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Prepared by: **Richard Simpson,**
Alan Richardson and
Mike McLaughlin
CSIRO Sustainable
Agriculture Flagship

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Review of phosphorus availability and utilisation in pastures for increased pasture productivity

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Abstract

The P-balance efficiency of southern Australian agriculture is only ~25% (i.e. 4 units of P are applied as fertiliser to produce only 1 unit of P in products). Inefficient P-use represents both a threat (graziers who use P-ineffectively will be viewed poorly in a P-limited world) and a major opportunity (efficiency measures will improve profitability and competiveness). Reductions in fertiliser inputs, in the first instance, of 25%-30% with concomitant environmental benefits appear feasible. However, this will require a committed RD&E investment. Wider implementation of industry best-practice can provide immediate benefits. To secure continued improvements it will be necessary to research the development of novel, lower-P farming systems, novel fertilisers or fertiliser management technologies, alternative P-efficient pasture legumes and P-efficient varieties of Australia's keystone pasture legumes.

Australia's extensive northern rangelands are P-deficient with few economic options for using P-fertilisers. A desktop audit indicated that the systems are all likely to be slowly extracting P without replacement. In most cases, the rates of P loss are low and not a threat to production at the present time. However, where productivity is higher nutrient extraction is thought to be a factor in the effective collapse of grazing system productivity and the issues of P extraction and replacement need to be explored. Direct strategic P-supplementation of cows in extensive breeding systems is likely to lift productivity and to bring the P-balance of these systems closer to an 'ideal' P-balance efficiency.

Executive summary

Background: Phosphorus (P) is an essential input for farms on low P soils and constitutes a significant input cost for most farming systems in southern Australia. Even in low-input agriculture it is essential to at least replace P removals to protect the sustainability of production. However, for most commercial farms, it is also essential for high production per hectare which allows a business to minimise overhead costs per DSE and to maximise profitability and return on investment. Presently, P-fertiliser inputs account for about 10% of all expenses (including wages) and amounts to about 21-26% of enterprise costs on "average" grazing farms (southern Australia).

Although the cost of P-fertiliser has been very volatile in recent years it has remained a profitable investment for a grazing business. However, increases in fertiliser cost directly reduce profitability and significantly increase the business risk associated with fertiliser investments. This can substantially reduce the attractiveness of applying fertiliser.

It has been forecast that peak P could occur within 25-30 years. This is the point at which global supply will not keep up with demand for P and the cost of P will escalate dramatically. This grim analysis prompted the International Fertiliser Development Center to re-assess global "reserves" and "resources" and they have claimed recently (September 2010) that the risk of peak P in this timeframe is remote. The debate about the sustainability of P-resources is, however, unlikely to dissipate because global food security is dependent on fertiliser use, high-quality rock P reserves are a finite resource, and the data underpinning estimates of the longevity of the reserves are of variable reliability. What is certain is that the price if P-fertiliser has doubled in the last 10 years and that as the world moves to mine new P-reserves, which are of lower quality or harder to extract, the cost of P fertiliser will continue to increase.

Presently Australia sources about half of its annual P requirements domestically and half from overseas. The majority is used in agriculture with a P-balance efficiency of only 25% (i.e. 4 units of P are applied as fertiliser to produce only 1 unit of P in products). About 90% of the P in agricultural products is exported, the rest is consumed domestically. In some countries, global P-shortages would result in increased emphasis on recovery and recycling of P from waste streams. For some countries, this will go close to covering P needs. However, in Australia recycling will cover only 5-10% of the annual P requirements of agriculture. 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 in agriculture. Significant opportunities exist to lift the profitability and sustainability of agricultural production and to improve the environmental credentials of farming, if the efficiency with which P is used in agriculture can be improved.

Threats: Estimates of the farmgate P-balance of the major southern Australian broadacre farm enterprises vary from extremely poor (5-15%, some horticultural enterprises), through poor (20-40% for grazing industries), to average (45-60% in cropping enterprises). Only very low-input, low-production systems or enterprises on very low P-sorbing soils (such as sands) approach 100% efficiency. In each case they do so at a cost (e.g. low productivity, or nutrient-leaky and environmentally problematic). The P-balance of extensive northern grazing systems are usually slightly negative (i.e. they extract P at a very slow rate). Rising P-costs present substantial potential threats to management of southern Australian grazing systems through the impact on profitability and business risks and will also make attempts to balance P-use in northern grazing systems even more difficult.

In addition, a number of commentators believe that human diets need to change to rationalise P use globally. Simple calculations of the P costs of meat-based diets indicate that meat production can require ~2-3 times as much P as a vegetarian diet and it is suggested that the consumption of meat should, therefore, be reduced. Unfortunately, these calls ignore many aspects of meat production in Australia that would mitigate the P-costs of production. Nevertheless, they highlight the fact that in a P-constrained world the image of meat as a sustainable product will come under scrutiny. Thus, the industry may face the dual threats of high prices for an input essential to productivity, and loss of market share.

- The P-efficiency footprint of Australian meat production systems should be quantified along with other aspects of the industry's environmental footprint so that the industry's position and environmental costs and benefits can be defended.

Opportunities: The large inefficiency associated with P use in agriculture and the grazing industries in particular, also represents a substantial opportunity to reduce costs by promoting a targeted approach to soil fertility management and by researching and developing P-efficient farming systems.

There is relatively little data about the nature and lability of the P that is accumulating in Australia's agricultural soils and consequently it is very difficult to estimate the magnitude of savings that can realistically be made by moving agriculture towards improved P-efficiency. However, examples of farming systems managed to maintain plant-available soil P at sensible levels, have inputs in the range 9-12 kg P/ha/year and accumulate between 4-8 kg P/ha annually depending on enterprise and soil type. It appears feasible that research to develop and implement novel low-P grazing systems could reduce "best-practice" fertiliser inputs by 25%-30%, in the first instance.

Currently, many farms appear not to be following "best practice" fertiliser recommendations and are operating at soil fertility levels in excess of the level necessary for maximum production. On these farms, immediate savings of a similar magnitude can also be achieved simply by encouraging adoption of current best practice. However, there appears to be a need to prove by demonstration to graziers and advisors, that soil fertility can be managed in a targeted manner using critical P values suitable for the farming system.

P-efficiencies derived by lowering the soil P concentration at which a farm can operate, may be obtained because the rate of P accumulation in sparingly-available soil P is slowed at the lower P concentration. It is possible that larger savings in P-fertiliser may be made if novel plants are found or developed, with traits that also enable solubilisation or extraction of P already accumulated in sparingly-available soil pools (e.g. organic acid secretion from roots; access to organic P). There are naturally-occurring examples of plants that can extract P from soils in this way but there are few examples of agricultural species with these desirable P-extraction traits.

RD&E to lift phosphorus-use efficiency: Achieving substantial improvements in the P-balance of Australian agriculture will not be an easy task despite the clear imperative and obvious production and environmental benefits that could be realised. P is such a universally important input in Australia that changes would already have been implemented were there easy solutions available. Despite this, there are some very obvious immediate goals that will deliver benefits with relatively little effort and there are a variety of options for improving the efficiency with which P fertilisers are used, for developing lower-P farming systems, and for reducing the rate at which P is accumulated in agricultural soils. Most of the latter options will take a committed RD&E investment and it is therefore essential that the benefits and feasibility of alternative options are clearly evaluated and understood.

***Immediate priority** - sharpen industry soil fertility management practices.* Despite widespread P use in grazing systems, it is clear that many graziers find it difficult to manage soil P fertility with confidence. Alternatively, they attempt to manage soil fertility without a clear understanding how pastures respond to P, or the relationship between soil P fertility and stocking rate. The proportion of farmers that use soil testing is believed to be low and, where tests are used, there is evidence to suggest that soils are often being over-fertilised. There is no financial or production benefit to be gained from applying more P than is necessary. Over-use is also environmentally undesirable and may be regarded as an irresponsible way to use scarce resources that can lead to adverse off-site impacts. Ensuring adoption of best management practices will provide relatively easy improvements in profitability and will reduce the costs associated with inappropriate fertiliser practice. Farmgate P-balance will also be improved where over-use of fertiliser has occurred.

- Promote wider adoption of soil testing and its interpretation by farmers
- Develop through demonstration and extension, confidence in the use of critical soil test values and targeted use of P-fertilisers
- Continue to focus on achieving improvements in the total factor productivity of grazing systems. The most profitable use of P arises from good pasture and livestock management and use of the best-available pasture and livestock genetics.
- Develop the capability necessary for future application of variable rate fertiliser technology in pasture systems *before* fertiliser prices rise to the level that will justify this technology.

For continued improvements into future: P-efficiency improvements in grazing systems have stalled. The industry needs to research the development of novel, lower-P farming systems that can provide measurable improvements in P-efficiency. If the timeframe to peak P is indeed only 25 years, this is only just enough time to develop novel pasture systems, new fertiliser technologies and/or new plants and to get them adopted. If this timeframe proves to be overly pessimistic, the same novel systems and technologies will still deliver input cost efficiencies, improved profitability and improved environmental outcomes.

Low-P farming systems. Operating agriculture at lower P concentrations than are currently necessary, is a powerful way to slow the accumulations of sparingly-available P in soils. Lower P concentrations will also minimise the chances of P loss to the environment by runoff and leaching.

- Prove the economic and P-efficiency benefits of low-P agricultural systems that can still support high productivity
- Quantify the P-requirements of the keystone and alternative legume resources that underpin Australian pasture systems
- Develop new high productivity, low-P grazing system options

Fertiliser technology. Improvements in fertiliser can arguably provide the fastest improvement in P efficiency as uptake and adoption can potentially be very rapid. However, the problems of matching P supply to plant demands, or minimising P sorption reactions in soil are substantial. There have been very innovative solutions addressing soil-specific P-use problems that have delivered large P-efficiency gains (e.g. fluid P fertiliser for calcareous soils). However, technology change has otherwise been relatively slow, probably reflecting the amount of research effort in this area.

- Reduce the amount of P that becomes sparingly-available in soils by developing technology or management options to control release of phosphate to soil and address the seasonal mismatch between availability of P in soil and pasture requirements for growth
- Examine fertiliser placement options to increase P availability for plants

Plant improvement. There is good evidence from crop species that a root trait-oriented approach to plant improvement can produce varieties with significantly improved P efficiency.

Although it seems likely that some low-P pasture systems can be developed based on a limited number of alternative, P-efficient legumes, there will still be large areas of agriculture reliant on the keystone species that carry modern Australian farming systems. Although P-efficiency may be gained by moving away from legume-based pasture to N-fed pasture, this is unlikely to be a viable option for grazing systems producing lower-value animal products and would bring substantial environmental issues as is the present experience in the dairy industry.

- Evaluate the variation in key root traits of the keystone pasture legumes; use this to select P-efficient cultivars
- Address the widespread problem of root damage on pasture legumes which may negate attempts to improve P-use efficiency and the value of improved legumes
- Position the industry to take advantage of nutrient efficiencies currently being developed in crop species using conventional and GM technology.

Northern grazing systems. Australia's extensive northern rangelands are P-deficient but there are few economic options for using P-fertilisers. A desktop audit indicated that the systems are all likely to be slowly extracting P without replacement. In most cases, the rates of P loss are low and are not considered to be a threat to production at the present time. However, where productivity is higher as a result of introduction of exotic species (e.g. *Leucaena*-based systems), nutrient extraction is thought to be a factor in the effective collapse of grazing system productivity and the issues of P extraction and replacement need to be explored. Direct strategic P-supplementation of cows in extensive breeding systems is likely to lift both productivity and to bring the P-balance of these systems closer to an 'ideal' P-balance efficiency.

- Conduct a benchmark audit of P- (and other nutrients: S, N) balances of Northern grazing systems that quantifies and extends the "calculations" undertaken for this report
- Develop practical methods for identifying when P-supplements will result in livestock growth responses and assess their role in closing the P-imbalance of extensive breeder systems
- Assess N and P constraints and options for nutrient restoration in established rangeland systems considered to be experiencing nutrient exhaustion

Underpinning knowledge. There are still a surprising number of gaps in knowledge about the reactions of phosphate in soil and around fertilisers; especially those leading to P accumulations as sparingly-available phosphate and organic P. Relatively little is known about the P-acquisition mechanisms of P-efficient plants and the role and ecology of soil micro-organisms (including mycorrhiza) in making P available to crops and pastures. Strategic investment in new knowledge is ultimately the only way to develop innovative answers to difficult problems. Presently innovative fertiliser technologies and the development of novel plants that may access organic P in soil are potentially constrained by a limited understanding of soil P reactions and the chemical forms of organic P in soil. However, if investment in fundamental knowledge is to be contemplated it should be sensibly aligned with applied research programs to ensure a well focussed research effort. *It is always difficult to know how to most effectively make investments in fundamental knowledge because scientific breakthroughs are not predictable. However, it is certain that if no investment is made, there will be no new discoveries.*

- Develop a measured program of investments in the science that underpins the most intractable problems of P supply, soil P reactions and P-use efficiency by plants. Ensure that it is linked to allied, applied research and use it to train young scientists who will go on to serve the grazing industries.

