Phosphorus in the landscape: a sustainable phosphorus future for Australian pastures

RJ Simpson

CSIRO Sustainable Agriculture Flagship / Plant Industry, Canberra ACT 2601: richard.simpson@csiro.au

Abstract: *Phosphorus (P) fertiliser is important for high productivity in Australian pastures but, for some paddocks where soil P fertility exceeds the level needed for maximum pasture growth, it is possible to reduce P fertiliser inputs by shifting from building soil fertility to maintenance fertiliser applications. Targets for soil P management can be determined using extractable-P and the Phosphorus Buffering Index soil tests which allow the critical soil test P to be identified. The information can then be used to develop a pasture 'response function' that reflects the likely response of the paddock to P fertiliser investments. Phosphorus fertiliser investment decisions that are appropriate for the stocking rate and management goals of the farm help to maximise the effectiveness of fertiliser use. However, even with best management practice, the P-balance efficiency of pastures in Australia is low, mainly because P accumulates in moderate to high P-sorbing soils. This is a cost that is built into current rates of fertiliser use. Low P-efficiency also presents an opportunity because improvements would mean reduced input costs. Improving P-use efficiency will be challenging and is likely to need changes to pasture legumes, soil biology and/or fertiliser technology that can reduce the net accumulations (or leakages) of P in soil.*

Key words: phosphorus use efficiency, superphosphate, grazing systems

Introduction

Before fertilisers were generally available, Australia experienced an era (1860–1900) in which soil nutrients were depleted and agricultural yields declined. Phosphorus (P) and nitrogen (N) deficiencies are relatively widespread, so the adoption of superphosphate fertiliser, followed later by the combination of superphosphate and pasture legumes led to large step changes in productivity on farms in southern Australia (Passioura 2002; Kirkegaard and Hunt 2010). These major innovations continue to underpin high productivity. Generally speaking, responses to P fertilisers were so widespread that it was unnecessary to question the use of fertiliser, and fertiliser application technology became rather formulaic: one hundred-weight of superphosphate/acre/year was a fairly standard application rate for pastures and was often used irrespective of soil type, pasture species or stocking rate.

However, recent evidence indicates that the situation has changed for some farms. Many paddocks in recent surveys of soil testing data from south-eastern Australia (January–April 2010) or from Western Australia (2008–10) were recorded as being well above the critical P levels need for maximum production (Simpson *et al*. 2011; Weaver and Wong 2011). These surveys are almost certainly 'biased' because they only record the status of farm paddocks where a farmer has been motivated to conduct a soil test. However, they do indicate that a more critical approach to soil fertility management is needed to ensure that P application rates are matched to the production goals of farms.

P costs and the prospect of 'peak' P

Higher P fertiliser costs and recent volatility in P prices are further reasons to take stock of our P use. In 2007–08, the world experienced a dramatic increase in P prices. At its peak, the cost of P fertiliser on world markets had risen about 6-fold. The subsequent decline in price was equally dramatic. This 'spike' in the cost of P was also accompanied by increases in other fertiliser costs (Figure 1). In Australia, price instability impacted on farm profitability and resulted in anxiety about the value or otherwise of fertiliser applications. Elsewhere in the world, the rise in fertiliser price coincided with increased food prices and was followed by riots, protests and the imposition of fertiliser trade barriers (Ryan 2010). The reasons for the spike in fertiliser prices are generally considered to have been a short term imbalance in demand and supply caused by 'a substantial increase in world demand for fertilisers associated with an expansion in agricultural production (particularly grains for food, feed for livestock and bio-fuels) and by rises in costs of production associated with the increasing cost of energy' (ACCC 2008).

By looking past the dramatic price spike of 2007–08, it can be seen that the cost of P has actually been remarkably stable in the recent past. However, it is also clear that since about 2000, the underlying cost of P fertiliser has been rising steadily and has doubled (Figure 1). The upward trend in the price for P is associated with the cost of mining new rock phosphate reserves that are of lower quality or harder to extract (Fantel *et al.* 1985; Van Kauwenburgh 2010). It seems likely that fertiliser prices will continue to rise as it becomes necessary to exploit more of these lower grade or less accessible P deposits.

