New insights into phosphorus cycling in pastures: implications for fertiliser management and for closing the phosphorus efficiency gap

RJ Simpson[A], GA Sandral[B], MH Ryan[C], TI McLaren[D], RJ Smernik[D], MJ McLaughlin[D,E], TM McBeath[F], H Lambers[C], CN Guppy[G] and AE Richardson[A]

[A] CSIRO Agriculture Flagship, Canberra, 2601: richard.simpson@csiro.au

[B] NSW Department of Primary Industries, Wagga Wagga, 2650

[C] University of Western Australia, Perth, 6009

[D] The University of Adelaide, Glen Osmond 5064

[E] CSIRO Land and Water Flagship, Glen Osmond 5064

[F] CSIRO Agriculture Flagship, Glen Osmond 5064

[G] University of New England, Armidale 2350

Abstract: *Farmers actively manage the natural phosphorus (P) cycle of grazing systems by applying fertiliser to lift production and avoid resource degradation. Fertiliser P inputs to a paddock are considerably less than the total amount of P cycling in the pasture system, but this strategic intervention boosts P cycling and underpins farm profitability. P cycle management needs to accommodate business and production goals, the P requirement of the soil-pasture system and to cover P exported from paddocks. Fertiliser decisions should be based on soil test information with soil P levels most effectively monitored using annual soil tests. Without this information there is a risk that soils may become over-fertilised. This is inefficient and provides little additional value. New research using radioactively-labelled superphosphate to trace P applied to subterranean clover pasture has found that, with good practice, the initial efficiency of P fertiliser uptake is substantially better than we previously believed was the case. However, most Australian soils still accumulate P ('P-fixation') and this creates a 'technical' inefficiency in P use that is hard to avoid. More new research is showing that there may be ways to manage pasture soils using an alternative group of pasture legumes (serradellas) that can potentially deliver similar levels of production, but at lower soil test P concentrations. These pastures may not be as 'easy care' as those based on subterranean clover and our experience with them under grazing in permanent pasture areas is limited at this stage. Initial research indicates that pastures based on serradellas may require less P fertiliser.*

Key words: *Ornithopus*, P sorption, phosphate, *Trifolium subterraneum*

Introduction

The reason phosphorus (P) fertiliser is applied to pasture in Australia is reasonably straight forward: the objective is to produce more saleable, high quality product per hectare than would otherwise be possible. All of the other reasons often given for using fertiliser: to correct soil P deficiency, to grow more pasture, to get more clover, are the process by which the objective is obtained. The least sensible reason for fertiliser application is 'to reduce my tax bill'.

When P fertiliser is first applied to unfertilised, agricultural soils, it often doubles pasture growth rates and, consequently, animal production per hectare (e.g. Alcock *et al.* 2012). Because the fixed cost of a grassland system is much the same whether it is fertilised or not, a major benefit is that the same fixed costs can be spread over a larger number of income-earning units. Consequently, if fertiliser use allows stocking rate to be doubled, it is not unreasonable to expect that profitability per hectare may be tripled. Having achieved higher production per hectare, the objective of fertiliser use shifts to maintaining that production with an appropriate (minimal) fertiliser investment.

The focus of this paper is P because it is almost universally deficient for plant growth in Australian soils, or will become so if P fertiliser applications are stopped. However, P is really only the 'headline' item on the nutrient score card and, as will be discussed later, attention to the overall balance of nutrients required for pasture production is also part of the deal.

We often think linearly about how fertiliser works on farms: e.g. P is applied each year (or sometimes 'every-so-often') so the pasture can take up more P and grow faster than it would otherwise do in a low P soil. This description of how P is used in pastures is not flawed, but it is an incomplete summary of what a farmer is actually doing when P fertiliser is applied. A broader view of the P cycle in pastures and our management of it can help us make better management decisions. It should also help us to evaluate the role, or otherwise, for new fertiliser and soil amendment products, and alternative ideas for managing nutrient availability in pasture systems.

The global P cycle and our place in it

P is an essential nutrient for plant and animal life because it is an important component of nucleic acids (e.g. RNA and DNA), in the membranes around cells (e.g. phospholipids) and is central to energy transfer systems of living organisms (e.g. ATP). Plants contain about 2 to 5 g P/kg of tissue dry weight and animals will have about 6 to 8 g P/kg of liveweight, mostly (~80%) in their teeth and bones because P is also important for the structural integrity of a skeleton.

Net flows of P in the nutrient cycle of a legume-based pasture system (the terrestrial P cycle)

Uptake and return of P through pasture and livestock: A pasture takes up the P it needs for growth from the soil. We can make a reasonable estimate of the amount taken up each year using the pasture yield and P content. For example, a pasture growing with ideal soil P fertility management, producing 13 tonnes of dry matter (DM) per ha per year with an average P concentration in herbage of 0.28% (Fulkerson *et al.* 1998; Pinkerton *et al.* 1997) and, below ground, about 6.5 t DM/ha of roots (0.14% P) must have accessed about 45 kg P/ha/year from the soil (Fig. 1).

If the pasture is being utilised effectively (let's assume 45% of the herbage is consumed), the livestock grazing this pasture will consume about 16 kg P/ha over the course of a year. About 40–50% of the P in pasture herbage will be in the phosphate form (also referred to as inorganic P). This is the form of P that plants take up from the soil. The remaining P in herbage (50–60% of the total herbage P), will be chemically bound in organic compounds (Bromfield and Jones 1970).