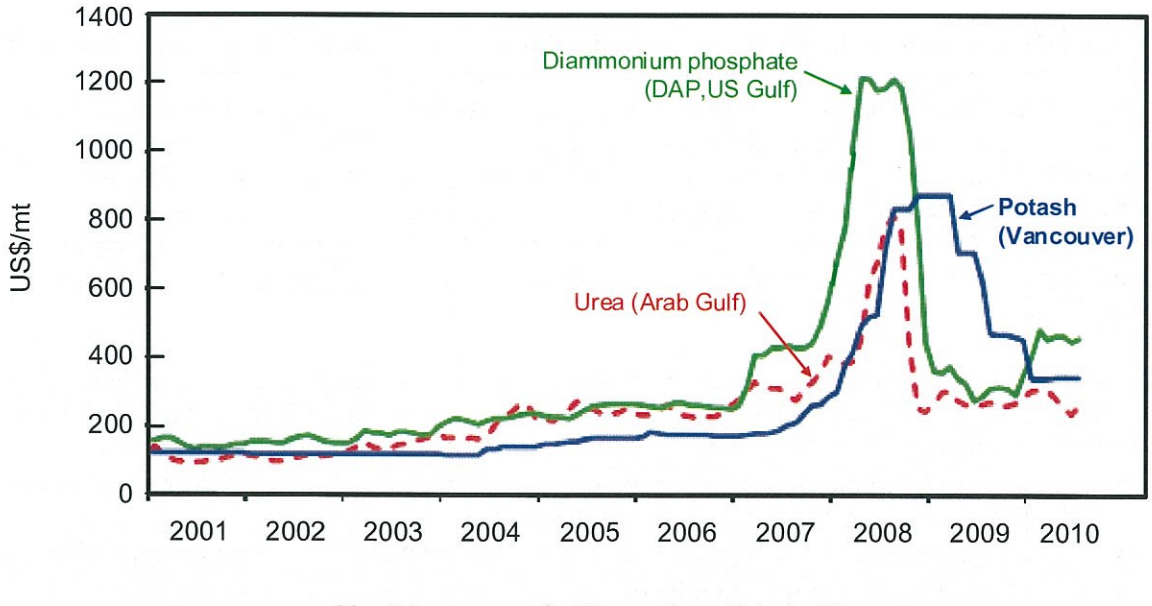
Contents

Background

There is renewed debate globally about the size and longevity of the world's remaining rock phosphate reserves. Cordell et al. (2009) have predicted recently using USGS data, that global phosphorus (P) supply will fall behind demand in about 25 years time (peak P in ~2035). However, at the other extreme Van Kauwenbergh (2010) and Fixen (2009) have argued that global reserves may last between 90 and 300-400 years at current rates of use. Differences arise because there are fundamental uncertainties in the estimates of the size of global P reserves and because the calculations are not directly comparable. Peak P estimates aim to assess when the cost of a scarce resource will increase substantially by assuming particular resource extraction logistics (Hubbert 1949). The alternative calculations of the longevity of global P reserves have assumed that rates of use are static. This is particularly unrealistic given current projections for world population (U.S. Census Bureau 2009) and demand for food. In reality, the supply and demand situation for P is dynamic and complex. Nutrient application rates in some developed economies (e.g. Western Europe) are, in fact, declining whilst those in developing economies (e.g. China, India) are increasing (Vitousek et al. 2009). Overall global demand for P is expected to increase for some decades at least. As reserves of P that are economic to mine now are depleted, the world will move to using sources that are of lower quality and more expensive to extract, process or decontaminate.

Despite the controversy, commentators agree that the life of the P reserves that are currently economic to mine is finite and that the cost of P fertiliser is, and will continue to rise as it becomes necessary for the world to move to lower grade P reserves. Over the last ten years, P-fertiliser costs have doubled (Fig. 1). This is in agreement with predictions made by Frantel et al. (1985;1988) who analysed the likely costs of production for new phosphate mines needed to replace existing capacity 1990-2010. The cost of P will most likely rise exponentially if a peak in P supply is attained.

The recent (2007-08) dramatic spike in P-fertiliser costs had nothing to do with "peak-P" or erosion of the world's P-reserves, it was due to temporary shortages associated with global supply and demand (Von Horn and Sartorius 2009). Nevertheless it had an immediate impact on fertiliser practice in Australia.



Monthly average fertiliser prices (fob, bulk)

Figure 1. Recent trends and fluctuations in the cost of fertilisers (from: Van Kauwenbergh 2010)

P-fertiliser use in Australia is relatively inefficient as a direct consequent of the low P status of most Australian soils. About 470 ktonnes of P is applied annually and mostly in the higher rainfall areas of southern Australia. About 40% of the P is applied to pastures. Nationally, only ~20% of the P applied as fertiliser is extracted in value-added food/fibre products for export. A further ~5% of the P that is applied is consumed domestically (Cordell and White 2010). This means that ~75% of the P applied in Australian agriculture is accumulated in the soil, and some is lost to the environment. In the majority of cases, most of the applied P is accumulated in the soil and only a relatively small, but environmentally-significant, proportion is lost to waterways (e.g. McCaskill and Cayley 2000). However, in sandy agricultural soils a significant proportion may also be lost by leaching (e.g. Lewis et al. 1987). P accumulation in agricultural soils slowly builds soil P-fertility and as such, it is not a disadvantage. However when P is in short supply and becomes very expensive, the accumulations in soil represent a gross and unaffordable inefficiency. Industry wide P-balance analyses suggest that grazing industries in southern Australia are amongst the least "efficient" (for example 20% recovery of applied P in products [wool, meat, milk, live export] cf. 45-54% for grain crops; McLaughlin et al. 1992).

It is likely that rising costs for P will be a major disincentive for P-fertiliser use and this will erode the productivity gains being achieved in Australian agriculture. High P prices also have the potential to seriously threaten the global competitiveness of Australian farming industries because agricultural productivity in Australia is so heavily dependent on fertiliser inputs to correct its naturally P-deficient soils. Northern Australian grazing systems include large areas of pastoral land that are managed with pasture growth and animal production limited by P availability because P-fertiliser use has been considered not to be economically viable. It is also timely to review the P-balance of these systems and the potential or otherwise for using P-fertilisers and/or strategic P supplementation in Northern grazing systems.

1 Project objectives

1. To review the scientific and technical literature related to the processes that mediate phosphorus availability and utilisation in southern and northern Australian livestock production systems .

2. To critically examine current and potential options for increasing the efficiency with which phosphorus is used in broadacre Australian agricultural production systems through increases in soil phosphorus availability and/or utilization. Phosphorus use and economy in southern and northern Australian grazing systems were specifically examined and compared with the phosphorus economy of crops and cropping systems. Where it was informative to do so, phosphorus acquisition and economy in international agricultural systems was examined. Where possible, changes to current practice that may impact adversely on other aspects of soil health, productivity, sustainability and/or the wider natural environment were identified.

3. To indentify potential opportunities to improve current agronomic practice and RD&E options to develop new plants, microbes and/or management systems capable of delivering reduced reliance on scarce P resources. New RD&E opportunities may potentially include:
    - ways to increase the availability of soil phosphorus for pasture plants or to increase the ability of plants to access to phosphorus sources in soil;
    - technology or plants that may reduce the phosphorus fertilizer requirements of pastures;
    - improved practices that eliminate wasteful fertiliser use, or lift the effectiveness of current practice; and/or

- alleviation of constraints to plant uptake of phosphorus without degradation of soil health and resilience (i.e. soil chemistry, nutrient cycling, biology and physical traits which influence productivity), or the wider environment.

2 Methodology

A major review was co-ordinated by CSIRO using a team of technical experts drawn from CSIRO, Department of Primary Industries, Universities, and including two leading International research scientists, to examine Australia's potential exposure to global shortages of P-fertiliser, the sources of P-inefficiency in broadacre agriculture and the options available for improving the effectiveness of soil-P and P-fertiliser use with particular, but not exclusive, reference to the Australian grazing industries.

A 2-day workshop involving the key review authors, MLA representatives and industry/research commentators was held in Canberra 8-9 June 2010 to discuss the issues and opportunities identified by the review process and to scope out the RD&E options most likely to improve phosphorus use efficiency and underpin the future productivity, profitability and sustainability of livestock systems

Participants in the review project

Sola Ajiboye	The University of Adelaide, Glen Osmond
Dana Cordell	University of Technology, Sydney
Richard Culvenor	CSIRO Sustainable Agriculture Flagship, CPI, Canberra
Manny Delhaize	CSIRO Sustainable Agriculture Flagship, CPI, Canberra
Chris Guppy,	The University of New England, Armidale
Paul Harvey	CSIRO Sustainable Agriculture Flagship, CES, Glen Osmond
Hans Lambers	The University of Western Australia, Crawley
Jonathon Lynch	Penn State University, USA
Therese McBeath	CSIRO Sustainable Agriculture Flagship, CLW, Glen Osmond
John McIvor	CSIRO Sustainable Agriculture Flagship, CES, Brisbane
Mike McLaughlin*	CSIRO Sustain. Agric. Flagship, & Univ. Adelaide, Glen Osmond
Dustin Moore	University of Technology, Sydney
Astrid Oberson	Institut für Pflanzenwissenschaften, Switzerland
Merv Probert	CSIRO Sustainable Agriculture Flagship, CES, Brisbane
Alan Richardson*	CSIRO Sustainable Agriculture Flagship, CPI, Canberra
Megan Ryan	The University of Western Australia, Crawley
Peter Ryan	CSIRO Sustainable Agriculture Flagship, CPI, Canberra
Richard Simpson*	CSIRO Sustainable Agriculture Flagship, CPI, Canberra
Ron Smernik	The University of Adelaide, Glen Osmond
Andrew Smith	The University of Adelaide, Glen Osmond
Sally Smith	The University of Adelaide, Glen Osmond
Sam Stacey	The University of Adelaide, Glen Osmond
R Velthuis	Novozymes Biologicals Australia, Sandhurst East
Erik Veneklaas	The University of Western Australia, Crawley
David Weaver	Department of Agriculture and Food-Western Australia, Albany
Stuart White	University of Technology, Sydney
Mike Wong	CSIRO Sustainable Agriculture Flagship, CLW, Wembley

* *project leaders*

3 Results and discussion

3.1 Potential exposure of Australian agriculture to global shortages of phosphorus [a]

3.1.1 Introduction

There is no substitute for phosphorus in crop growth and ensuring the availability and accessibility of phosphorus in both the short and longer term is critical to food production.

Historically most of the world's farmers have relied on natural reserves of phosphorus in soil to grow crops. Local manures and human excreta were also used to supplement soil phosphorus to some extent. Increased famine and soil degradation particularly in Europe led to a search for external sources of phosphorus fertilizers to enhance the productivity of crops. The discovery and consumption of phosphorus-rich guano and phosphate rock in certain geological deposits of the world contributed to increased global crop yields and has saved billions from starvation over the past half-century. Prominent science writers such as chemist Isaac Asimov described phosphorus as "life's bottleneck": "*We may be able to substitute nuclear power for coal, and plastics for wood, and yeast for meat, and friendliness for isolation - but for phosphorus there is neither substitute nor replacement*" (Asimov 1974). Today, humanity is effectively dependent on mined phosphate rock to maintain high crop yields as food and fibre demand increases.

3.1.2 Global phosphorus scarcity

The main source of phosphorus for fertilizers is phosphate rock. Around 90% of phosphate rock is used for food production (mainly fertilizers, but also animal feed and food supplements) (Prud'homme 2010a). Like oil, phosphate rock is a non-renewable resource and the supply the highly-concentrated and easily-accessible phosphate rock reserves of the world is becoming increasingly scarce at a time when demand for phosphorus is expected to continue to increase (Cordell et al. 2009a). Debates on phosphorus scarcity often focus on the physical availability of global resources: i.e. how many million tonnes of phosphate rock remain (FAO 2008a; IFA 2008; Gilbert 2009). However, *physical*, *managerial*, *economic*, *institutional* and *geopolitical* factors all contribute to resource scarcity (Cordell 2010):

(i) **Phosphorus is *physically* scarce** because only a small and finite percentage of phosphate is naturally present in high concentration. A proportion of the highly-concentrated deposits are not readily accessible (e.g. nodes of phosphate on the deep sea bed and continental shelves), or the deposits may contain too many contaminants (e.g. Cd, U). Other reserves simply

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[a] This information is derived primarily from the draft review by White S, Cordell D, and Moore D (Appendix 1) with additional information from other sources. Subsequent to the writing of the review, Van Kauwenbergh (2010) from the International Fertilizer Development Center (IFDC) has estimated that the size of global P reserves may be nearly 4-fold that estimated by the USGS. The increase is almost entirely associated with a substantial increase in the estimated size of phosphate rock reserves in Morocco and is based on a relatively old report that has previously not influenced the USGS estimates of phosphate rock reserves. It seems almost certain that we have not heard the last word on this issue. If confirmed, the IFDC estimate indicates the world has a longer period (probably several decades) before a peak in P availability might occur.

contain lower concentrations of phosphorus (% P_2O_5) (Prud'homme 2010a). Current high-grade reserves are expected to be depleted in 50-100 years (Runge-Metzger 1995; Steen 1998). However, as with oil, the important point is not when 100% of the reserve is depleted, but when the production rate reaches a peak, based on the finite nature of non-renewable resources, after which production will decline (Hubbert 1949). The production of phosphate rock will eventually reach a peak due to the economic constraints of accessing more difficult and lower quality layers. Based on current estimates of reserves, and demand growth, peak phosphorus is estimated to occur around 2035 (Fig. 2; Cordell et al. 2009a).