For Australia, P is a critical input that supports high agricultural productivity and the competiveness of our agricultural products on world markets. From a global perspective, P is also very important because crop yields are limited by P supply from soil on more than 30% of the world's arable land (Vance *et al.* 2003). Rock phosphate-reserves are consequently one of the resources that underpin global food security. Given that the world's population is projected to be nine billion by 2050 and because competition for land and fertiliser resources between crops and biofuel production is also expected to increase, the need to use P resources efficiently and equitably has never been clearer.

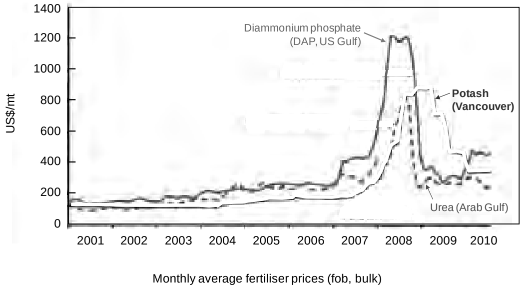

Figure 1. Prices of fertiliser on world markets over the recent decade (from Van Kauwenburgh 2010).

Will we run out of P?

Shortly after the spike in P prices, it was predicted that 'peak phosphorus' (the point where global demand for P would exceed P supply from 'low cost', high-quality reserves) might occur by ~2033 (Cordell *et al.* 2009). This would be a grim prospect given the projections for global population and the social instability associated with even a short-term spike in fertiliser prices. The prediction of peak P prompted renewed research into more efficient use of P, and reviews of the global supply situation. The size of global P-reserves has subsequently been revised upwards and it is now considered very unlikely that peak P will occur in the foreseeable future. High quality P reserves are estimated to be four-fold greater than acknowledged in 2009 and the world has vast low-grade P resources that are presently considered uneconomic to mine (Van Kauwenburgh 2010). In addition, demand for P is continually shifting. In Europe, for instance, demand for P fertiliser is declining because soil P reserves have been built to levels that exceed crop requirements (Sattari *et al.* 2012). Even in China, a country with increasing P demand, implementation of better farming practices has slowed the rate of P use in recent years (Li *et al.* 2011).

Currently, there is a heightened awareness of the importance of P for global food security. Phosphorus fertiliser is presently an affordable input for farms in Australia and its use generates improved crop and pasture yields, more effective use of farmland and water resources, and improved profitability. However, elsewhere where food production can be inadequate or barely enough to meet current needs (e.g. in Africa), some of the world's poorest farmers already struggle to afford P fertilisers (Syers *et al.* 2011). The world's high-quality rock phosphate reserves are effectively a finite resource and there is a need to strive for more efficient and equitable use.

P use in Australia

Prior to the recent prolonged period of drought, P consumption in Australia peaked at about 480 kilotonnes (kt) of P per year (P use has declined since 2004 reaching 282 kt in 2009; Ryan 2010). The majority (~450 kt/year) is used in agriculture with a P-balance efficiency of only ~25% (i.e. on average four units of P are applied as fertiliser to produce only one unit of P in products) (Cordell and White 2008; McLaughlin *et al.* 1992). About 90 kt P/year is exported in agricultural products, and 21 kt P/year is consumed domestically. The rest accumulates in the soils that are used for agriculture with a small proportion also lost to waterways. Some P is already recycled from waste streams for re-use in agriculture. Increasing prices will encourage more recovery and recycling of P from waste streams (e.g. Syers *et al.* 2011). For some countries, this alone could go close to covering their P needs. However, on the basis of the numbers that are available for Australia, the amount of P available for recycling from domestic consumption would cover only 5–10% of the annual P requirements of Australian agriculture. So, while there is no doubt that there will be an increasing role for P fertilisers derived from waste streams, the major avenue for addressing increases in P fertiliser costs in Australia will be through improved P-use efficiency on farms.

