill	+47	+7
Wheat-Subclover	Mulch, 3 cultivations	+5	+2

required more P fertiliser when plant residues with a high C:P ratio were present. Application of P fertiliser alone resulted in three times as much plant-available P than if the equivalent rate of P was added as half fertiliser and half in residues.

Perhaps more applicable to northern NSW is a field study on an acidic soil with high organic carbon (>3.0%) in Canada which specifically measured P mineralisation from root residues of several crops (peas, canola and wheat). The authors concluded that root residues exhibited no tendency to immobilise P although the rate of P mineralisation was less than shoot materials (Soon and Arshad 2002). Residues of mustard or rapeseed varieties high in glucosinolates (Morra and Kirkegaard 2002) could also potentially be used for increasing the suppression of soil-borne diseases and thus maintaining a healthy root system for P uptake. This appears to be possible without undue effects on beneficial soil organisms such as mycorrhizae eg. in a study on Vertosols in south-eastern Australia there was no effect on arbuscular mycorrhiza fungal colonisation of wheat grown in rotation after brassica crops with different levels and types of root glucosinolates (Ryan *et al.* 2002).

#### Pastures in rotations

Some twenty years ago, tracer studies in annual legume pastures on an alkaline sandy loam soil from the cereal/sheep belt in South Australia showed that P from medic residues accumulated in wheat plant shoots, roots and in soil microbial biomass in similar proportions (6.7, 7.0 and 8.1 per cent of total P added); ie. in one season a total of 21.8 per cent of the residue P became labile or potentially more available to the plants (McLaughlin and Alston 1986). Under field conditions the amount of residue P incorporated into microbial biomass (22–28 per cent) was even greater (McLaughlin *et al.* 1988b) and may be related to the fact that there was a rapid release of soluble P directly via autolysis of the residues upon initial wetting of the soil at the break of the season (McLaughlin *et al.* 1988c). Further work measured the relative uptake of P from fertiliser and medic plant residues in the field and showed that most of the P taken up by a wheat crop originated from historic soil sources ie. not sources from the immediate season's fertiliser or last year's residues (McLaughlin *et al.* 1988a). This underlines the fact that system P fertility is an integration of many years of inputs and that long term P management strategies need to be evaluated to fully understand the sustainability of particular systems. Overall, this work highlighted the contribution that annual legume pastures in southern Australia can make to P cycling in rotations. Studies on P cycling for perennial pastures in Australia appear to have focussed largely on the potential for losses of P (both inorganic

and organic) from run-off under high rainfall conditions (Dougherty *et al.* 2008; Melland *et al.* 2008), and these studies emphasise that careful management is required to minimise the risks associated with the maintenance of soluble P in soil for plant uptake using inputs that contain P including those from grazing animals. In relation to pasture management practices and P cycling, there was some interesting work undertaken in sown and native pastures in northern NSW suggesting that over-sowing subterranean clover and applying fertiliser to native pastures markedly improved rates of litter and organic matter decomposition and N recycling (Lodge *et al.* 2006). It is likely that P cycling also increased, although this was not directly measured.

#### Species that can solubilise P

There are several mechanisms that allow plants to access poorly available inorganic and organic soil-P fractions and thus increase the pool of soil P that contributes to plant P nutrition. Briefly, these include release of protons (H<sup>+</sup>) or hydroxyl ions (OH<sup>-</sup>), organic acid anions, increase in reduction capacity and rhizosphere phosphatase activity. A number of crop species used in Australian farming systems are known to excrete P solubilising compounds, especially legumes such as lupin, pigeonpea, chickpea, fababean and peas, lucerne, white clover but also wheat and cocksfoot (Ae *et al.* 1990; Gardner *et al.* 1983; Li *et al.* 1997; Nuruzzaman *et al.* 2006). Other species, such as medics, radish and canola, have been shown to excrete P solubilising substances under P-deficient conditions (Hedley *et al.* 1982; Hoffland *et al.* 1992; Lipton *et al.* 1987; Zhang *et al.* 1997) and might therefore be suited to systems where plant-available P is low. Furthermore, if P is mobilised by plants in excess of their own requirements then it may contribute to the P nutrition of other less P-efficient crops grown in rotation or inter-cropped in the farming system. Reports from field experiments on the P benefits of growing these species in rotations or with inter-cropping in Australia are sparse although over 20 years ago a beneficial effect on P uptake by wheat when grown with lupin in Western Australia was demonstrated (Gardner and Boundy 1983). Seed and soil microbial inoculants that solubilise P and facilitate improved shoot P uptake have been developed in Canada and are currently being field tested in Australia.