Predictions of this nature are always difficult to make and there is presently a strong debate stimulated by the Cordell et al. papers about just how exposed the world is to phosphate scarcity. For example, Fixen (2009) argued that reserves that are "currently able to be mined economically", may last up to 90 years. His calculations differ because there is uncertainty in the base data and he also assumed static (2008/09) rates of phosphate use which is probably unrealistic given current projections for world population (U.S. Census Bureau 2009) and demand for food. However, it is recognised that phosphate demand in some countries (e.g. parts of Europe) may stabilise or decline because soils have been saturated with phosphorus after many years of fertiliser use whilst those in developing economies (e.g. China, India) are increasing (e.g. Vitousek et al. 2009). Overall global demand for P is expected to increase for some decades at least.

The debate lead Prud'homme (2010b) to write "these articles...*are*...sensationalist, alarming the public and policy makers about the consequences for food security...the debate is based on ...misleading facts and obsolete information..." and, consequently, in September 2010 the International Fertilizer Development Center (IFDC) released a paper in which the size of the global reserves and resources of P was reassessed (Van Kauwenbergh 2010). This report estimates that the size of global P reserves may be nearly 4-fold that estimated by the USGS. The increase was mainly associated with a substantial increase in the estimated size of phosphate rock reserves in Morocco and is based on a relatively old report that has previously not influenced the USGS estimates of phosphate rock reserves. If confirmed, the IFDC estimate indicates the world has a longer period (probably several decades) before a peak in P availability might occur. Given the source and uncertainty of the data used for the revision, it is likely that the debate about the size and longevity of P reserves will continue. Prud'homme (2010b) has stated that the IFDC will follow this reanalysis with an assessment of the "technical and economic aspects of phosphate supply" and will then make "long-term projection(s) of phosphate fertiliser consumption.....that allow for increases in demand, improved plant nutrient efficiency, stabilising consumption in mature markets".

Whilst the reliability of the data on which the prediction of peak phosphorus is presently subject to debate, other analysts have concluded that demand for P will rise over the next 2-3 decades and may stabilise at around 30 Mt/yr or possibly fall as global population stabilises (~9 billion by 2060). This combined with slowing demand due to improved soil P fertility in developing countries, more efficient fertiliser use, increased recycling, new technology and price rises (which make it economic to mine the large P-'reserve base') may mean a prolonged "demand plateau" rather than a "peak" in P supply (Cornish 2010).

Most analysts agree, however, that the underlying problem remains the same: production of phosphorus is shifting from mining the 'cheap and easy' reserves, to more 'difficult and complex' layers and growing demand is therefore expected to outstrip current economically-viable production at some point, irrespective of advances in technology and efficiency. For a resource that underpins agricultural productivity in Australia and, indeed, global food production this is a potentially serious concern.

Increases in the cost of phosphate are expected: The most common response to resource scarcity is increased commodity prices, triggering increased exploration and technological developments. For example, the short-term tightness between supply and demand (and
associated price spike) that occurred over 2007-2009 resulted in increased interest and investment in exploration of new phosphate rock deposits, mining and in the commissioning of new mines, most notably in Saudi Arabia, Australia and seafloor sediments off the coast of Namibia (Jasinski 2009; Drummond 2010; Jung 2010). While these developments may increase the overall tonnages of world phosphate rock reserves in the coming years, the quality and accessibility of these reserves are markedly lower than current reserves. Inevitably, mining lower grade phosphate rock resources, or phosphate found on continental shelves will involve substantial environmental and economic costs due to the difficultly of physical accessibility and/or increased processing resources and costs. That is, extracting the same nutrient value from lower grade rock will increasingly require more inputs if energy, raw materials and costs, while resulting in increased volumes of waste and pollution.

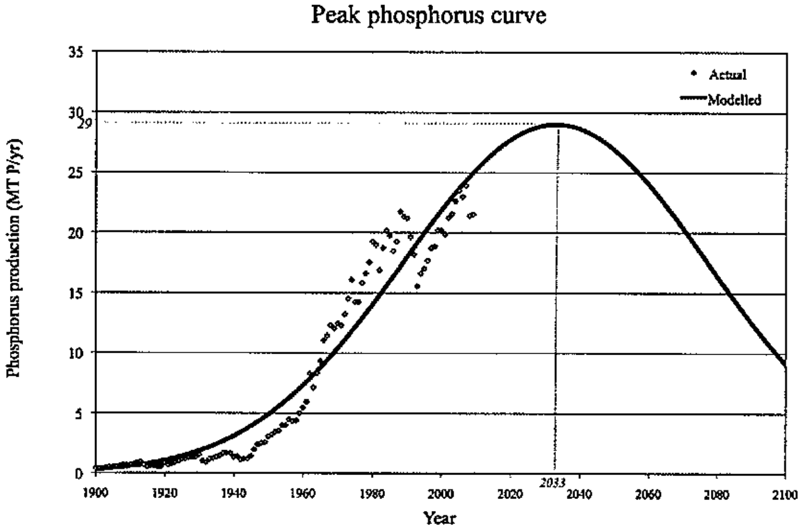

Figure 2. Peak phosphorus: global annual production of current phosphate rock reserves is estimated to peak 2033 at 29 million tonnes of P/yr (equivalent to approximately 220 million tonnes of phosphate rock/yr) while demand will continue to increase (based on best available industry and USGS data. Source: Cordell et al (2009a).

(ii) A **scarcity of *management*** also influences the availability of phosphorus. Only one-fifth of the phosphorus in phosphate rock mined for food production is extracted in the food the world eats due to substantial losses in the entire food production and consumption system (Cordell et al. 2009a). Phosphorus is lost during mining and processing, transport, fertilizer application, food processing and retail, food preparation and consumption. Many of these inefficiencies are at the same time resulting in pollution of waterways (from agricultural runoff and sewage effluent) which are environmentally damaging and costly to society.

Globally, humans consume around 3 M tonnes of elemental phosphorus in food but about five times this amount (14.9 Mt/year) in phosphate rock is mined for food production. This means that while phosphorus is becoming increasingly scarce, there are opportunities for avoiding losses and recovering phosphorus through improved management. Prud'Homme (2010) recently estimated losses in the mining and fertiliser sector to be 15-20% losses during mining and a similar percentage during fertilizer production. Of the phosphate rock mined, processed into fertilizers and applied to crops and pastures only a smaller percentage will be taken up by plants. The UN's Food and Agricultural Organisation (FAO) (FAO, 2006) estimates that plants only take up approximately 15-30% of P in applied fertilizers each year. The remainder either builds up in a temporarily unavailable soil 'stock', or is lost permanently to water or non-agricultural soils via erosion and runoff.

In Australia, farm-gate phosphorus balances are similarly low. Of the 470 ktonnes of P that is applied annually in fertilisers, only about 25% is recovered in food and fibre products (McLaughlin et al. 1992). The reasons for this, the differences between agricultural enterprises and the opportunities for change are the focus of the following review and analysis.

(iii) ***Economic* phosphorus scarcity** also occurs when phosphorus users (mainly farmers) cannot access phosphorus sources, usually due to a lack of purchasing power or an inability to access credit. The current demand for phosphorus only represents those users who have the capital enabling them to procure phosphate rock or fertilizers. In order to maximize crop yields globally to feed 9 billion mouths by 2050, there will need to be a boost in soil fertility, particularly in areas with phosphorus-deficient soils and a high rate of food insecurity like Sub-Saharan Africa. Many of the unprecedented 1.02 billion hungry people today are smallholder farmers (IAASTD 2008; FAO 2009). This means ensuring farmer access to phosphorus is critical to both maximising agricultural productivity, securing farmer livelihoods and feeding the global population (Cordell 2010).

Indeed, the 2008 fertilizer price spike resulted in many farmers not purchasing fertilizers. Governments from Australia to India urged farmers to apply fertilizers (Cordell 2010). Financial scarcity on the supply side can occur when investments in new capacity (such as phosphate rock mines) and commercial production do not keep up with market demand for the resource (time lags can be 5-10 years). This was thought to be a significant factor leading to the 2008 short-term phosphate rock scarcity situation (IFA 2008).

(iv) ***Geopolitical* scarcity** can restrict the availability of phosphorus resources in the short- or long-term. For example, while all farmers need access to phosphorus, 85% of the world's remaining phosphate rock reserves are controlled by 5 countries, and mainly Morocco and China (Jasinski 2010). In 2008 China imposed a 135% export tariff to secure domestic supply for food production (Fertilizer Week 2008); a move which essentially halted exports from the region overnight. The US is expected to deplete its own high-grade reserves in the coming decades and increasingly imports rock phosphate from Morocco. However, Morocco currently occupies Western Sahara and controls that region's reserves in defiance of UN resolutions (Corell 2002). Trading with Moroccan authorities for Western Sahara's phosphate rock is condemned by the UN, and importing phosphate rock via Morocco has been boycotted by several Scandinavian firms (Hagen, 2008). There are two important dimensions here: a) an ethical dimension of consumers and companies knowingly or unknowingly supporting an occupation that breaches international human rights conventions (Corell 2002; WSRW 2007); and, b) the potential geopolitical consequences of a disruption of phosphate rock supply from the region.

(v) ***Institutional* scarcity** is also considered to be inhibiting the productive use of phosphorus by humans because there is a lack of effective policies and actors explicitly governing global phosphorus resources to ensure availability and accessibility of phosphorus for food security, (Cordell 2010). Further, there are no structures for monitoring and evaluating the situation. It is of concern that data on global phosphorus resources and consumption patterns is subject to lack of availability, reliability and consistency (Cordell 2010). This impacts on the ability of observers to analyse the resource issues and on the users and producers of phosphorus to make informed decisions.

While phosphorus is relevant to numerous different sectors (for example, a 'commodity' in the mining sector, a 'pollutant' in the water and wastewater sector) phosphorus *scarcity* is not a priority within any sector, and hence long-term phosphorus security has no obvious home in any sector. Phosphorus is by default governed by the market system, which may be appropriate for efficiency of trade), but may not be sufficient to adequately address the much broader sustainability and food security implications (Cordell 2010).

3.1.3 Australia's phosphorus balance

The major phosphorus flows through the Australian food production and consumption system are shown in Figure 3. Flows are indicative rather than precise, due to poor data availability. Despite the uncertainties, there is general agreement with an earlier of the phosphorus budget for Australia (McLaughlin et al. 1992) but with growth in both inputs and outflows of P on a national basis (Table 1). The data from both budgeting exercises indicate that 83%-88% of P inputs to Australia are used in agriculture (the total input to agriculture currently being ~470 ktonnes P/year), and that somewhere between 18%-25% of P applied as fertiliser is recovered in food and fibre products, the bulk of which are exported. At the present time about 46% of P inputs to Australia are sourced from domestic phosphate mines.

Because the proportion of P captured in agricultural products is low, and only 28% of the P in those products is used domestically (the rest is exported), Australia cannot cover is present demand for P by recycling P from domestic waste streams. Also, if Australia was able to completely eliminate inefficient use of P in agriculture and achieve a perfect farm-gate P-balance (i.e. P inputs = P outputs), the export orientation of our agricultural industries would still result in Australia being unable to cover its P needs by recycling P from waste streams. At best, only 28% of Australia's requirements would be met.

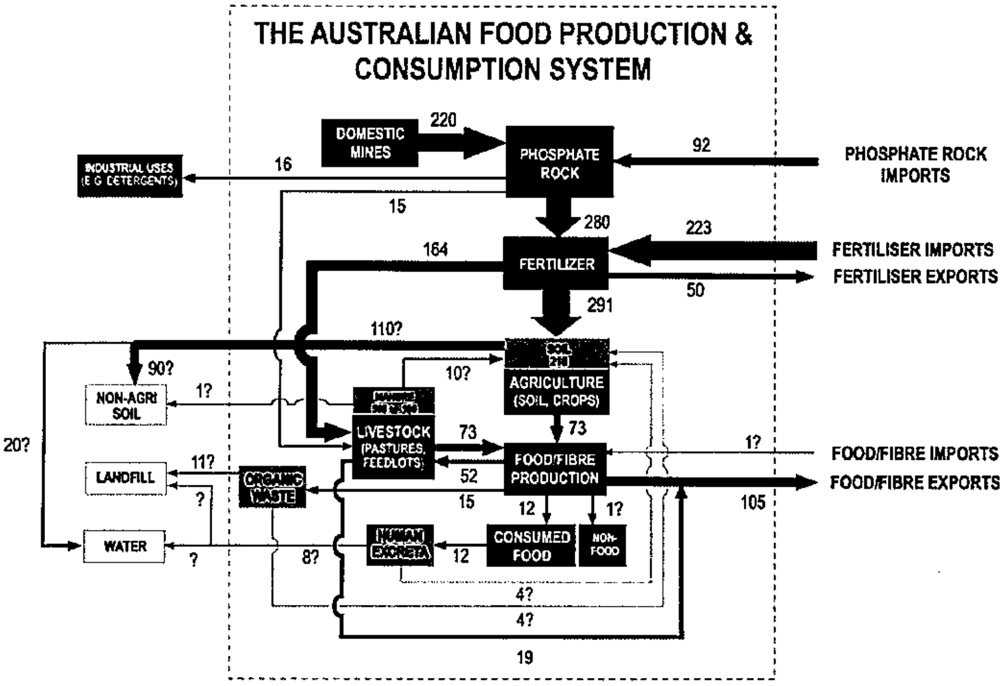

Figure 3. Australia's phosphorus budget. Major phosphorus flows through the Australian food production and consumption system – from mine to field to fork. Units are ktonnes P/year (Source: updated from Cordell 2010). Flows are indicative rather than precise, due to poor data availability and the fact that no complete dataset exists for any given year. In this case, care was taken to use 2006-7 data where possible with some data extrapolated from earlier years where 2006-7 data is not available. Data for each form of phosphorus has been obtained from multiple sources, as indicated in the following sections. Oral information with key Australian stakeholders was also used in some instances to triangulate or compliment existing data due to a lack of publically available information and is referenced as such. Remaining figures were based on material balance calculations (ie. inputs = outputs + accumulation) by working both forwards from the start of the food chain and backwards from excretion and consumption up the chain (see White, Cordell and Moore, Appendix 1).