Efficiency of P-use in Australian agriculture

Estimates of the P-balance efficiency of the major southern Australian broadacre farm enterprises vary from extremely poor (5–15%, some horticultural enterprises), through poor (10–30% for grazing industries), to average (45–60% in cropping enterprises) (McLaughlin *et al.* 1992; Weaver and Wong 2011). If a crop is grown with 50% P-balance efficiency, it means that two units of P have been applied as fertiliser to achieve one unit of P in products sold off the farm. For a grazing enterprise operating at 20% efficiency, it means that it was necessary to apply five units of P to achieve one unit of P in farm products.

In Australia it is most often necessary to apply more P to soil than is exported from farms because our soils react with a proportion of the fertiliser P and render it sparingly-available for plants (a process sometimes referred to as P 'fixation'). Some of the P also gets incorporated into organic materials in soil that resist degradation. The net result is accumulation of P in soil in these sparingly-available forms and consequently reduced efficiency in P fertiliser use.

Better targeted fertiliser applications

A typical response of pasture growth to soil P fertility is shown in Figure 2. When soil P levels are very low, the pasture cannot get enough P to grow rapidly. Adding P fertiliser to the soil promotes pasture growth up to a soil fertility level where the pasture gets enough P to grow at its maximum growth rate. The soil fertility level that corresponds to near-maximum pasture growth is known as the 'critical' soil P level (Figure 2). Adding fertiliser to build soil fertility beyond this point does not result in extra pasture yield and the critical P level is, therefore, a sensible upper-boundary for soil fertility management.

The numerical value of the critical P level may vary for different plant species, different soil test methods and different soils. However, we now have good critical P guidelines for white clover and subterranean clover-based pastures (Gourley *et al.* 2007). These legumes have similar P requirements. When using the Olsen extractable P test, the critical value for all soils is ~15 mg P/kg soil. However, the critical Colwell P test value varies with soil type and can be determined by also using a Phosphorus Buffering Index (PBI) test (Burkitt *et al.* 2002; 2008) at the same time you test for Colwell P (see Figure 3).

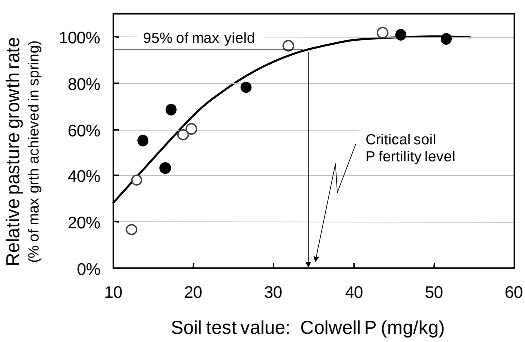

Figure 2. Relative yield of subterranean clover-rich pasture to soil P fertility at Bookham, NSW. The PBI of surface soil at this site was 80. Open circles 2002; closed circles 2003 data.

Aligning P investments with stocking rate and management goals

Applying fertiliser to grow more pasture that cannot be eaten because of constraints to stock numbers is a waste of money. For a wool enterprise, it can be even more costly because sheep with excess feed are likely to ‘blow out’ their micron and devalue their wool. Also, there are many instances where it does not suit the business, or it is inappropriate for a whole range of management reasons to push stocking rates to high levels. It is, therefore, really important to be able to achieve a balance between fertiliser use and the stocking rate, production or other management goals of the farm. This is easier said than done.

The ‘Five Easy Steps’ approach

To understand the relationship between soil fertility and carrying capacity of a paddock, we ideally need to know how much pasture will grow in response to soil P fertility and how to convert pasture grown into an appropriate carrying capacity. These questions are often very hard to answer. A grazed soil fertility study in the local area could provide some of the answers; but how many of us have a convenient local grazing trial?