P is particularly important for growing animals because they need to incorporate P in developing muscle and bones, and for lactating animals because they secrete large amounts of P in milk. By contrast, non-lactating, mature animals (e.g. wethers) do not accumulate P and will excrete P in faeces and urine in amounts equivalent to the amount they consume. This knowledge allows us to calculate rates of P export from a grazed pasture. Most P export will be accounted for by estimating the proportion of fleece-free liveweight gain that is culled from a flock, sold as lamb or beef, or in the milk and culled animals that are sold from a dairy farm. An outstanding feature of grazing systems is that the amount of P exported in animal products is often relatively small (0.5–2 kg P/ha/year for sheep/beef systems) when compared with the amounts removed, for example, in grain from a crop (~3.5 kg of P is exported per tonne of grain yield).

For this exercise, we will assume that 2 kg P/ha is exported from the paddock each year. This means that 14 of the 16 kg P/ha consumed by the animals is recycled back to the pasture, mainly in dung (some in urine). The P composition of dung varies depending on the amount and P concentration of herbage being consumed (both of which are influenced by P fertiliser use). However, for sheep consuming green herbage 75–90% of the P in dung is likely to be present as phosphate, the form that is readily available to plants. The rest is in organic compounds (Barrow and Lambourne 1962; Bromfield and Jones 1970). On dry pastures, the percentage of

How P export from a paddock can be calculated:

P export from a pasture grazed continuously by 15 wethers/ha with a 20% replacement policy (sold at 50 kg (fleece-free liveweight, replaced with 25 kg weaners) will only be about 0.5 kg P/ha: (15*0.2) * (25 *0.006) = 0.45 kg P/ha/year

i.e. (number removed) * (livewt gain/sheep * kg P/kg livewt)

A ewe-lamb system producing 7 lambs/ha at 46–48 kg liveweight will remove about 2 kg P/ha: 7 * (47 * 0.006) = 1.97 kg P/ha/year

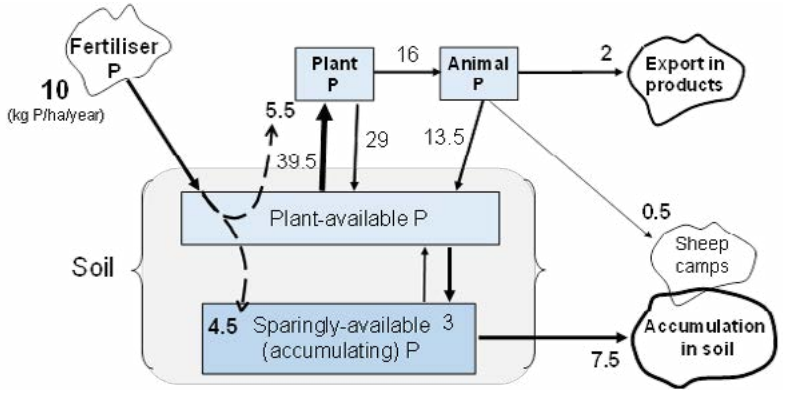

Figure 1. Net flows of P in the P cycle of a subterranean clover-based pasture. The data are derived from a grazed, long term soil P fertility experiment near Hall, ACT that was being maintained close to the critical soil test P concentration for maximum production by annual P fertiliser applications. This is 'Phase 2' of the grazing experiment (P1 treatments) for which soil test P results are shown in Figure 3. Values in bold are measured P flows. Other values were deduced (see text).

phosphate-P in dung is a little less (about 50%). So, of the 14 kg P/ha being recycled back to the pasture over the course of a year, about 12 kg P/ha will most probably be as phosphate and 2 kg P/ha as organic P.

During the year, the P in the uneaten pasture will also return to the soil when herbage is trampled or when it dies and decays. This is obvious for an annual pasture, which is dead by early to mid-summer. Pasture residues are mostly decomposed by the following autumn, when new pasture growth is appearing. The same is true of perennial pastures because there is inevitable turnover of leaves and roots. If this were not the case, pastures would 'clog up' with accumulating herbage. We do see this occasionally, but rarely when pastures are being grazed with adequate numbers of stock. We can deduce from this, that in most situations about 29 kg P/ha will also return to the soil as a result of death and decay of leaves, stems and roots over the course of the year. About 13 kg of P/ha will return as phosphate, and 16 kg P/ha as organic P (Bromfield and Jones 1970).

All together, we have about 25 kg P/ha/year being returned to the soil as phosphate and about 18 kg P/ha/year as organic P.

Soil P audits in the grazing experiment that is represented in Figs. 1 and 3, indicate that despite this large annual input of organic P to the soil, only about 3 kg P is accumulated in organic compounds each year (McLaren *et al.* 2015a; George *et al.* 2007). This tells us two things: (i) a pasture fertilised using mineral P fertiliser has a very active organic P cycle. Add to this, the fact that most nitrogen entering the pasture is via a legume and it is clear that the productivity of Australian pastures depends heavily on organic nutrient cycling processes. (ii) Soil microbial activity must be very high and working in favour of the high productivity we are striving to achieve, because more than 80% of the organic P entering the soil each year

must have been mineralised to phosphate for potential use by plants, microorganisms or soil fauna.

P in soil: The reactions of P in soil are complex (e.g. McLaughlin *et al.* 2011). However, for the purpose of understanding how P cycling influences pasture production we can reduce the complexity to the net flows of P between the main notional pools of P in a soil.

All soils contain relatively large **total** amounts of P (e.g. between 0.1–0.4 g P/kg soil in the topsoil (0–10 cm depth); McLaughlin *et al.* 1990). This means there is likely to be at least ~130–520 kg P/ha in the soil under a pasture (equivalent to about 1.4–5.7 tonnes superphosphate/ha). P exists in the soil either as phosphate or as organic P (i.e. the P that is chemically bound in soil organic matter compounds). However, only a small proportion of the P in the soil is potentially available for immediate use by a growing pasture.