Table 1a. Phosphorus budgets for Australia

Process	Flux (ktonnes P/year)	
	McLaughlin et al. (1992)	White et al. (2010, Appendix 1)#
Inputs		
Atmospheric deposition	77	*
Food, fish, timber imports	<1	1?
Phosphate rock	326	312
Fertiliser and acid imports	54	223
Subtotal	458	536
Outflows		
Food and fibre exports	56	105
Fertiliser exports	*	50
Urban discharge	11	27
Domestic industrial uses	*	16
Soil erosion	6-32	20?
Leaching	<3	8?
Fire	4	*
Subtotal	80-106	226

predominantly 2006-7 data
* not reported

Table 1b. Derived phosphorus budgets for Australian agriculture

Process	Flux (ktonnes P/year)	
	McLaughlin et al. (1992)	White et al. (2010, Appendix 1)
Inputs		
Fertiliser (incl. phosphate rock products)	380	470
Subtotal	380	470
Outputs		
Food and fibre exports	56	105
Food / fibre domestic consumption	11 ?	12
Soil erosion *	6-32 ?	20 ?
Leaching *	<3 ?	8 ?
Subtotal	65-91	133

* it is unclear what proportion of these national fluxes may be attributed to agriculture

3.2 Phosphorus-efficiency of Australian broadacre agriculture [b]

3.2.1 Definition of phosphorus-use efficiency

The efficiency with which P is used can be defined in a number of ways depending on the way in which a systems analysis or an experiment is being conducted. The method chosen to define efficacy will depend on the purpose of the comparison being made. This report aims to determine the scope and method by which it may be possible to reduce the amount of P-fertiliser required to support productive agricultural systems and most discussion will, therefore, be in terms of mainly in terms of their P-balance efficiency. Various methods for evaluating the efficiency of P use have been discussed by Syers et al. (2008) and we have adopted their terminology for this review.

Agronomic efficiency (eqn1) defines the yield gained by using P compared with the control (no P):

$$Agronomic\ efficiency = \frac{\left(Yield_{with\ P} - Yield_{without\ P}\right)}{Applied\ P} \quad \text{..................................eqn 1.}$$

The agronomic efficiency of P is used as a way of measuring crop response to applied P. This diminishes with increase in the plant-available P level of the soil in a manner that can typically be described by a Mitscherlich equation. Agronomic efficiency is very low and tends to zero at, and above the critical value of the crop-soil system (Fig. 4). There is no yield benefit from fertilising soil to levels of plant-available P above the critical P level. However, removal of P in harvested materials, losses from the system, or accumulations of P in sparingly-available soil pools need to be balanced by fertiliser use if plant-available P concentrations are to be maintained at (or near) the non-limiting concentration so that crop yield may be maintained.

Agronomic efficiency is an appropriate measure and is often used for comparing the phosphorus use-efficiency of different plant species, cultivars or crops provided they are being grown in soil that is sufficiently P-deficient that the responses of the lines or crops being compared is not close to the asymptote for yield response. Alternatively, the **critical P level** of the soil-plant system, reported either as amount of fertiliser applied or as the soil's plant-available P level at which 90 or

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[b] Information drawn primarily from draft reviews by Weaver and Wong (Appendix 2), McLaughlin et al. (Appendix 4) and Simpson et al. (Appendix 5) with additional information from other sources.

95% of maximum yield was obtained, may also be used to compare the "efficiency" by which plants acquire phosphorus.

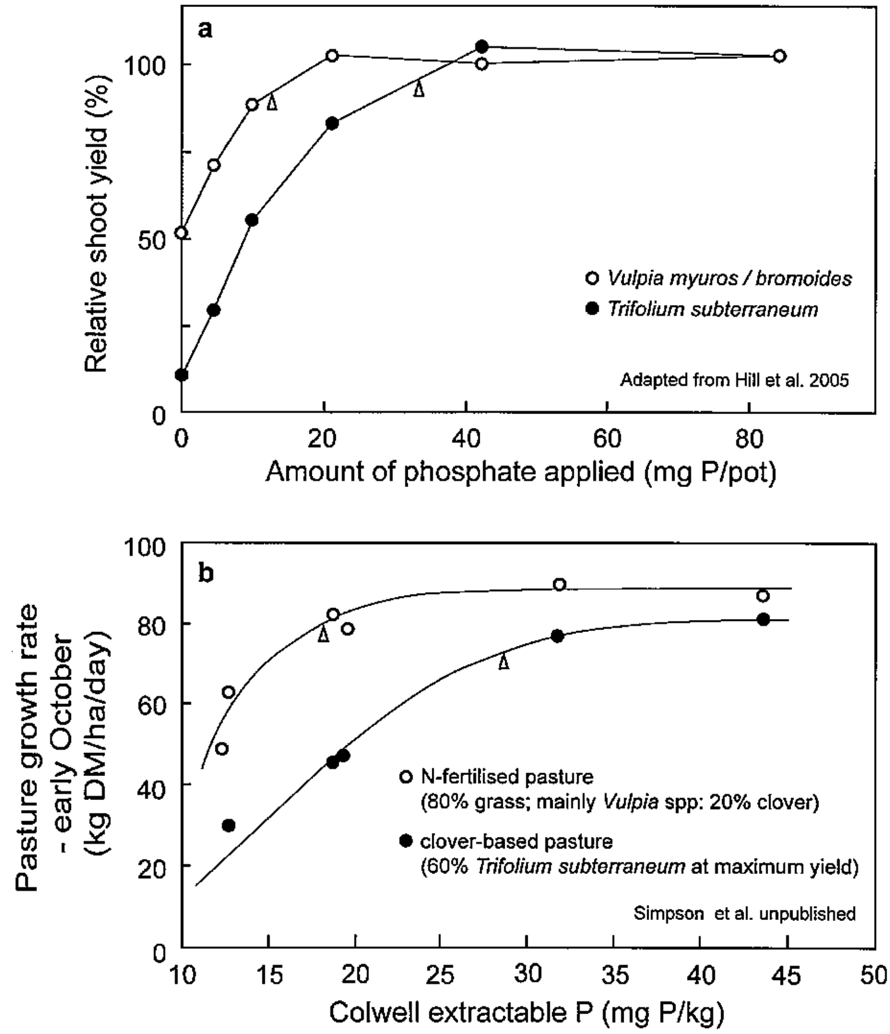

Figure 4. Yield responses of (a) silver grass and subterranean clover to applications of phosphate in a glasshouse experiment (after Hill et al. 2005) and (b) grass-dominant (nitrogen-fed) and subterranean clover-rich pasture at Bookham, NSW showing critical P levels (corresponding to 90% of yield maximum) for each response function (arrow).

P-recovery efficiency (eqn 2) is a variant on agronomic efficiency that seeks to directly measure the yield response of the crop relative to the amount of fertiliser P applied to the soil.

$$P\ recovery\ efficiency = \frac{(Uptake_{with\ P} - Uptake_{without\ P})}{Applied\ P} \times 100 \ \ldots\ldots\ldots\ldots\ \text{eqn 2}$$

The results of both the "difference" and "direct" methods for calculating efficiency depend on the intrinsic fertility of the soil in which the comparisons are being made because they are affected by the proximity of the soil-plant system to the critical P level of the soil and because plants gain P from both "fresh" fertiliser applications and from the "residual" P remaining after prior P applications. Care must therefore be taken when interpreting P-use efficiency measured by these means. For example, Carter and Day (1970) in a wether trial on Kangaroo Island in South Australia reported that 181%, 108% and 75% of applied P (8.5, 16.9, 25.4 kg P ha^{-1}) was removed in harvested pastures. This reflects the fact that residual soil P (from previous P applications) was supplying some part of the pastures' needs and when low P application rates are used, the residual P contribution can be demonstrated to be large relative to the amount of P that was applied. This problem can only partly be addressed by using an isotope of P (^{32}P or ^{33}P) to measure recovery directly because these isotopes have very short half-lives (14.3 and 25.0 days, respectively) and because P from freshly-applied fertiliser may only ever directly supply a small component of the annual P uptake by a crop (e.g. McLaughlin *et al.* 1988a; Dorahy *et al.* 2008).

P-balance efficiency (eqn 3) is used to address, in part, the issues associated with these other measures of efficiency and because it can be used to assess the overall efficiency of P-fertiliser use in farming systems under 'steady-state' management conditions. As such this measure gives a useful measure for comparing the P-economy of crops, farm enterprises, farming systems, farms and indeed countries.

$$P\text{-}balance\ efficiency = \frac{P_{output}}{P_{input}} \times 100 \ \ldots\ldots\ldots\ldots\ \text{eqn 3.}$$

However, as with all measures of P-use efficiency, it is important to understand the context in which P-balance efficiency is being measured so the efficacy of P-use may be interpreted correctly. To illustrate this point, the expected P-balance efficiency of three contrasting soil fertility management scenarios are discussed.

(i) Low-fertiliser input systems in which the plant-available P level of the soil is being allowed to decline.

When P inputs to a farming system are less than the sum of P exported in products, P losses and P accumulation in sparingly-available soil pools, plant growth depends on phosphate released from soil P reserves which are not being replenished. Crop or pasture yields will be relatively low but P-balance efficiency will appear to be high and may approach, or exceed 100% (e.g. Carter and Day 1970; Burkitt et al. 2007). However, this is only possible because soil P reserves are supporting production. Although appearing to be highly efficient, such a farming system is depleting soil reserves and current production levels will not be sustainable over the longer term.

(ii) Fertilised systems in which the plant-available P concentration of the soil is being increased (e.g. soil fertility build-up phase; Fig. 5)