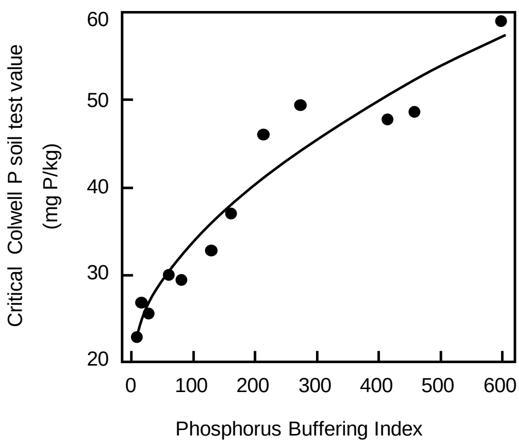

Figure 3. Relationship between the critical Colwell P(0–10 cm) soil test value (corresponding with 95% of maximum pasture growth rate) and PBI of soil for clover-based pasture (from Gourley et al. 2007). The relationship is based on an analysis of many past fertiliser experiments and is backed by similar analyses reported by Moody (2007).

A framework for exploring how pasture production and the carrying capacity of a paddock may respond to fertiliser can be developed using soil test information, carrying capacity estimates and local experience. This is then used to plan fertiliser investments. Consider the following example which applies to the paddock featured in Figure 2.

Prior to receiving regular superphosphate application, this paddock was carrying 6 wethers/ha and had a Colwell P soil test value of about 10 mg P/kg soil. The soil in this paddock has a PBI = 80, which means the critical Colwell P soil test value is 32 mg P/kg soil (see Figure 3). This estimate is more ‘precise’ than is sensible for practical on-farm management, but it means that if near maximum pasture yield was wanted, soil P fertility would need to be lifted into the range: 30–35 mg P/kg (Colwell), and maintained there.

The next question is: how many animals can be carried sustainably on this paddock when soil P is maintained between 30–35 mg/kg (Colwell)? This is the really hard question. Relationships between stocking rates and growing season length derived from the ‘Triple P’ program (Saul and Kearney 2002) were used to estimate that, potentially, 20 dry sheep equivalents (DSEs)/ha might be carried. In this case, a further piece of evidence is that locally ~15 wethers (15 DSE) were being carried per ha on a similar soil that had been fertilised to maintain Colwell P in the range 17–20 mg/kg.

Putting all of this together gives us Figure 4, which is a surrogate pasture response function for the paddock. If it is reasonably accurate, we can now also estimate the appropriate level of soil fertility we need for the stock we plan to carry, or the stock numbers we need if we are planning to improve soil fertility (e.g. see dashed intersect lines for examples).

Once a target level of soil P fertility has been decided, enough fertiliser is applied annually to build soil P levels towards the target. In this soil fertility ‘building phase’, the rate of build-up must fit with the rate at which the additional livestock (needed to use the extra pasture) can be obtained. When the target soil fertility level is reached, the 'maintenance phase' begins and annual P fertiliser applications are adjusted (down) to a rate of application that keeps soil fertility within the target range.

How do we know that the soil P targets are real and the relationship between stocking rate and soil fertility is robust? The critical P targets for clover-based pastures are derived from field experiments conducted over a number of years (Moody 2007; Gourley *et al.* 2007). In essence, you do not really know initially how robust the inferred relationship is between stocking rate and your levels of soil fertility. However, this framework for decision making is based on field and demonstration trial experiences (Simpson *et al.* 2009; Saul and Kearney 2002) and is a rational way to make good use of information that is readily obtainable. Most importantly, it is essential to treat fertiliser as you would any other longer term strategic investment. This means continuing to monitor soil fertility outcomes using annual soil tests and critically evaluating your success in carrying the stock numbers you expected to be able to carry. Over time, experience will assist you to refine your soil fertility/pasture yield guideline and gradually will help to build confidence in the targets that can be set for soil fertility and stocking rate management. This has been the experience of producers in the Bookham area who have followed these principles over the last eight years (P Graham, *pers. comm.*).