'Plant available' phosphate: Plants take up water soluble phosphate (e.g. (HPO_4^{2-} and $H_2PO_4^{1-}$) via their roots from the thin film of water that sits around soil particles (the 'soil solution'). The concentration of phosphate in soil solution is always very low (e.g. ~ 0.1 mg/L [range <0.02–0.34 mg/L]; Lambers and Plaxton 2015), so at any one time the soil solution contains only a small amount of P and this is not enough to grow a pasture (e.g. probably only about 50–100 P/ha). Much more phosphate is adsorbed to the electrically charged outside surface of soil particles. As roots take up phosphate from the soil solution, phosphate that is adsorbed to the soil particles is released to the soil solution to replace the P being removed by the plant. (See next page)

Collectively the phosphate in soil solution and that able to be readily exchanged into solution from soil particles is notionally referred to as 'plant available' P.

'Sparingly available' phosphate: In soils that have intrinsically low P fertility (e.g. many Australian soils), a proportion of the phosphate that is adsorbed to the soil particles slowly diffuses into the soil particle itself (solid-state diffusion) where it reacts with the surfaces of iron (mainly) and aluminium oxides at a rate that is determined by the concentration of phosphate in soil solution, the soil's intrinsic chemistry, and temperature (Barrow 1983). The longer the phosphate is in contact with the soil, the more phosphate will be 'sorbed' in this way. These slow reactions inevitably decrease the effectiveness of phosphate fertiliser applications because (i) the phosphate diffusing within soil particles slowly reduces the amount of adsorbed phosphate that can be readily released to replenish the soil solution and (ii) once within the soil particle it can only diffuse back out relatively slowly.

The consequence of the slow reaction of phosphate with soil has previously been described as 'P-fixation'. Inevitably it can lead to accumulation of P in soil under fertilised pasture. In the example shown in Figure 1 (pasture being maintained at optimal soil P fertility with inputs of ~10 kg P/ha/year), about 4.5 kg P/ha was accumulated as phosphate in the soil each year. However, the accumulated P is not fixed irreversibly in the soil. If fertiliser is withheld, pasture growth and P uptake lowers the phosphate concentration in soil solution and draws on phosphate from the exchangeable pool. This sets up the conditions under which sorbed P begins to diffuse slowly back to the surface of the soil particle and back into the soil solution. Unfortunately, in a low P soil the rate at which phosphate diffuses into a soil particle after fertiliser has been applied is faster than rate that it can diffuse back out.

Organic P: We have estimated that 18 kg P/ha/year is added to the soil as organic P in plant residues and animal excreta. In addition, the residues of microorganisms and soil fauna (worms, nematodes, insects, etc.) that have consumed organic P and phosphate will be added to the organic P pool. Soils host a community of these organisms (a food web) that utilise soil organic matter to generate energy and nutrients. The driving influence on their activity in soil is the amount of organic matter in the soil (Haynes 1999). The organic matter content of the soil, and consequently its microbial activity, is improved when P fertiliser

is applied because the extra pasture growth is the source of new organic matter. P fertiliser also enhances growth of nitrogen-fixing clovers. This is particularly important because legume nitrogen fixation is usually the major source of nitrogen for the pasture system. The degradation of organic matter containing P by soil fauna ultimately releases phosphate that plants can take up from the soil solution. Roots also secrete phosphatase enzymes that release phosphate from many of the simpler organic P compounds (e.g. sugar phosphates and nucleic acids). These compounds are so readily degraded by plant and microbial enzymes that

Interpreting soil tests: Soil tests for P (e.g. Colwell P or Olsen P) measure only a component of the plant-available phosphate pool in the topsoil (0–10 cm depth). The tests are intended to be useful as a predictor of likely response to fertiliser P application. There is no soil test that measures all of the plant-available P in soil so they are more correctly described as extractable-P tests. Using a soil test for P is similar to using a 'dip-stick' to measure liquid in a tank. The test result can only be interpreted if you also know the critical soil test P value, above which further pasture growth responses to fertiliser P are unlikely (i.e. the critical P value indicates when the tank is 'full').

By convention, critical soil test P is usually defined in Australia as the soil test value that corresponds to 95% of maximum pasture yield in spring. (NB: 90% of maximum yield is used for crops).

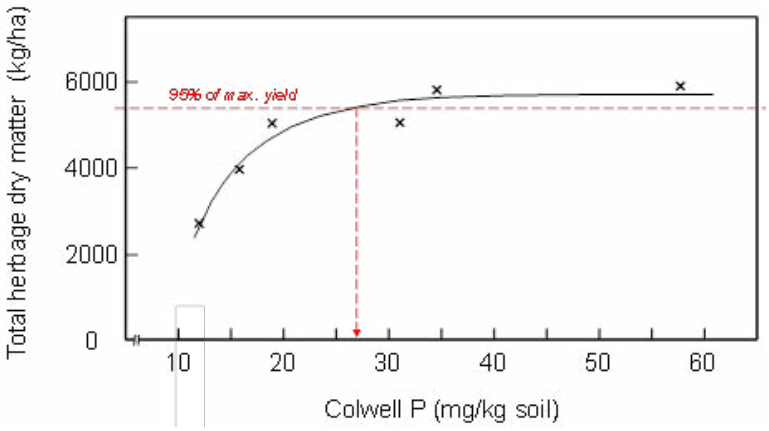

Figure 2. An example of how pasture responds to P when it is applied to a low P soil. This example is for a pure stand of subterranean clover growing at Burrinjuck, near Bookham, NSW in 2013. The soil tests (0–10 cm depth) were taken in spring near the peak of herbage production. Above the critical soil test P level for the soil-pasture system, there will be very little extra pasture produced (Sandral *et al.* unpublished data).