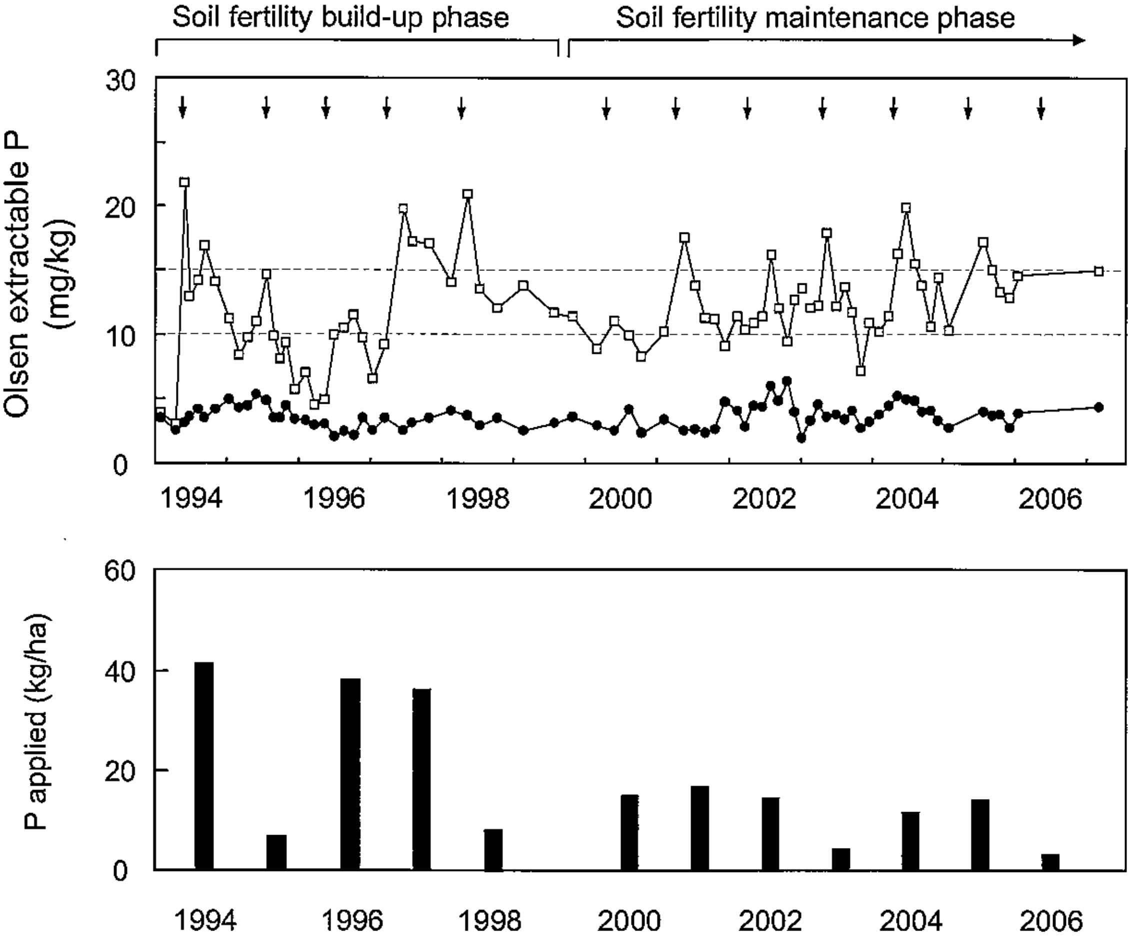

Figure 5. Extractable soil P concentration (Olsen soil P test) of surface soil (0-10 cm) in paddocks that received P-fertiliser to increase and then maintain soil P fertility (squares) or received no fertiliser (circles) at CSIRO's Ginninderra Research Station, Hall, ACT. Pastures were grazed continuously by 18 yearling Merino wethers/ha (fertilised pasture) or 9 wethers/ha (unfertilised pasture). The target range for soil fertility management in the fertilised grazing system is delineated by the dashed lines and times that fertiliser was applied are indicated by the arrows. Fertiliser amounts were intended to achieve the target soil fertility after each application. The soil fertility build-up phase was characterised by the need for higher but decreasing amounts of P fertiliser; the maintenance phase by a lower more stable P input requirement. Fluctuations in the extractable soil P concentration reflect the consequences of P-fertilizer applications and typical seasonal variations in P availability (from Simpson et al. 2010).

In this instance, P inputs must exceed the sum of P exported in products, P losses and P accumulation in sparingly-available soil pools by an amount that supports the increase in soil P fertility. P-balance efficiency will appear to be low but this is in part because the P-balance includes an amount of P on the input side of the equation that is invested in soil fertility increase.

(iii) Fertilised systems in which the plant-available P concentration of the soil is being maintained (e.g. soil fertility maintenance phase; Fig. 5)

P inputs, by definition, now equal the sum of P exported in products, P losses and P accumulation in sparingly-available soil pools and P-balance efficiency calculations reflect the true efficiency of the farming system for the level of production that is being achieved. For a grazing system, the components of the P-balance of the system are summarised by Equation 4.

$$P_{fertiliser} = P_{export} + P_{erosion/leaching} + P_{waste\ dispersal} + P_{soil\ accum} \ldots\ldots\ldots\ldots\text{eqn 4.}$$

Where: P_{export} = removal of P in products; $P_{erosion/leaching}$ = P lost by leaching, runoff or soil movement; $P_{waste\ dispersal}$ = P accumulated in small areas of paddocks/farms as a result of uneven dispersal of animal excreta rendering the P less available; $P_{soil\ accum}$ = P accumulating as sparingly-available phosphate or organic P compounds that are slowly mineralised.

To further demonstrate the importance of understanding the P-management context of a P-efficiency evaluation, consider a farming system on a soil with low plant-available P content (i.e. considerably less than critical P). If P is being applied to simultaneously increase production and raise the soil fertility level, the system may have high agronomic efficiency but a relatively low P-balance efficiency because a proportion of the fertiliser P is used to build soil P reserves. Alternatively, if the system is receiving low P inputs, it will have lower plant yields, similar agronomic efficiency and high apparent P-balance efficiency. If the soil were at or above its critical P value, agronomic efficiency would be relatively low but P-balance efficiency may be either low or high. The P-balance outcome depends, in this instance, on the size of the P-loss and P-accumulation terms; these in turn depend on the P-buffering capacity of the soil. For these reasons it is expected that there will appear to be a reasonably wide range in P-balance efficiency represented in any particular agricultural sector (e.g. see Fig. 6).

From the standpoint of fertiliser design and evaluation, fertiliser efficiency is most commonly measured by the "direct" or "difference" methods. Comparing the long-term efficiency of fertiliser P formulations is time-consuming and difficult to measure as it requires evaluation against freshly added P for each crop cycle over several years. Because the "balance" method includes the influence of residual P, the measured efficiency is higher when evaluated by this method (Syers et al. 2008). A drawback of the balance method for fertiliser evaluations is that it assumes all residual P in the soil derives from previous fertiliser applications. This would, for example, not be true in some northern cropping or grazing regions of Australia or indeed for many low P-input systems in southern Australia and this is the reason why P-balance efficiencies in excess of 100% are sometimes recorded. Consequently, for comparing fertiliser formulations isotope techniques (e.g. direct nutrient tracing or via isotopic dilution: Fried and Dean 1952; Larsen 1952), or comparisons using the difference method are favoured.

Various studies document material and nutrient transfers and storage by what are variously called nutrient budgets or balances (Watson et al. 2002; Oenema et al. 2003; Syers et al. 2008), element or **farm-gate balances** (Öborn et al. 2003), or input:output (IO) accounting systems (Goodlass et al. 2003). These balances have been carried out at spatial scales ranging from the farm (Moody, et al. 1996; Berry et al. 2003) to regional and national scale (Cassell et al. 1998; Lord et al. 2002; Sacco et al. 2003; Keller and Schulin 2003). In The Netherlands, farm-gate balances are used in the 'Mineral Accounting System' (MINAS), to assess farm P and nitrogen (N) surplus on dairy farms (van der Meer 2001), and provide the basis for regulating farm nutrient use. Three types of balance can be identified at farm scale (Öborn et al. 2003) ranging from the 'farm-gate balance' which is a simple assessment of inputs and outputs using available data for nutrient contents of inputs and outputs (Reuter and Judson 2003) to 'soil surface balance' which require more-detailed data on fluxes across the soil surface. 'System balances' are more detailed, and deal with "partitioning of the changes in net loading between system components" (Öborn et al. 2003). The different levels have specific benefits associated with understanding nutrient cycling processes, but become progressively more difficult to undertake due to the uncertainties associated with the more detailed data requirements. **Farm-gate P-balances** are used here to provide a synoptic view of the P-balance efficiency of different industries.

3.2.2 Farm-gate P-balance of temperate agricultural systems (southern Australia)

P-fertilisers are regularly used in the higher rainfall areas of southern Australia to increase production per hectare. However, the farm-gate P-balances of pasture and cropping enterprises in are generally relatively low (Fig. 6a). The survey of farming enterprises undertaken for this review demonstrated that there was, as expected, large variations in the P-balances within each enterprise type. For example, there were instances where P output exceeded P input and P-balance efficiency was greater than unity. These are usually instances where P inputs were very low or nil, and hence where the removal of products has mined P from existing soil reserves. Similarly, there are instances of very low P-balance efficiency which could, for example, reflect over-use of fertiliser.

Median P-balance efficiency values are considered most likely to reflect industry or enterprise norms. They differed significantly between the major farming enterprises that were examined: 48% for cropping, 29% for dairy cattle, 19% for beef cattle and 15% for sheep grazing (Fig. 6a).

Phosphorus inputs to cropping, cattle for beef and sheep grazing were not significantly different when the log values were compared using ANOVA, whereas with cattle for dairy, P inputs were significantly greater than the other enterprises (Fig. 6b). Median P inputs were 9.8 kg P/ha/yr for sheep grazing, 11.3 kg P/ha/yr for cattle for beef and cropping, and 25.6 kg P/ha/yr for cattle for dairy. Phosphorus outputs differed significantly between enterprises with sheep grazing (median = 1.1 kg P/ha/yr) < cattle for beef (1.9 kg P/ha/yr) < cropping (5.6 kg P/ha/yr) < cattle for dairy (7.7 kg P/ha/yr) (Fig. 6c). Cattle for dairy had a median surplus P of 18.1 kg P/ha/yr which was significantly greater than the other enterprises, whilst cropping had the lowest of 6.1 kg P/ha/yr (Fig. 6d).

Median P-balance efficiency values derived from the farm-gate analyses reported here agree surprisingly well with an earlier whole-of-industry analysis reported by McLaughlin et al. (1992) (Table 2) indicating a degree of robustness in the relative P-balance estimates for the various agricultural industries in Australia. The significant questions that these analyses raise are:
(i) why are there such large differences in the P-balances of differing agricultural enterprises, and (ii) can the P-balance efficiency of each enterprise type be improved significantly?

On the first point, Weaver and Wong (Appendix 2) argue that high relative efficiency is associated with enterprises that have a high potential for P-export in products, whereas McLaughlin et al. (1992) suggested that the higher level of inefficiency associated with grazing industries may be an inevitable consequence of harvesting an agricultural system at a higher trophic level. The second question is specifically addressed in section 3.3.

Figure 6 (following page) (a) Farm-gate P-balances (denoted as "phosphorus use efficiency") of major temperate Australian farming enterprises, and their (b) phosphorus inputs, (c) P outputs and (d) P surpluses. Inputs and outputs were derived from numerous published sources and P contents were assumed to be similar to those published by NLWRA (2001). From Weaver and Wong (Appendix 2).

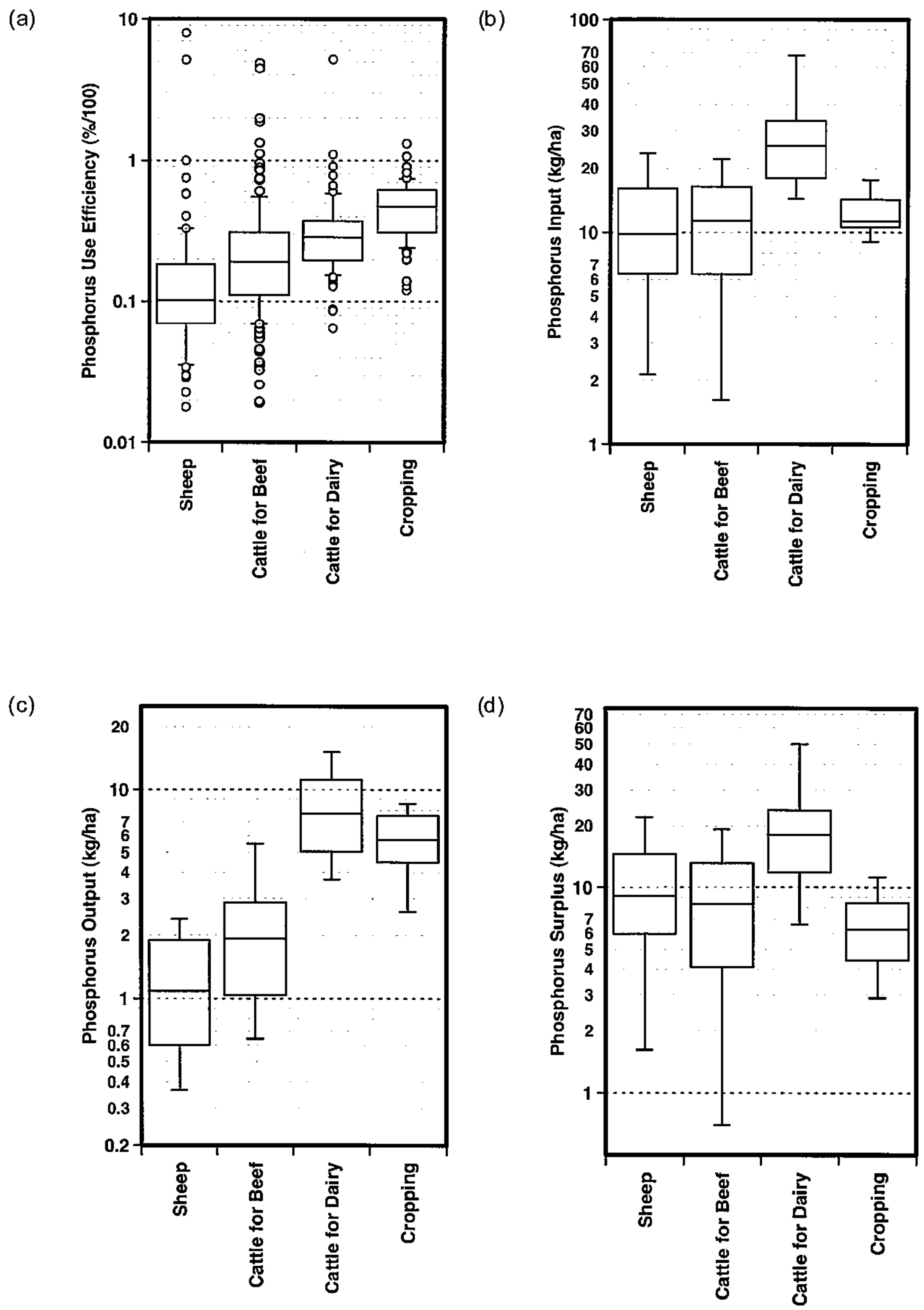
(a)
Phosphorus Use Efficiency (%/100)
10
1
0.1
0.01
Sheep
Cattle for Beef
Cattle for Dairy
Cropping
(b)
Phosphorus Input (kg/ha)
100
70
60
50
40
30
20
10
7
6
5
4
3
2
1
Sheep
Cattle for Beef
Cattle for Dairy
Cropping
(c)
Phosphorus Output (kg/ha)
20
10
7
6
5
4
3
2
1
0.7
0.6
0.5
0.4
0.3
0.2
Sheep
Cattle for Beef
Cattle for Dairy
Cropping
(d)
Phosphorus Surplus (kg/ha)
70
60
50
40
30
20
10
7
6
5
4
3
2
1
Sheep
Cattle for Beef
Cattle for Dairy
Cropping

Table 2. P-balance of major agricultural enterprises calculated from national budgets for fertiliser inputs and the amounts of product harvested (adapted from McLaughlin et al. 1992).