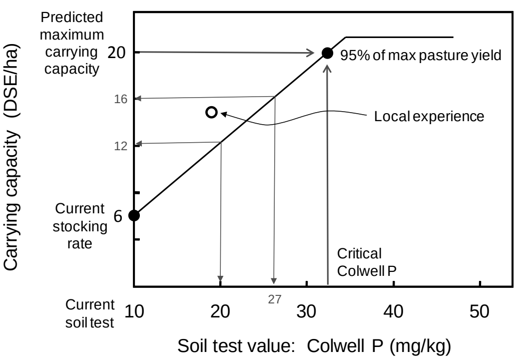

Figure 4. Construction of a framework for understanding the relationship between stocking rate and soil P fertility of a paddock. Current carrying capacity is known and current soil fertility can be measured. Critical Colwell P can be determined after measuring the soil's PBI (from relationship in Figure 3). This should support the maximum carrying capacity of the paddock provided there are no other factors limiting yield (e.g. another nutrient deficiency, poor pasture composition, etc). Maximum sustainable carrying capacity is hard to determine. One starting point is to use the relationships based on growing season length from Saul and Kearney (2002). Local experience can sometimes be used to check whether you are on the right track.

The complete 'Five Easy Steps' approach to P management in pastures starts with soil testing, develops the expected relationship between soil P fertility and stocking rate and encourages financial checks to ensure the investment is profitable. However, the investment strategy is also an iterative process in which other factors (other nutrients, pasture composition, sustainability issues) are considered when setting targets for management. Continued soil testing and review are always necessary to ensure that the original framework for decision making was developed correctly or, if necessary, to determine when adjustments are required. A guide to the process and a more detailed discussion of the issues is given in Simpson *et al.* (2009).

Future options to achieve a step-change in the P use efficiency of pastures

The low P-balance efficiency commonly achieved in fertilised pastures is both a cost (we apply up to five-fold more P as fertiliser than we remove from the paddock in products) and an opportunity (improvements in efficiency would directly reduce input costs). To capture the opportunity it is essential to understand how inefficiency arises. Phosphorus budgets calculated for some longer term studies of three contrasting pasture systems are shown in Table 1. The fertiliser applications in these systems ranged from 9–12 kg P/ha; P exports were typically low (1–2 kg P/ha) for the systems dominated by sheep grazing and higher when wheat production was the main enterprise (7 kg P/ha). This resulted in fairly typical P-balance efficiencies for these systems: 13–19% for sheep-grazing systems and 61% for the wheat-pasture rotation. Phosphorus-inefficiency was associated with accumulation of P in soil or P loss by erosion or leaching. In Australia, P leaching losses occur on sandy soils that have very low P-sorption capacity (i.e. very low PBI values). These soils are typically found in coastal areas and in parts of SA and WA (e.g. the Willalooka example in Table 1) and, in some cases, are associated with significant environmental problems when P leaks into waterways. Phosphorus losses from sandy, low-PBI soils can be managed partially by using fertilisers with lower P-solubility (e.g. coastal superphosphate; Bolland *et al.* 2003). In the majority of Australian soils with moderate to high P-sorption capacity, inefficiency is due to accumulation of P in the soil. Therefore, a key potential avenue for reducing the P costs of pastures is to find ways to reduce P accumulation in fertilised soil.

It is known that the rate of phosphate accumulation is increased by high concentrations of P in the soil and the time that P is in contact with soil (Barrow 1980). Phosphorus accumulates in phosphate compounds that are only sparingly-available, and in organic compounds that resist degradation and turnover; a process sometimes referred to as 'P-fixation' in soil (McLaughlin *et al.* 2011). Consequently, there are two basic approaches to reducing P accumulation: (i) strategies to slow P accumulation and (ii) faster extraction of P from the sparingly-available pools in soil. Neither is particularly easy to do; but there are options to optimise on-farm management of soil P and some avenues for reducing P accumulation in soils that are the subject of current research.