The example shown here is for a soil with a Phosphorus Buffering Index (PBI) of 50–65. The PBI soil test measures the short-term sorption of phosphate to soil particles. The Colwell P test varies with the PBI value of a soil and the PBI value can be used, therefore, to estimate the critical Colwell soil test P that is appropriate for each soil. For the soil at Burrinjuck, the predicted critical Colwell P is 30 mg P/kg soil for a clover-based pasture. This is close to the critical Colwell P that was found for subterranean clover in the experiment described above. If an Olsen P soil test is being used, it is thought that the critical value is 15 mg P/kg soil irrespective of the soil PBI value (Gourley *et al.* 2007). Best practice would be to use the critical soil test value to set the upper boundary for soil P fertility management. For example, if the objective was maximum pasture production a target range of 30–35 mg P/kg (Colwell) would be appropriate. Other factors (pasture composition, business objectives, etc.) may mean that a lower target is chosen for soil management. This is entirely legitimate; it is a business decision (i.e. lower pasture yield and potential carrying capacity objectives). However, soil fertility targets that are well in excess of the critical P for the soil-pasture system are not a sensible use of P fertiliser; see text for discussion.

they are only found in relatively small quantities in soil. However, a proportion of the organic P in soils is also found in both small and complex compounds that resist degradation. In fertilised pasture soils, a proportion of the resistant organic P compounds accumulate each year. Audits of P in soil under the optimally fertilised pasture soil represented in Figure 1 has shown that most probably ~3 of the 7.5 kg P accumulated in the soil each year is organic P (McLaren *et al.* 2015a; George *et al.* 2007).

Fertiliser inputs: The only substantial input of P to the terrestrial cycle in a pasture[1] comes in the form of fertiliser P. The amount of P that needs to be applied depends on how the P cycle in being managed (for reasons of simplicity, we will confine this discussion to use of soluble P fertilisers).

The example discussed so far (Fig. 1) is a pasture, continuously grazed by sheep, with soil P being maintained near the critical concentration for maximum production (i.e. Olsen P between 10 and 15 mg/kg in the top 10 cm of soil; Figure 3). This was achieved by annual P fertiliser applications that, by definition, must have covered:

(i) the P exported each year in animal	2
(ii) the P that accumulated in the soil either as phosphate or as organic P	7.5
(iii) any P accumulated in sheep camps due to uneven distribution of dung within the paddock	0.5
(iv) any losses of P resulting from soil erosion, runoff or leaching	negligible
P applied as fertiliser (Fig. 1) = 105 kg P/ha	

When soil P fertility is low and less than ideal for pasture production, the objective may be to increase the soil test P concentration over time. In this case, the amount of P fertiliser applied each year will also include additional P to achieve an increase in the soil test P level. Additions of P that also build soil P fertility are building the phosphate and organic P cycles in the pasture system. When the critical soil test P concentration of the system is reached, it is time to reduce the rate of P application back to an amount that will be sufficient to hold the soil test P level close to the target for management.

An example of management in which soil P fertility was first built and was then maintained (i.e. soil test P concentrations were held within a target range) is shown in Figure 3. The amount of P that had to be applied to achieve the target soil test P range was initially high, but declined to a relatively stable rate of P input during the maintenance phase of the experiment (Fig. 3b). The soil tests, in Phases 1 and 2 of this grazing experiment, were taken at about 6-week intervals and reveal typical seasonal variability in soil test values. It is usually recommended that soil tests be taken, on farms, at a similar time each year to minimise the seasonal variability in your test results (for example, see Phase 3 of the experiment).

The direct supply of P from a superphosphate application to pasture plants has been measured in the soil P management systems illustrated in Figure 3 using radioactively labelled P. Fertiliser (20 kg P/ha) was applied shortly after the opening rains of the 2014 season to establishing subterranean clover in the unfertilised pasture (P0 treatment), the pasture with near-optimal soil P fertility (P1) and the over-fertilised pasture (P2). Uptake of fertiliser P into the shoots of the plants during the season was 40%, 45% and 42%, respectively (McLaren *et al.* 2015b). If we make similar assumptions about P uptake into the roots of these pastures, as done earlier in this paper, this may mean that up to 56% of the fertiliser P was used by the pasture for growth during the season in which it was applied.

P fertiliser use – a strategic intervention in the P cycle: The size of the P cycle in a productive pasture managed for optimal soil P fertility (Fig. 1) is surprisingly large. At least 45 kg P/ha (the equivalent of 0.5t/ha of superphosphate) was cycled each year via the

1 Very minor inputs may come in the form of P attached to wind-blown dust or spray from an ocean, and the net amount cycling in the plant-available pool may be added to by soil formation (weathering of rocks) but the amounts are small (e.g. Costin 1980) and very unlikely to be significant for high production.