#### Maximising P efficiency

P use-efficiency by crops or pastures in simple agronomic terms can be defined as the amount of shoot biomass per unit of P present in the plant. It represents the integration of plant P uptake from soil and P translocation within the plant, processes that are both extremely complex (Holford 1997). Traditionally, pasture grass species are considered more efficient than pasture legume species at acquiring and using P, both

on an individual plant basis and under competition in a mixed sward (Biddiscombe *et al.* 1969; Caradus 1980; Ozanne *et al.* 1976; Ozanne *et al.* 1969). Some years ago, Australian researchers showed stylo was more efficient under low P conditions than white clover (Chisholm and Blair 1988) and later work further identified that some scope existed for selection for P efficiency within white clover accessions, particularly under P stress (Godwin and Blair 1991). However, this does not appear to have been undertaken.

There appears to be a growing consensus that sufficient genotypic variation of P efficiency within cereals exists to warrant breeding efforts. A comprehensive Australian study that screened over 100 cereal genotypes in the glasshouse demonstrated a wide variation in soluble P uptake efficiency (Osborne and Rengel 2002c), as well as in the capacity to use less soluble forms of P such as phytate and iron phosphate (Osborne and Rengel 2002a; Osborne and Rengel 2002b). Rye and triticale appeared more efficient than wheat at taking up and utilising P at low rates of P supply, and in being able to access less soluble forms of P. Work using soils-based screening for P efficiency has also concluded there is germplasm in Australian wheat genotypes that may be valuable for breeding (Liao *et al.* 2004), although these researchers emphasise that breeding for P-uptake efficiency would only be feasible provided the trait is heritable and controlled by relatively few genes.

Another aspect of managing for P efficiency is to consider the plant root system architecture and morphology in relation to the ability to access more P from the soil. Plant root architecture and morphology are important for maximising P uptake, because root systems that have higher ratios of surface area to volume, such as those with long fine roots and abundant root hairs, will more effectively explore a larger volume of soil. Furthermore, a smaller radius of fine roots and root hairs causes a slower decline in P concentration at the root/hair surface, enabling a higher rate of P influx to be maintained, which may also contribute to greater P uptake. Therefore enhancing opportunities for P transport via soil-root contact through growing species or genotypes with greater lateral root formation (Blair and Godwin 1991; Gahoonia *et al.* 1999; Manske *et al.* 2000), longer root hairs (Gahoonia and Nielsen 1997; Gahoonia and Nielsen 2004b), or reduced root diameter (Fohse *et al.* 1991) will give greater potential for increased P acquisition by plants. Agronomic evaluation in the field has been undertaken for barley in Europe demonstrating the efficacy of root traits such as root hair length for increased plant P uptake (Gahoonia *et al.* 2000; Gahoonia *et al.* 1999), as well as sustaining high grain yields under low P conditions (Gahoonia and Nielsen 2004a), although the relationships for wheat were reported as being less clear (Gahoonia *et*

*al.* 1999). These European studies suggest that genetic modification could be used for upgrading P efficiency in barley genotypes, although the time frame is long-term. Currently, these kinds of traits are being investigated for Australian cereal and pasture cultivars but it will be some time before growers benefit from new releases.

## Conclusions

Input of soluble P is necessary to sustain productivity in northern NSW pasture-based systems but as mineral fertilisers become more expensive (and sources are depleted) then alternative inputs such as biosolids, composts and manures will become more cost-effective and more attractive to use. These organic fertilisers have additional benefits – they contain other nutrients (N and K) as well as P, and they increase carbon in the soil (improve the organic matter) as well as feeding the soil microbial capacity. However, organic P sources are relatively slow-release and also it is not easy to predict exactly when the soluble P will be released. So, a combination of mineral and organic sources for P is the best option. Currently, sustainable management goals should also consider the use of species in the system that are known to mobilise P from the less available pools and also the tactical use of green-manuring to return high quality residues into the soil if the soluble P pool is depleting. Beyond the horizon in the longer term will be the use of new cultivars that have been modified or bred to be P-efficient, either due to improved root architecture or to enhanced translocation of P into shoots.

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