Product	P in fertiliser applied (I) (ktonnes)	P in product harvested (O) (ktonnes)	P-balance efficiency (I/O * 100)
Wheat	85	42.2	50%
Barley, oats	35	15.8	45%
Sorghum, maize, rice	8	4.3	54%
Fresh fruit	6	0.4	7%
Vegetables	8	1.3	16%
Wool, meat, milk, and live animals	179	35.8	20%

3.2.3 P-balance of northern Australian grazing systems [c]

Northern Australia is considered to include all of Queensland and the Northern Territory, and the Pilbara and Kimberley regions of Western Australia. The boundary with southern Australia is blurred in Queensland where the cropping and mixed cropping-grazing enterprises have many similarities to those in southern Australia. The grazing industry in northern Australia is dominated

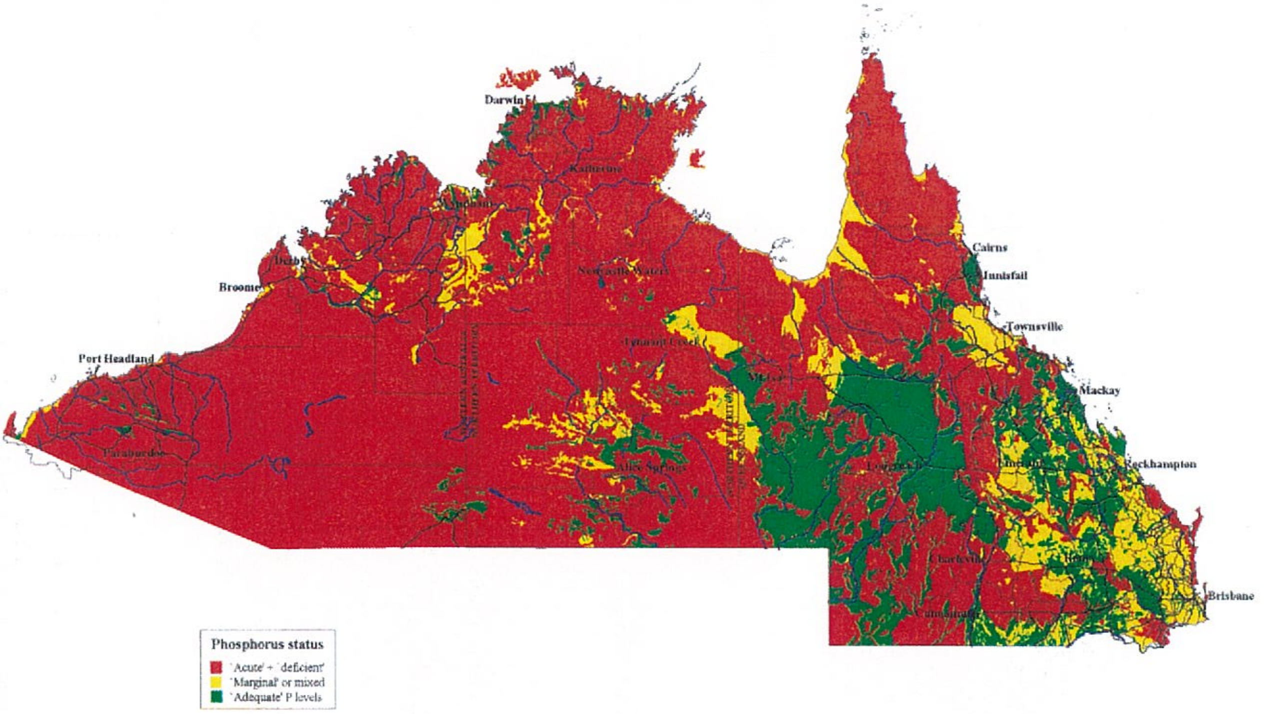

Figure 7. The phosphorus status of land in northern Australia as it relates to animal performance (acute and deficient (red shading), ≤6 ppm extractable P; marginal (yellow), 7-8 ppm extractable P; and adequate (green), ≥8 ppm extractable P) (from McCosker and Winks 1994).

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[c] Information drawn primarily from the draft review by McIvor and Probert (Appendix 3).

by beef production. The dairy industry is restricted to localised areas in eastern Queensland, and while wool and sheep meat production are still important in some areas, they have declined in the past four decades.

Although the behaviour of phosphorus in soil-plant-animal systems is likely to be similar in northern and southern Australia there are some reasons why northern Australia might differ:
(i) temperatures are higher, particularly during the winter months
(ii) the majority of the rainfall occurs in summer rather than winter leading to a hot growing season
(iii) the majority of the grasses have the C_4 photosynthetic pathway.

Much of the beef production in northern Australia occurs on soils that are low in nutrients, notably nitrogen (N) and phosphorus (P) and to a lesser extent sulphur (S) (Coates et al. 1990). The pastures reflect the fertility of the soils through differences in yield, botanical composition and plant nutrient concentration. However for the extensive grazing systems, due to variation in soil and vegetation a grazing area will contain areas where P levels are higher than average; diet selection undoubtedly disguises the worst effects of low pasture P (Miller et al. 1990). Figure 7 from McCosker and Winks (1994), shows that the diet of cattle would be deficient in phosphorus over 68% of northern Australia (≤ 6 ppm extractable P), marginally deficient over 12% (7-8 ppm extractable P), and adequate over 20% (≥ 8 ppm extractable P).

Many of the soils of northern Australia are ancient relics. The high degree of weathering has resulted in the loss of nutrients including P (Beadle 1962). Detailed soil, field and glasshouse pot studies have shown that phosphorus deficiency for plant growth is widespread in northern Australia and occurs on a number of soil types and in a number of regions (Gilbert and Shaw 1987; Gilbert et al. 1987; Jones and Crack 1970; Jones 1973; Kerridge et al. 1971; Maltby and Webb 1983; Standley et al. 1990; Webb 1975). The exceptions are extensive areas of cracking clay soils, the red-brown texture contrast soils (Probert and Jones 1982) [although Crack (1971) reported responses to P in pot studies], and red and brown soils formed from basalt in semi-arid areas (Miller and Jones 1977; McIvor et al. 1988). The latter soils are some of the most deficient in S for the growth of pasture legumes.

There is little fertiliser applied to pastures in grazing systems in northern Australia. There is some used on dairy pastures (in higher rainfall areas and often supplemented by irrigation) and also on beef pastures in these regions, but there is none over most of the extensive grazing areas. (Garry Kuhn, pers comm.).

Because only limited data are available, the expected P-balances of four contrasting northern beef production systems were calculated: extensive breeding (with and without phosphorus supplement), intensive backgrounding, and a mixed grazing/cropping system (Table 3).

All of the beef grazing systems were calculated to be net exporters of phosphorus (P-balance > unity). The amounts of phosphorus exported annually are very low for the extensive breeder enterprises and the small output is almost balanced when the breeders are provided with strategic phosphorus supplements.

In the more intensive operations with higher animal numbers and turnover, and faster growth, the phosphorus outputs were much higher and were not matched by the fertiliser applied to the fodder and grain crops. These losses will have to be balanced in the long-term to maintain phosphorus supply to plants and animals.

Table 3. Farm-gate phosphorus balance of beef production systems in northern Australia.

Production system	Annual P input (kg/ka)	Annual P output (kg/ha)	P efficiency	Soil fertility
Extensive breeder herd in north Queensland – no P supplement	0	0.04	Net extraction	No fertiliser
Extensive breeder herd in north Queensland – P supplement	0.04	0.06	150% Net extraction	No fertiliser; P input via supplement to the cattle
Intensive backgrounding	1.25	2.40	192% Net extraction	5 kg P/ha on fodder crops
Mixed grazing/cropping systems	1.25	2.35	188% Net extraction	5 kg P/ha on grain crops

Calculation assumptions:

Extensive breeder herd in north Queensland - no phosphorus supplement

Property size: 80,000 ha

Animal numbers: the herd contains 3000 breeders that have their first calf at three years and are sold at ten years when they weigh 450 kg. The branding percentage is 50%, and annual mortality rates are 8% for breeders and 1% for young animals. For these numbers, 503 replacement heifers are needed each year and there are 275 cast for age cows.

Markets: young store cattle for the live export trade or sale to other producers at two years of age weighing 300 kg. The herd produces 1500 calves per year so 1440 are available for sale at two years. After providing replacement heifers, 937 are sold.

Inputs: Nil - no fertiliser, supplements, feed or animals are purchased.

Outputs: Liveweight contains approximately 0.8% phosphorus (ARC 1980) so the annual output is 3240 kg [(937*300*0.008) + (275*450*0.008)] or 0.041 kg P/ha.

Extensive breeder herd in north Queensland - phosphorus supplement

Property size: 80,000 ha

Animal numbers: the herd contains 3000 breeders that have their first calf at three years and are sold at ten years when they weigh 450 kg. The branding percentage is 70%, and annual mortality rates are 3% for breeders and 1% for young animals. (Note that this hypothetical example represents a well managed herd with weaning, good animal husbandry, etc; using phosphorus supplements alone is unlikely to increase branding percentage by 20%.) For these numbers, 420 replacement heifers are needed each year and there are 336 cast for age cows.

Markets: young store cattle for the live export trade or sale to other producers at two years of age weighing 300 kg. The herd produces 2100 calves per year so 2058 are available for sale at two years. After providing replacement heifers, 1638 are sold.

Inputs: no fertiliser, feed or animals are purchased. All breeders are supplemented with phosphorus at 6g/day/animal for six months during late pregnancy and early lactation. Inputs would be 6*183 = 1098 g/breeder/year or 3000*1.098 = 3294 kg or 0.041 kg P/ha.

Outputs: Liveweight contains approximately 0.8% phosphorus (ARC 1980) so the annual output is 5140 kg [(1638*300*0.008) + (336*450*0.008)] or 0.064 kg P/ha.

Intensive backgrounding

Property size: 4,000 ha

Animal numbers: 2000 growing steers (1 steer/2 ha). Steers are purchased at approximately 250 kg and sold after 6 months weighing 400 kg (a gain of 150 kg). Approximately 1000 ha of fodder crops (sorghum, oats) are used to supplement pastures.

Markets: feedlots

Inputs: fodder crops receive 5 kg P/ha each year or 1.25 kg/ha over the whole property.

Outputs: the annual liveweight gain of 300 kg (2 drafts @ 150 kg) contains 2.4 kg P or 1.2 kg/ha.

Mixed grazing [fattening]/cropping systems

Property size: 4,000 ha

Crop area: 1000 ha of wheat and sorghum

Animal numbers: 1500 growing steers (1 steer/2 ha grazed). Steers are purchased at 1-2 years weighing 250 kg and sold weighing 550 kg after 18 months (a gain of 300 kg).

Inputs: crops receive 5 kg P/ha each year or 1.25 kg/ha over the whole property.

Outputs: the annual liveweight gain of 200 kg contains 1.6 kg P or 0.6 kg/ha. A crop contains approximately 0.35% P (Dalal and Probert 1997) so a crop yielding 2 t/ha removes 7 kg P/ha or 1.75 kg/ha over the property.

Note: that in all grazing system calculations no allowance is made for bulls in the breeding systems, or for any phosphorus losses in soil or runoff, or by leaching.

3.3 Options for improving the effectiveness of soil-phosphorus and phosphorus-fertiliser use

3.3.1 The strategies by which significant P-efficiency gains can be made [d]

Although the reactions of phosphate with soil and the processes leading to P accumulation in soil are very complex (McLaughlin et al. review, Appendix 4), it is possible to assess the options for improving P-balance efficiency by envisaging the main sources, flows and effective sinks for P in farming systems (Fig. 8). The amount of P held in the cycling pools of soil P (i.e. plant-available P) is the working capital of the soil and it is the effective concentration of plant-available P in this pool that supports potential productivity. In the higher-rainfall agricultural systems of southern Australia, this is often considerably above the concentration of available P in natural ecosystems because of the yield imperatives imposed by commerce, and the need to use water and land resources efficiently.