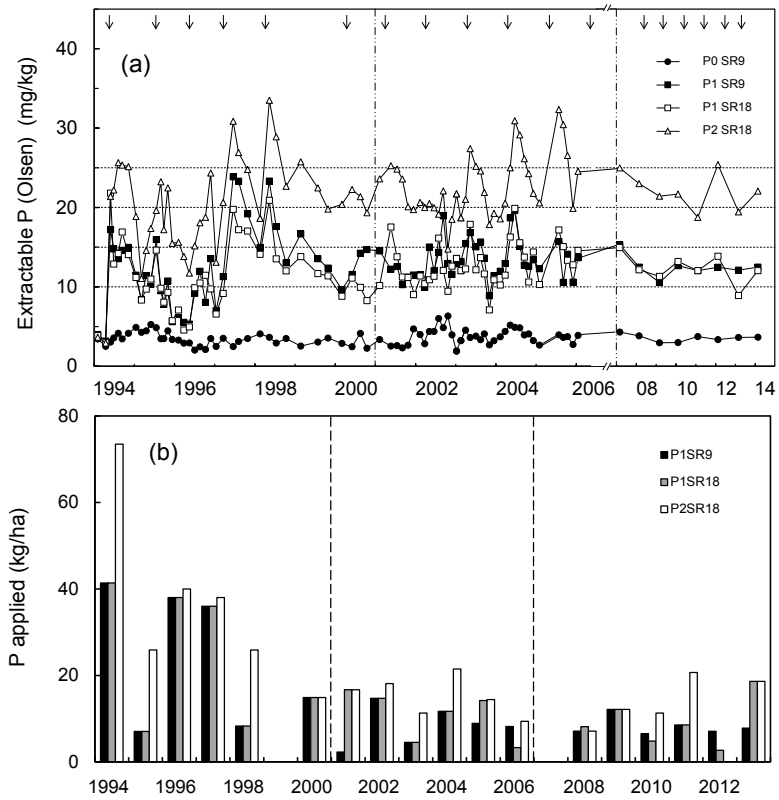

Figure 3. (a) Soil test P concentrations (Olsen P) of topsoil (0–10 cm) in paddocks that were not fertilised (P0), were fertilised to be near-optimal for pasture growth (target soil test P range = 10–15 mg P/kg (P1)), or were excessively fertilised (target soil test P range = 20–25 mg P/kg (P2)). Paddocks were stocked with either 9 (SR9) or 18 (SR18) sheep per hectare. Soil tests were conducted at about 6-week intervals to the end of 2005 and annually thereafter. (b) Amounts of P applied to each fertilised pasture each year. Three phases of the experiment were observed: Phase 1 (1994–2000), a soil fertility build-up phase; Phase 2, (2001–2006), a soil fertility maintenance phase with frequent measurements; Phase 3 (2007–2014), a maintenance phase with less frequent monitoring (adapted from Simpson *et al.* 2015).

P fertiliser types: P fertilisers come in various forms although the most commonly used P fertilisers (e.g. superphosphate, triple super, MAP and DAP) predominantly contain P as ***water soluble phosphate***. When they are applied to soil, they directly recharge the soil solution and the exchangeable phosphate pools in the soil. Rock phosphate fertilisers are ***less soluble forms of phosphate*** (with relatively low proportions of immediately available phosphate) and when applied to the soil, they initially add to the less available phosphate pools and release phosphate to the available pools relatively slowly. The more reactive forms can be useful fertilisers but need high rainfall and acidic soil conditions to facilitate soluble phosphate release (Sale *et al.* 1997). ***'Organic' fertilisers*** (manures, composted products) often have variable proportions of organic P, soluble phosphate and other nutrients; some can contain surprisingly high proportions of soluble P. Some products are adjusted to a specification before being sold, but others (e.g. manures) can vary from batch to batch in P concentration and composition. These products add P to the phosphate and organic P pools of the soil.

soil, pasture and livestock. Because livestock consume pasture and deposit excreta at sub-daily time intervals, it is inevitable that some of the P (and other nutrients) will have cycled more than once in a year, so the actual rate of P cycling will be even faster than these estimates suggest. We know that a substantial proportion of the P applied as fertiliser is directly used by plants in the pasture. However, the outstanding observation is that the amount of P applied as fertiliser was only a quarter or less of that required for pasture growth. The bulk of the P required annually for pasture production is derived from P cycling in the soil-pasture-animal system.

The take home message is that P fertiliser applications are most accurately viewed as strategic management interventions in the P cycle that either build soil P fertility, or top up the P cycle to ensure that P supply to the pasture is sufficient for high production.

P export from the farm (and its entry into the aquatic P cycle)

P leaves the farm in animal products destined mostly for human consumption in major cities of the world. This can lead to a major break in the terrestrial P cycle because P in diets is ultimately channelled via waste and excreta into landfill and sewage systems from which there is often poor recovery and return of P to agricultural land (e.g. Cordell *et al.* 2013). The main problem is one of cost. P fertilisers derived from rock phosphate are still cheap by comparison with the cost of recovering P from waste streams and transferring it back to agricultural land. Recovery, where it occurs, is often driven by the economics of waste disposal rather than the value of the P as a potential fertiliser. A lot of P ending up in these pathways is ultimately disposed of in the world's oceans.

Relatively small proportions of total soil P are also lost continually from the global terrestrial cycle to streams and ultimately the oceans; it is important to recognise that agricultural practices can sometimes accelerate these losses. So far we have discussed the situation for a fairly typical Australian grassland where the amount of P loss via soil erosion, by leaching and in runoff from farmland is small e.g. (<0.4%–<5% of applied P, Costin 1980; McCaskill and Cayley 2000; Ridley *et al.* 2003; Melland *et al.* 2008). Even small losses are environmentally important because P that finds its way into streams and lakes can cause major environmental problems (e.g. eutrophication). However, farming systems overloaded with P (soils with high intrinsic P fertility or where P fertilisers and manures are applied in excess; Nash and Halliwell 1999), or on soils will low P-sorbing soils with poor capacity to retain P (e.g. sandy soils in WA, SA and in coastal areas; e.g. Ozanne *et al.* 1961, Lewis *et al.* 1987) can also lose P in relatively large quantities. This is neither financially or environmentally desirable. Changes to P fertiliser and soil management to address the losses are necessary.

P entering the oceans has re-entered the slowest part of the global P cycle. It accumulates as insoluble sedimentary deposits which are normally only brought to the surface in rock strata uplifted during major geological events. The timeframe for re-accessing P that has entered the oceans is millions of years. This is one of the reasons why P is regarded as a finite and scarce resource.