Slowing P accumulation

Recent research has shown that the accumulation of P at a paddock scale (i.e. the sum of P accumulation in soil as phosphate and organic P, and accumulations due to poor distribution in sheep camps) is also increased by high soil P concentrations (Figure 5). The experiment demonstrated that the first rule for minimising P accumulation is to ensure that paddocks are not over-fertilised. We know that P applied in excess of the critical P requirement of the pasture fails to produce extra pasture; the experiment shows that it also promotes unnecessary P accumulation in the paddock.

It follows that if productive pastures can be managed at lower soil P concentrations, the rate of P accumulation will be slowed and less fertiliser would be required. Critical soil P concentrations for pastures (Gourley *et al.* 2007) are determined by the P requirements of pasture legumes because they fix the N that drives

Table 1. P-balance budgets (kg P/ha/year) for farming systems maintained with "steady-state" plant-available P levels. Pi is the phosphate component of P estimated to accumulate annually and Po is the component of organic P accumulated annually (from Simpson *et al.* 2010a).

P-balance equation / Farming system	P_{input} =	$P_{excreta\ dispersal}$ +	$P_{erosion/leaching}$ +	$P_{soil\ accumulation}$ +	P_{export}
Wheat-sheep rotation, Wagga, NSW (wwww-pp treatment; Helyar *et al.* 1997)	11.8	~0	-- [c]	Pi = 2.4 Po = 2.2 Total = 4.6	7.2 (61%) [e]
Wool production, Canberra, ACT (P1SR18 treatment; Simpson *et al.* 2010b)	9.8 [a]	~0.6 [b]	-- [c]	Pi ~ 4.3 [d] Po ~ 3.0 Total = 7.3	1.9 (19%)
Grazed annual pasture, Willalooka, SA (Lewis *et al.* 1987)	9.2	~0.4 [b]	4.1	Pi ~ 0.8 Po ~ 2.7 Total = 3.5	1.2 (13%)

[a] input for stable soil fertility after drift in Olsen P accounted for
[b] estimated as 5% of input based on Metherell (1994) and McCaskill and Cayley (2000)
[c] not measured but expected to be negligible in this system/soil
[d] proportions of Pi and Po are estimated for this system by assuming the same proportions reported by George *et al.* (2007)
[e] P-balance efficiency = $(P_{export} / P_{input}) * 100$

pasture growth. Pasture legumes also often have the highest P requirements of the plants present in the pasture. To lower the P targets for legume-based pastures we need to find productive pasture legumes that have lower critical soil P requirements. Most commonly, plants that have extensive, fine root systems also have lower critical P requirements. However, it will not be an easy task to find alternatives to plants, such as subterranean clover, that are as widely and successfully adapted to the temperate Australian environment. Alternatively, shifting to N-fertilised grassy pastures (as is happening in the dairy industry) could also lower P-fertiliser use because grasses usually have lower critical P requirements. However, such a move would carry extra costs, and risks associated with N losses to the wider environment.

Novel fertiliser technologies may also have a role, especially if they result in better placement of P near roots, can modify P-sorption by the soil, or reduce the time that phosphate is in contact with soil. There are numerous ideas being investigated but, for broadcast applications of P to pastures nothing presently stands out as better than current technology (McLaughlin *et al.* 2011).

Faster mobilisation of sparingly-available P

Microorganisms play a fundamental and major role in the cycling of inorganic and organic P

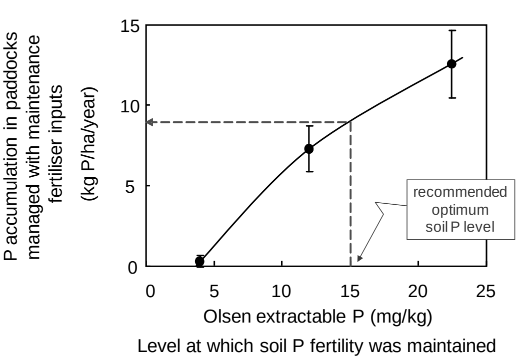

Figure 5. Accumulation of P in paddocks grazed continuously by sheep and maintained at contrasting soil P fertility levels (from Simpson et al. 2010b). This experiment used the Olsen soil P test; the equivalent Colwell P soil test values for this site are approximately two times the Olsen value.