For agricultural production to be maintained, the cycling pools of P must be topped up by fertiliser applications whenever P is removed or lost from this pool. Alternatively, productivity may be increased by applying fertiliser P in excess of the amount removed or lost from the cycling pool up to the point where the cycling pool of available P equals the critical level for the soil-plant system being farmed.

In a system where a target level of soil fertility is being maintained, the rate at which P must be applied ($P_{fertiliser}$) and the P-balance of the system ($P_{export}/P_{fertiliser}$) are determined by the rates of P removal or loss. This is also summarised by Equation 4 (section 3.2.1 and Table 4).

In a sustainable farming system, improvements in farm-gate P-balance and thus long-term reduction in P-fertiliser requirements can ultimately, only be achieved when fertiliser technology, agronomic, microbial or plant-based interventions lead to reductions in the P-loss or P-accumulation terms (see Eqn 4, Table 4 and Fig. 8).

The relative size and importance of the P-loss or P-accumulation terms to the apparent P-balance efficiency of any system appears to depend mainly on:

(i) the level of soil P-fertility at which the farming system is being managed *and is consequently also related to the productivity per hectare of the system* (see sections 3.2.1 - 3.2.3);
(ii) the capacity or otherwise of the farming system to export large amounts of P in products (section 3.2.2);
(iii) the trophic level at which the system is operating (McLaughlin et al. 1992);
(iv) the P-sorption characteristics of the soil on which the system is operated.

There have been very few experiments that have examined P-balance of farming systems that are managed with "steady-state" soil-P fertility to illustrate this unequivocally. However, Table 4 shows three contrasting examples of farming systems that were managed in this way or can be analysed to extract this information. These examples demonstrate how the P-loss or P-accumulation components of P-balance efficiency can vary with farm enterprise and soil type. They also provide some idea of the magnitude of improvements in P-balance efficiency that might be achieved by targeting different components of the P-balance of a farming system.

The wheat-sheep rotation at Wagga, NSW and the wool production system at Canberra, ACT were located on soils with moderate Phosphate Buffering Indices (PBI, Burkitt et al. 2008) and loss of phosphate by leaching does not occur. For these farming systems, the most significant

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[d] Arguments drawn primarily from draft reviews by Simpson et al. (Appendix 5) and McLaughlin et al. (Appendix 4)

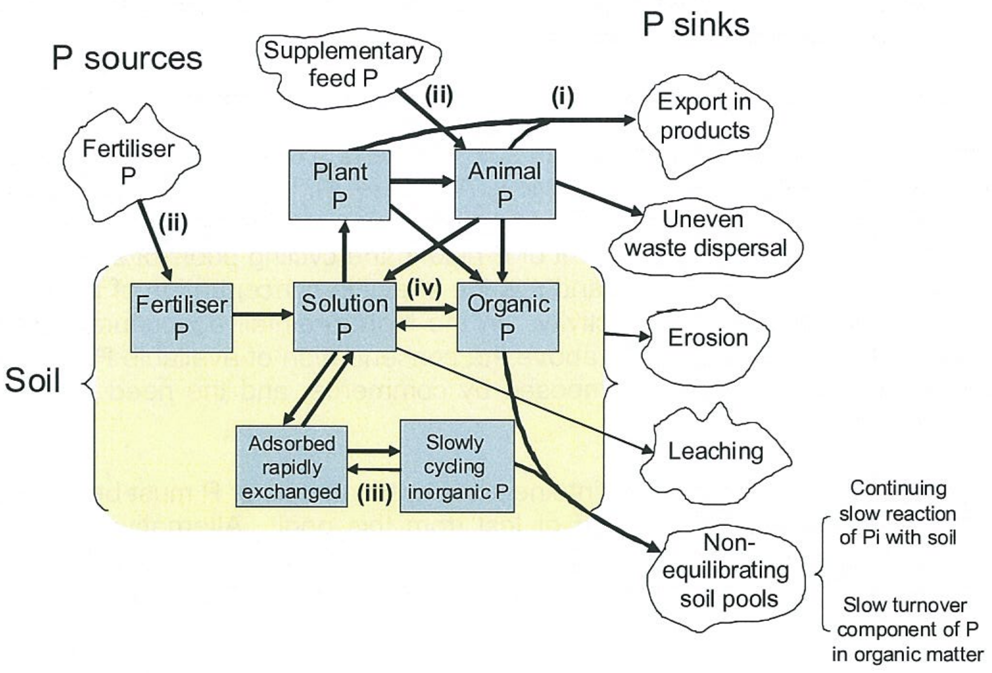


Figure 8. Diagrammatic representation of the inputs, flows and outputs of P in agriculture illustrating the potential components of the P-balance of a farming system (see also Table 4 and Equation 4, section 3.2.1). The Roman numbered paths indicate the main places where it may be possible to alter P-use efficiency (Modified from Helyar and Godden 1976)

Table 4. P-balance budgets for farming systems maintained with "steady-state" plant-available P levels (kg P/ha/year). Pi is the component of phosphate and Po is the component of organic P accumulated annually.

Equation 4: Farming system	P_{input}	=	$P_{waste\ dispersal}$	+	$P_{erosion/leaching}$	+	$P_{soil\ accumulation}$	+	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. 2010)	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 accumulating Pi and Po estimated for this system from George et al. (2007)

[e] P-balance efficiency = $(P_{export} / P_{input}) * 100$

terms contributing to P-balance inefficiency are the accumulations of phosphate and organic P in the soil. Helyar et al (1997) demonstrate that in ley-farming systems, longer pasture phases tend to favour accumulation of P in organic matter. The annual grazing system at Willalooka, SA was located on sandy soil (low PBI) with high potential for phosphate leaching. Consequently P-loss by this path features as a large component of the P-balance inefficiency of this system. P-accumulations in soil are much reduced, especially the phosphate component, but with moderate organic P accumulation still occurring. It is very clear from these examples that the strategy for improving P efficiency must take into account the nature of the farming system and the characteristics of the soil on which it is located.

It is the purpose of this review to examine how agronomic interventions, fertiliser technology and plant or microbial strategies may improve the P-efficiency of agricultural systems or plants, or facilitate the extraction of the sparingly-available P that is accumulating in agricultural soils when P-fertilisers are used. However, if these strategies do not reduce the rates of P-loss or P-accumulations in agricultural systems they will provide only short-term benefits and will make little difference to the effectiveness with which scarce P resources are used. Briefly, therefore, we first outline the rationale by which agronomic, plant or microbial strategies may minimise P-losses and accumulations enabling improved P-balance efficiency.

P export in products (intervention point: (i) Fig. 8)
The objective of applying P-fertiliser is to increase or maintain agricultural production and export of P in products is inevitable. The amount of P exported in products represents the minimum amount of P that must be replaced by fertiliser application if the farming system is to be sustained. In most situations, attempts to reduce P export simply by accepting a lower level of production will be counterproductive. Even if care is taken to appropriately reduce nutrient (P, N, etc.) inputs to achieve a system where P_{input} approaches P_{output}, production per hectare will be low, profitability compromised, and the farm system will not be using land or water resources efficiently.

However, P-balance and agronomic efficiency can be lifted by any practice that addresses constraints to yield and leads to increased P_{export} for a given level of P input. This requires, or will lead to a greater level of P-extraction from the soil. Alternatively, improved agronomic efficiency will also be achieved if larger quantities of product with a lower P content can be produced, provided that product quality or value are not compromised. Two outcomes are possible: (i) P-balance will be improved, if the farming system is managed near critical P because less fertiliser will be required, or (ii) production will be increased with little change in P-balance efficiency if the farming system is operating at a soil P level below critical P.

However, it is perhaps ironic that agricultural enterprises that export more P in products tend to be those with lower farm-gate P-balances (section 3.2.2; Weaver and Wong REVIEW, Appendix 2).

P inputs (ii)
Because a large component of the inefficiency in P-balances is associated with P accumulations in soil strategies that "fertilise" the farming system whilst bypassing the soil have the potential to deliver more efficient use of P. Examples of such practices include the supplementation of livestock either with feed (e.g. dairy systems) or P-supplements to address dietary deficiencies (e.g. grazing systems of northern Australia; section 3.2.3), and the use of foliar fertilisers (e.g. Bouma 1969). However, whilst these strategies have their place in agriculture, they are often not applicable in all situations. For example, supplementary feeding is only suitable when it is economically viable and the efficacy of feeding plants through their leaves (foliar fertilisers) is often constrained by issues of unreliability, leaf damage, timeliness of application or nutrient uptake capacity limitation (Noack et al. 2010; McLaughlin et al. review Appendix 4).

Nevertheless, Noack et al. (2010) have reviewed the case for foliar application of P to wheat crops and argue that there is a window of opportunity for foliar fertiliser applications in strategic management of crops provided small improvements in the efficacy of foliar P applications can be achieved. There is less opportunity in situations where fertiliser is to be applied in a single annual dose (because of limits to the amount of P that can be absorbed via leaves) or to sensitive plants where high levels of foliar uptake tend can be toxic (e.g. clovers). Other fertiliser application strategies intended to modify fertiliser-P reactions with soil are further discussed in section 3.3.4.

P-losses (erosion, runoff and leaching)
Reducing loss of P from a farm system will directly improve P-balance efficiency. However, in many systems P loss due to erosion and runoff should be a relatively small component when best-practice management is followed (e.g. appropriate forms and placement of fertiliser, appropriate timing of fertiliser in relation to rain and crop growth, use of soil amendments to reduce nutrient transport, and the use of buffer strips to capture mobilised nutrients, attention to ground cover: Nash and Halliwell 1999; Mathers et al. 2007). Losses due to leaching vary considerably with soil type, fertiliser management and botanical stability. Farming systems on soils with moderate to high P-sorption capacity (the majority of soils Australia-wide) are usually subject to relatively small losses (<0.4% - <5% of applied P: Ridley et al.2003; McCaskill and Cayley 2000; Melland et al. 2008).

However, farming systems on low P-sorbing soils with poor P retention capacity (e.g. in coastal areas, and parts of South Australia and Western Australia) can experience very large P-losses (43% - 69% of applied P: Lewis et al. 1987 ; Ozanne et al 1961) which need to be addressed for both financial and environmental reasons.

Irrespective of the magnitude, any loss of P from a farming system to the wider environment is environmentally undesirable and where losses are large they can clearly contribute to major environmental problems.

Waste product dispersal
Accumulations of P within paddocks, within farm systems or within regions (e.g. associated with feedlots) due to uneven distribution of excreta is a unique problem of livestock systems. Adjustment to farm management can address these accumulations to some extent and will make a contribution, albeit sometimes relatively small, to improved farm-gate P-balance. This is discussed in more detail in section 3.3.4.

P accumulation in "non-equilibrating" pools in soil (iii and iv)
P accumulation is sparingly-available soil pools is often a large contributor to P-use inefficiency (e.g. Table 4). When phosphate is applied to many soils as fertiliser, it is subject to continuing reactions with the soil particles and incorporation into organic matter that leads ultimately to accumulations as sparingly-available phosphate and organic P. In low P soils the processes also manifest themselves over time as a decline in the residual value of freshly-applied fertiliser (Barrow and Carter 1978; Barrow 1980c). In early literature, the pools of sparingly-available phosphate were sometimes referred to as "irreversibly adsorbed" or "fixed", but this incorrect. After the initial adsorption of phosphate to the surface of soil particles or precipitation with Ca, Al and Fe (McLaughlin et al. review Appendix 4; Sample et al 1980; Pierzynski et al. 2005), phosphate continues to react with the soil and becomes increasing less-available for uptake by plants (Barrow 1999).

The initial adsorbtion and/or precipitation of phosphate to, or within soil particles and the continuing reactions of phosphate are decribed in more detail by McLaughlin et al. (Appendix 4). In this section, we will use the term "sorption" (see Barrow 1999) to describe the overall process of transfer of phosphate from soil solution to the solid phase of the soil (i.e. adsorption, precipitation and continuing reactions), without specifying any particular mechanism unless otherwise stated, as this greatly simplifies the description of the processes that lead to phosphate becoming less available for plant uptake. Likewise, for simplicity in this section "desorption" will be used to describe release of P from the solid phase to the liquid phase (soil solution) whether it be by the reverse of adsorption, chemical exchange or dissolution reactions.

The forward sorption reaction is driven by the phosphate concentration in the soil solution and is considerably faster than the back (desorption) reaction that will occur when the soil solution phosphate concentration is depleted (Barrow 1983a; 1983b). Conceptually, the accumulation of P in slowly cycling organic matter is similar. The various components of organic matter that are returned to soil are mineralised at very different rates depending on biological activity of the soil, and their chemical and physical protection (Krull et al. 2003). All organic matter, even the more resistant materials (e.g. humus), turnover albeit sometimes at very slow rates (Krull et al. 2003). However, for a farming system being fertilised annually, to maintain soil P fertility the rate of organic P accumulation will be determined by those components of soil organic matter that take longer than a year to be mineralised.

In simple conceptual terms, the accumulations of P in fertilised soils are thus the net result of phosphate sorption/desorption and precipitation/dissolution reactions, and the slower cycling components of soil organic matter that release phosphate at rates slower than the rate of P supply necessary for commercial agricultural production. To slow accumulation of P in sparingly-available pools, it will be necessary to shift the equilibrium between sorption and desorption rates, and/or soil organic-P input and mineralisation.