Rock phosphate is often derived from sedimentary deposits that can now be accessed in land-based mining operations. Some is also derived from guano (bird or bat excreta) deposits. Global P resources are notionally divided into 'reserves' (high quality phosphate rock able to be mined at current prices) and 'resources' (deposits uneconomic to mine at today's price). Presently, the world is thought to have 300–400 years of phosphate rock 'reserves' (at current rates of use) and there are vast global P 'resources' but they are either very expensive to mine, or will require new technology if they are to be extracted and utilised relatively cheaply (Van Kauwenbergh 2010). The immediate issue for farmers is that the price of P fertiliser has been rising steadily since about 2000 (IFDC, http://ifdc.org/) and this puts pressure on the terms of trade for farming; especially in the Australian context where P is an important input for maintaining production.

Inefficiencies and opportunities

Constraints to achieving high P-use efficiency

The chemical and nutrient supply balance of your soil: One of the 'laws' of plant nutrition is that the most limiting nutrient for plant growth will impose the largest constraint on production. In Australian pastures that is usually either nitrogen (N) or P. In most grazing systems we address N by using pasture legumes (in dairy pastures N is also applied as a fertiliser). P is applied to cover P deficiency, ensure high clover content (i.e. N supply) and consequently pasture production. However, many Australian soils also have additional nutrient constraints which must be addressed simultaneously to ensure that maximum can be obtained from P fertiliser investments. Figure 4 shows an extreme example of how ineffective a P fertiliser can be if the supply of other essential nutrients is forgotten. Typically, the supply of sulphur, potassium, molybdenum and other micronutrients may need to be considered using the published critical nutrient concentrations for maximum pasture production as a guide (Peverill *et al.* 1999; Gourley *et al.* 2007; Simpson *et al.* 2009). Toxic nutrient concentrations (e.g. salinity, high aluminium in a very acid soil, etc.) can also constrain the potential response of pasture to P fertiliser.

P accumulation in paddocks

The slow reactions of phosphate in low P soils that cause them to accumulate P when fertiliser is applied have been discussed above. The net result of these reactions has been examined during the maintenance phases of the fertilised pasture systems that were illustrated in Figure 3. In this example (Fig. 5), the amounts of P accumulated in the paddocks also includes a small net accumulation (probably ~0.5 kg P/ha) as dung in sheep camps. This work indicates that when pasture soils are maintained at higher soil test P concentrations they will accumulate P faster than if they were managed at lower soil test P concentrations. This reflects laboratory studies which predict that rates of P sorption in soil will be influenced by phosphate concentration, soil temperature and time of contact (Barrow 1983).

The lessons for optimal soil P management

Avoid excessive fertiliser applications. Managing soil P levels at concentrations well above the critical P levels for the pasture system is unproductive as: (i) no extra pasture will be grown, (ii) more of the P applied will accumulate in the soil and pasture system, and (iii) higher soil P concentrations are also associated with greater potential for P loss

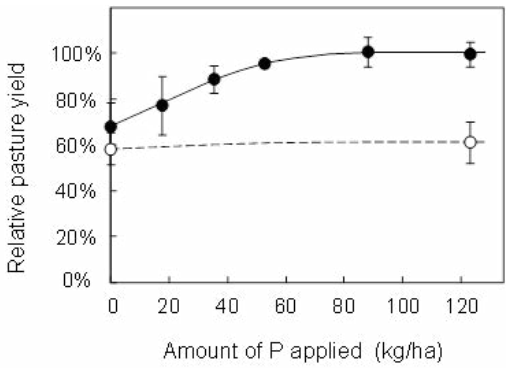

Figure 4. Response to P applied as triple superphosphate by a phalaris-subterranean clover pasture grown near Taralga, NSW when additional potassium and sulphur was also applied (●) and at the highest and lowest P application rates when potassium and sulphur had not been applied (○) (from Simpson *et al.* 2009).

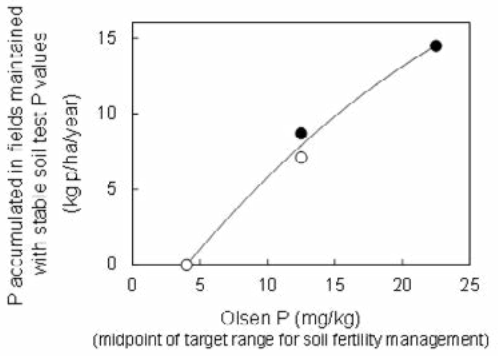

Figure 5. Amounts of P accumulated annually in the grazing systems for which soil test data are presented in Figure 3a during the soil P fertility maintenance phase (Phase 2). P inputs each year are shown in Figure 3b. Closed symbols (●) indicate pastures grazed with 18 sheep/ha, open symbols (○) indicate pastures grazed with 9 sheep/ha (data from Simpson *et al.* 2015).

to the wider environment (e.g. Melland *et al.* 2008).

Plants with lower 'critical P' requirements. The relationship between soil test P levels and the amount of P accumulated in paddocks (Fig. 5) gives clues to a possible strategy for reducing the P costs of pasture production because P accumulation in soil is the major reason why more P must be applied to maintain soil fertility than is removed in animal products. In clover-based pasture systems, it is the clover plant that has the highest critical P requirement and this sets the soil test P levels to which we fertilise pastures. Presently, a national research program funded jointly by Meat & Livestock Australia and Australian Wool Innovation Ltd is benchmarking the critical P requirements of a range of alternative legumes, so that the P fertility of pastures based on them can be better managed. The work also aims to identify legumes that can yield as well as subterranean clover but at a substantially lower critical soil P concentration.