in pastures. Bacteria, actinomycetes and fungi are all involved in the release of phosphate from inorganic and organic substrates (Richardson *et al.* 2011). About 15 and 5 % of the total culturable bacterial and fungal communities, respectively, are reported to have P-solubilising activity. Microbial turnover of organic P is boosted in soils where organic P reserves have been built up by adding manures or by fertilising legume-based pasture systems. However, there is still a net accumulation of organic P in these systems when soil fertility is being maintained (Oehl *et al.* 2004; Simpson *et al.* 2011).

Some of the more promising P-mobilising soil microbes have been used to inoculate seeds at planting. For example, *Penicillium bilaiae*, has been shown to solubilise P and improve plant P uptake by many plant species (wheat, canola, pasture legumes) with inoculated wheat obtaining up to 18% of its P from sources unavailable to non-inoculated plants under glasshouse conditions (Asea *et al.* 1988). However, the positive responses to non-symbiotic inoculants observed in laboratory and glasshouse environments are observed less consistently in the field. The results obtained from some broadly-based field trials have been described as inconsistent, not significant, or even random events (e.g. *P. bilaiae* on wheat; Karamanos *et al.* 2010 and papers cited therein). Indeed, it is the inconsistencies in the field performances that has significantly impeded the development and adoption of P-solubilising, plant growth promoting and root disease suppressive inoculants for cropping and pasture systems (Bowen and Rovira 1999).

Inoculants and inoculant mixes intended to aid plant nutrition are available for application to pastures. Of these, only inoculants containing *Rhizobium* spp. for N-fixation by pasture legumes have a proven track record. Although strong claims are made concerning the ability of some inoculant products to mobilise unavailable P in pasture soils there is little support for these claims in the scientific literature.

There are a limited number of plants with proven ability to mobilise sparingly-available phosphate. There are also plants that can stimulate the release of phosphate from some organic P sources in soil. The most notable plants include some Australian native species such as banksias and a few crop species: for example, white lupin, chickpea, etc. Of these, the banksia family (*Proteacea*) and white lupin are most studied. They produce specialised roots (cluster roots) under low P conditions and exude organic anions (such as citrate) which mobilise phosphate from sparingly-soluble compounds in soil. These naturally occurring, phosphate 'mining' plants have stimulated considerable research into plants that can exude organic anions, acidify their rhizosphere, or excrete phosphatase enzymes to liberate phosphate from organic P (Richardson *et al.* 2011). Some pasture grasses (e.g. wallaby grass [*Austrodanthonia* spp]) are suspected of having similar abilities. However, because soil P fertility management is dictated by the relatively high P requirements of pasture legumes, P-efficient grasses have minimal real impacts on reducing the fertiliser requirements of our pastures (Simpson *et al.* 2011). Ideally, pasture legumes with 'P-mining' attributes are required.

Conclusions

P fertiliser is still a critical input for highly productive pastures. However, in some paddocks P fertility has been built up to levels that make it possible to shift to maintenance fertiliser applications. Maintenance fertiliser rates should be aimed at holding soil P fertility within a target range that is appropriate to the stocking rate and production goals of the farm. In many cases, soil test information can be used to develop a pasture 'response function' that reflects the likely response of the paddock to P fertiliser and this can be used to guide P-fertiliser investment decisions. Continued monitoring of the investment (using soil tests and by recording animal production from the paddock) will permit fine tuning. This approach maximises the effectiveness of current fertiliser technology. However, the P-balance efficiency of pastures is low. This is a cost that is built into our current rates of fertiliser use. It also presents an opportunity, because improved P-balance efficiency could mean reduced input costs. Improving P-use efficiency will be challenging and it is likely to need changes to pasture legumes, novel ways to manage soil biology and/or development of fertiliser technologies that can reduce the net accumulations (or leakages) of P in soil.

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