It is early days for this research but one legume genus (*Ornithopus* spp., the serradella group; NSW DPI Primefacts, Hackney *et al.* 2013) appears to have a substantially lower P requirement. In field trials near Yass, French serradella (cv. Margurita) has yielded as well as subterranean clover (cv. Leura) at considerably lower rates of P application (Sandral *et al.* 2015). Yellow serradella (cv. Santorini) also had a lower critical P requirement but had relatively poor winter production and did not yield as well as subterranean clover during spring in this environment. Yellow serradella does yield as well as subterranean clover in other locations and can do so at low rates of P application (e.g. in WA; Bolland and Paynter 1992). Further work is required to better understand the adaptation range of the serradella group. French and yellow serradellas are already used successfully in some pasture situations (particularly in crop rotations, and in acid, sandy soils); their potential role, productivity and persistence in the permanent pasture zone of eastern Australia is less well understood and will be the subject of on-going research.

Can more P be extracted from sparingly available sources in soil?

A popularly held view is that it should be possible to use plants and microbes to access the sparingly available phosphate and organic P that accumulates in fertilised soil. A limited number of naturally occurring plants have this capacity. The most well known is the white lupin (*Lupinus albus*) which produces specialised 'cluster' roots that exude citrate (an organic anion). The citrate increases desorption of some of the phosphate that other plants cannot access. Banksias and a few other plant species also have this capacity (Shane and Lambers 2005). Unfortunately, there are no plants with equivalent attributes that we are aware of that are suited to use in Australian pastures. Considerable research effort has been expended attempting to mimic the organic anion release attributes of white lupin roots in other agricultural species, and to produce plants with increased root-exuded, phosphatase enzyme activity with the aim of increasing access to organic P in soil. Microbial inoculants that, in glasshouse studies at least, appear to mobilise sparingly available P have been promoted from time to time. However, real progress in mobilising the accumulated P in fertilised soil has been limited (Richardson *et al.* 2011).

Conclusions

Pastures are predominantly supplied P as a result of nutrient cycling in the soil-plant-animal system. The amount of P applied as fertiliser every year is relatively small compared to the amount that is cycling naturally. However, fertiliser inputs are important strategic interventions that ensure the P cycle can maintain a concentration of 'plant-available' P that is close to the critical concentration needed by a highly productive pasture. To do this, the amount of P that is being applied must replace P exported from the paddock in farm products, and it must also cover P that accumulates in the soil when phosphate is sorbed to soil particles or is incorporated into organic matter that resists mineralisation. The amount of P accumulation in paddocks is higher when the soil is over-

fertilised. Managing soil test P concentrations to avoid exceeding the critical soil test P of your soil-pasture system is important for efficient use of P fertiliser.

Acknowledgments

Meat & Livestock Australia and Australian Wool Innovation Ltd funded much of the recent research described in this paper.

References

Alcock DJ, Pope L, Powells J, Garden D (2012) Why fertilise native pastures? *In*: 'Proceedings of the 27th Annual Conference of the Grassland Society of NSW', Eds C Harris, G Lodge, C Waters (Grasslands Society of NSW, Orange NSW), pp. 66–75.

Barrow NJ, (1983) A mechanistic model for describing the sorption and desorption of phosphate by soil. *Journal of Soil Science* **34**, 733–750.

Barrow NJ, Lambourne LJ (1962) Partition of excreted nitrogen, sulphur and phosphorus between the faeces and urine of sheep being fed pasture. *Australian Journal of Agricultural Research* **13**, 461–471.

Bolland MDA, Paynter BH (1992) Comparative responses of annual pasture legume species to superphosphate applications in medium and high rainfall areas of Western Australia. *Fertilizer Research* **31**, 21–33.

Bromfield SM, Jones OL (1970) The effect of sheep on the recycling of phosphorus in hayed-off pastures. *Australian Journal of Agricultural Research* **21**, 699–711.

Cordell D, Jackson M, S. White (2013) Phosphorus flows through the Australian food system: identifying intervention points as a roadmap to phosphorus security. *Environmental Science and Policy* **29**, 87–102.

Costin AB (1980) Runoff and soil and nutrient losses from an improved pasture at Ginninderra, Southern Tablelands, New South Wales. *Australian Journal of Agricultural Research* **31**, 533–546.

Fulkerson WJ, Slack K, Hennessey DW, Hough GM (1998) Nutrients in ryegrass (*Lolium* spp.), white clover (*Trifolium repens*) and Kikuyu (*Pennisetum clandestinum*) pastures in relation to season and stage of regrowth in a subtropical environment. *Australian Journal of Experimental Agriculture* **38**, 227–240.

George TS, Simpson RJ, Hadobas PA, Marshall DJ, Richardson AE (2007) Accumulation and phosphatase-lability of organic phosphorus in fertilised pasture soils. *Australian Journal of Agricultural Research* **58**, 47–55.

Gourley CJP, Melland AR, Waller RA, Awty IM, Smith AP, Peverill KI, Hannah MC (2007) Making better fertiliser decisions for grazed pastures in Australia. Victorian Government Department of Primary Industries, Melbourne. http://www.asris.csiro.au/downloads/BFD/Making%20Better%20Fertiliser%20Decisions%20for%20Grazed%20Pastures%20in%20Australia.pdf

Hackney B, Rodham C, Piltz J (2013) Using French serradella to increase crop and livestock production. 25pp. (Meat & Livestock Australia Ltd)

Haynes RJ (1999) Size and activity of the soil microbial biomass under grass and arable management. *Biology and Fertility of Soils* **30**, 210–216.

Hill KD (1989) The spatial distribution of Mallee Eucalyptus in Australia. In 'Mediterranean Landscapes in Australia – Mallee Ecosystems and their Management'. (Eds CS John, PJ Parker). pp. 93–108. (CSIRO Publishing: Melbourne)

Lambers H, Plaxton WC (2015) Phosphorus: back to the roots. In 'Annual Plant Reviews Volume 48: Phosphorus Metabolism in Plants'. (Eds. WC Plaxton, H Lambers). pp. 3–22. (Wiley-Blackwell Publishing, Chicester)

Lewis DC, Clarke AL, Hall WB (1987) Accumulation of plant nutrients and changes in soil properties of sandy soils under fertilised pastures in south-eastern South Australia. I. Phosphorus. *Australian Journal of Soil Research* **25**, 193–202.

McCaskill MR, Cayley JWD (2000) Soil audit of a long-term phosphate experiment in South-Western Victoria: total phosphorus, sulfur, nitrogen and major cations. *Australian Journal of Agricultural Research* **51**, 737–748.

McLaren TI, McBeath TM, Simpson RJ, McLaughlin MJ, Guppy CN, Richardson AE (2015b) Improved fertiliser phosphorus management for maximum clover production and fertiliser phosphorus efficiency. *In*: 'Proceedings of the 17th Australian Agronomy Conference, Hobart.' www.agronomy2015.com.au/

McLaren TI, Simpson RJ, McLaughlin MJ, Smernik RJ, McBeath TM, Guppy CG, Richardson AE (2015a) An assessment of various measures of soil P and the net accumulation of P in fertilized soils under pasture. *Journal of Plant Nutrition and Soil Science* (accepted).

McLaughlin MJ, Baker TG, James TR, Rundle JA (1990) Distribution and forms of phosphorus and aluminium in acidic topsoils under pastures in south-eastern Australia. *Australian Journal of Soil Research* **28**, 371–385.

McLaughlin MJ, McBeath TM, Smernik R, Stacey SP, Ajiboye S, Guppy C (2011) The chemical nature of P-accumulation in agricultural soils – implications for fertiliser management and design: an Australian perspective. *Plant and Soil* **349**, 69–87.

Melland AR, McCaskill MR, White RE, Chapman DF (2008) Loss of phosphorus and nitrogen in runoff and subsurface drainage from high and low input pastures grazed by sheep in Australia. *Australian Journal of Soil Research* **46**, 161–172.

Nash DM, Haliwell DJ (1999) Fertilisers and phosphorus loss from productive grazing systems. *Australian Journal of Soil Research* **37**, 403–429.

NSW DPI Primefacts and Agnotes: various factsheets concerning the serradella varieties http://www.dpi.nsw.gov.au/aboutus/resources/factsheets/finder?topic=141261&queries_type_query_posted=1&queries_type_query=Factsheet&queries_topic-id_query=http://www.dpi.nsw.gov.au/agriculture/field&queries_topic_query=Crops%20and%20pastures&search_page_65537_submit_button=Submit

Ozanne PG, Kirton DJ, Shaw TC (1961) The loss of phosphorus from sandy soils. *Australian Journal of Agricultural Research* **11**, 927–924.

Peverill KI, Sparrow LA, Reuter DJ (1999) Soil analysis: an interpretation manual. CSIRO, Melbourne

Pinkerton A, Smith FW, Lewis DC (1997) Pasture species. In. 'Plant analysis: An interpretation manual', 2nd Edition, (Eds. DJ Reuter, JB Robinson). pp. 287–346. (CSIRO Publishing, Collingwood).

Richardson AE, Lynch JP, Ryan PR, Delhaize E, Smith FA, Smith SE, Harvey PR, Ryan MH, Veneklaas EJ, Lambers H, Oberson A, Culvenor RA, Simpson RJ (2011) Plant and microbial strategies to improve the phosphorus efficiency of agriculture. *Plant and Soil* **389**, 121–156.

Ridley AM, Christy BP, White RE, McLean T, Green R (2003) North-east Victoria SGS National Experiment site: water and nutrient losses from grazing systems on contrasting soil types and levels of inputs. *Australian Journal of Experimental Agriculture* **43**, 799–815.

Sale PWG, Simpson PG, Lewis DC, Gilkes RJ, Bolland MDA, Ratkowsky DA, Gilbert MA, Garden DL, Cayley JWD, Johnson D (1997) The agronomic effectiveness of reactive phosphate rocks 1. Effect of the pasture environment. *Australian Journal of Experimental Agriculture* **37**, 921–936.

Sandral G, Simpson R, Price A, Hildabrand S, Fuller C, Stefanski A, Yang Z, Culvenor R, Kidd D, Lambers H, Ryan M (2015) Phosphorus efficient pastures: response of alternative legumes to fertiliser application. *In:* 'Proceedings of the 17th Australian Agronomy Conference, Hobart'. www.agronomy2015.com.au/

Shane MW, Lambers H (2005) Cluster roots: a curiosity in context. *Plant and Soil* **274**, 101–125.

Simpson R, Graham P, Davies L, Zurcher E (2009) Five easy steps to ensure you are making money from superphosphate. (CSIRO & Industry and Investment NSW), *Farm advisory booklet and computer decision-support tool*. Available at: www.mla.com.au

Simpson RJ, Stefanski A, Marshall DJ, Moore AD, Richardson AE (2015a) Management of soil phosphorus fertility determines the phosphorus budget of a temperate grazing system and is the key to improving phosphorus-balance efficiency. *Agriculture, Ecosystems and Environment* (accepted)

Van Kauwenbergh S (2010) *World Phosphate Reserves and Resources*; International Fertilizer Development Centre (IFDC), (Washington, DC, USA).