3.3.2 The ground rules for influencing P accumulations in soil

Desorption of sparingly-available phosphate

Barrow (1980d) cited comparisons of the ability of agricultural plants to access residual fertiliser phosphate that had not revealed any significant differences between species, and the very slow rates of phosphate desorption once phosphate had diffused within soil particles as reasons for pessimism about the chances of finding plants that can usefully access sparingly-available phosphate. However, it is possible that plants that can lower the pH of the rhizosphere or are able to secrete organic acids from their roots, for example, may have improved access to some component of the sparingly-available phosphate pool because low pH (Barrow 2002) and organic acids such as citric acid (Gerke 1994) do increase phosphate desorption rates. In the case of the much studied white lupin (*Lupinus albus* L.), it is very clear that citrate exudation from proteoid roots confers an ability to access P-pools inaccessible to many other plant species (Gardner et al. 1983; Dinkelaker et al. 1989; Hocking et al 1997) and, when grown in close association with other species, enables the companion plant to also access sparingly-available phosphate (Gardner and Boundy 1983; Horst et al. 2001). On the other hand, buckwheat (*Fogopyrum exculentum* Moench) which produces exudates with a lower pH in response to low P conditions (Amann and Amberger 1989), has high P-uptake efficiency in calcareous soils (Zhu et al 2002) but is less effective in soils dominated by Fe and Al phosphates (Otani and Ae 1996). However, the general effectiveness of strategies intended to enhance phosphate desorption remains an open question as there have been few demonstrations of crop species that gain substantial P nutrition benefits by the "desorption" mechanisms observed in the limited number of exceptional, P-efficient plants.

Reducing accumulation of sparingly-available phosphate

It should also be possible to reduce the accumulation of phosphate by slowing the rate at which phosphate continues to react slowly with soil making it less available for plant growth. The key elements that determine the potential extent of P sorption in soil are the chemical and physical nature of sorbing surfaces; the ionic environment in the soil solution and the P concentration in solution (Ryden and Syers 1975). Sorption of P in agricultural soils is therefore influenced by soil clay content, organic matter content, soil pH, soil texture, and Al, Ca and Fe concentrations in soil solution (Pierzynski *et al.* 2005; Hedley and McLaughlin 2005). Although the reactions of phosphate with soil are potentially complex (McLaughlin et al. Appendix 4), it is helpful here to consider the simpler empirical relationship between net phosphate sorbed by a soil (Ps), P concentration in the soil solution (c) and time (t) observed for non-calcareous soils (Barrow 1980a; 1980b).

$$Ps = a.c^{b1}.t^{b2}$$

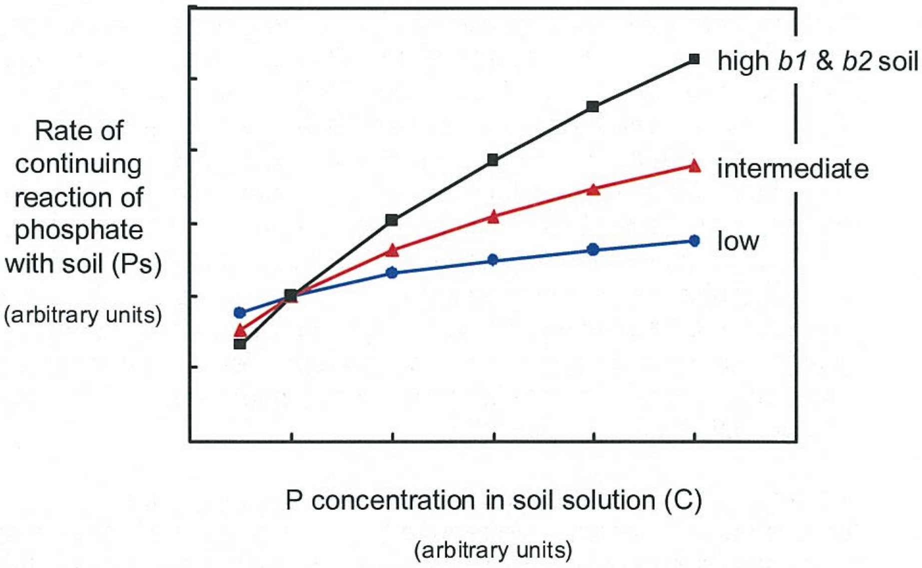
where: *a* approximates the amount of sorbing material in a soil, and *b1* and *b2* are coefficients that describe the shape of the sorption relationship.

In calcareous soils this equation also applies initially, but precipitation of calcium phosphates decreases the phosphate concentration of the soil solution to levels that are determined by the solubility product (Barrow 1980a).

For soil at approximately equivalent solution phosphate concentrations the sorption of P through time is determined by the value of *b2*. Soils with a low *b2* value have a fast initial rate of phosphate reaction followed by a slow rate of reaction, whereas phosphate reaction with soils that have a high *b2* value are initially slower but the rate of the phosphate reaction persists. These soils (which include many from Australia; Barrow 1980b) are expected to accumulate sparingly-available phosphate. Soils with relatively low *b2* values are be expected to require maintenance P applications that approximate the rate of P export from the soil (i.e. high potential P-balance efficiency).

In practice, Ps is found to vary somewhat between soils that differ in sorption capacity (Barrow 1973) but it is influenced very strongly by the characteristic *b1* and *b2* values of a soil. The *b1* and *b2* parameters tend to correlated when compared across a wide range of soils (Barrow 1980a; 1980b). Because they are correlated, Ps can be shown to be influenced by the P concentration at which soil solution is maintained in the generalised manner shown in Figure 9. This indicates that fertiliser, plant or agronomic strategies that allow a farming system to be

Figure 9. Generalised relationships between the rate of the continuing reaction of phosphate with soil (Ps) and the concentration of phosphate in soil solution (C) for soils with differing phosphate reaction capacities. *b1* and *b2* coefficients are assumed to be correlated according to the relationship observed by Barrow (1980b): $Ps = a.c^{b1}.t^{b2}$



operated at lower soil phosphate concentrations should reduce the rate at which slow reactions of phosphate and soil lead to P accumulation. Feasible ways to achieve this include fertilisers designed to release phosphate at rates matched to plant demand to reduce the opportunity for accumulation in sparingly-available inorganic and organic pools, and farm systems based on plants that have low external critical P requirements to slow the rates of accumulation. The effectiveness of these strategies in slowing phosphate accumulation will be greatest in soils with high *b1*/*b2* values and least in soils with low *b1*/*b2* values. However, the latter soils would be nearing P-saturation, would have low P buffering capacity and P-inefficiency will tend to be associated with other issues such a leaching losses.

Soil organic P accumulation

Phosphorus application to pastures on low P soils in Australia generally results in accumulation of organic matter and consequently organic P in the soil. The rate of organic matter accumulation in terrestrial systems is directly related to their net primary productivity and the subsequent rate of organic matter return to soil (Grace et al. 1998). For geographical regions or farming systems, relationships are thus found between soil organic carbon accumulation and factors such as annual rainfall (e.g. Jackson et al. 2002) or P-fertiliser use (e.g. Williams and Donald 1957; Russell 1960a; 1960b; Chan et al. 2010) when these inputs regulate the net primary productivity of the system. The amount of organic P accumulated will consequently also be correlated with the amount of fertiliser P applied (e.g. Williams and Donald 1957; Kohn et al. 1977; Lewis et al. 1987).

Rates of net organic P accumulation of the order 1.7 - 4 kg P/ha/year have been recorded for Australian pastures on P-deficient soils (Williams and Donald 1957; Russell 1960a; 1960b; Barrow 1969; Kohn et al. 1977). There are few reports of P-balance and distribution in farming systems where plant-available P concentrations have been maintained unequivocally in a steady-state condition. However, the pasture-crop rotation experiment of Helyar et al. (1997) was managed in this way for 18 years and organic-P accumulation in the soil (a red earth) accounted for 2.2 - 3.0 kg P/ha/year, or 19%-25% of the P applied annually as fertiliser. The range in accumulation rates was associated with the length of the pasture phase; rotations with shorter pasture phases accumulated less organic P. Other estimates of organic P accumulation rates in permanent pastures which are of a similar order of magnitude are shown in Table 4.

When P-fertiliser applications are used to lift soil fertility and are then adjusted to maintain it in a steady-state condition, the rate of organic P return to the soil should stabilise because no further increase in primary productivity is possible. However, it is expected that soil organic carbon (and organic P) will continue to accumulate in the soil for some time because the capacity of the soil to retain organic matter (e.g. Six et al. 2002) has not been saturated and/or the balance between input of plant residues and mineralisation has not been reached (Baldock et al. 2007). Although silt+clay content, aggregate structure (which physically protects organic matter from mineralisation) and the biochemical complexity of resistant organic materials (chemical protection) will determine the potential organic carbon saturation limit of a soil (Baldock and Skjemstadt 2000), in many cases the practical limit will be set by the climatic constraints of the farm, farming practices and the rates of soil organic matter turnover.

Fractionation of soil organic matter into physical (conceptual) classes (for example: Plant residues (>2 mm in size), Particulate organic matter (0.053-2 mm), Humus (<0.053 mm) and Recalcitrant organic carbon which is close to being inert and dominated by pieces of charcoal [Baldock and Skjemstadt 1999]; or variants on this theme [e.g. Amelung and Zech 1999]), permits the prediction of organic matter accumulation in soil because the fractions have characteristic turnover rates (Skjemstadt et al 2004). It is clear that soil organic matter (and consequently organic P) accumulation will equilibrate at some point but modelling of soil organic matter accumulation for a pasture at Yass, NSW predicted that soil organic matter pools would only equilibrate after ~200 years of regular fertiliser use at this location (Baldock et al. 2007). The soil organic carbon saturation level in this example was determined by the pasture yield that can be achieved realistically at the site. This concept of eventual equilibration of organic P accumulations is supported by empirical data from farming systems fertilised over very long time periods: e.g. Park Grass (Rothamstead, UK) where after 100 years of superphosphate fertilisation, only low proportions of accumulating P (1%-6% topsoil, 10%-18% subsoil layers) were in the form of organic P (Oniani et al. 1973), from various examples of soil organic carbon stabilisation (as cited by Stewart et al. 2007a) and from pedological studies (e.g. Smeck 1985). For many soils, it appears that the time frames for organic P equilibration may be sufficiently long relative to the predicted longevity of global phosphate reserves (section 3.1.2), that waiting for the equilibration of soil organic matter concentrations will not provide a practical solution to the issue of P-balance efficiency.

The stoichiometric relationships between C:N:S in soil organic matter fractions are relatively stable across a wide range of soils. However, C:organic P ratios can vary considerably (Kirkby et al. 2010; Kirkby 2010). Presently it is unclear whether the variance in C:P ratios is a result of differences between analytical methods or is reflecting real differences in the composition of organic P in soils. Whilst orthophosphate monoesters (e.g. phytate) have been identified as a major form of organic P in many soils, along with lesser amounts of phospholipids, nucleic acids, phosphonates and other compounds (Turner et al 2005; Smernik and Dougherty 2007), often large proportions of the soil organic P remains poorly identified and this limits our understanding of the opportunities for mobilising organic P reserves for plant growth (Guppy and McLaughlin 2009).

If the stoichiometric ratios for C:N:S and C:P in soil organic matter prove not to be tightly coupled, it is possible that enhancing release of phosphate from specific organic-P compounds in soils by release of phosphatases from plant roots or soil microorganisms (section 3.3.5) could potentially lower net rates of organic P accumulation independently of effects on soil organic matter accumulation. However, for P-balance efficiency to be improved by limiting organic P accumulation in soil, it is ideally necessary to also increase the rates of organic matter turnover (section 3.3.5) so that equilibration is achieved at lower soil organic matter concentrations. In this instance, the objective of reducing organic P accumulations would potentially compete directly with objectives to increase carbon storage in soils (Dalal and Chan 2001; Lal 2004). However, limits to the use of P-fertilisers in agriculture will also impact adversely on carbon storage in soils.

3.3.3 Agronomic interventions [e]

Removing constraints to yield

Constraints to crop yield, other than those due to P-availability itself, can influence P-balance efficiency in two ways. In some cases (e.g. compacted subsoil or an additional nutrient deficiency), addressing the constraint to yield will increase the demand for P and require additional fertiliser inputs. Alternatively, when yield is constrained by factors that limit root growth and soil exploration (e.g. soil acidity, root diseases), alleviating the constraint will increase P export for a given level of P input and will directly improve the P-balance of the farming system. However, in practice it is impractical for the published targets for soil fertility management (e.g. Moody 2007, Gourley et al. 2007a) to recognise the existence of other constraints to yield, and P will often have been supplied in excess of actual requirements when a yield constraint of any sort exists. Thus, the alleviation of any constraint to yield will often improve P-use efficiency.

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[e] Information drawn primarily from draft the review by Simpson et al. (Appendix 5) and from Weaver and Wong (Appendix 2).

Factors that constrain root growth directly affect yield and also inhibit the root foraging capabilities of a plant. This directly reduces a plants ability to acquire P from soil and P-use efficiency. Constraints to yield associated with **acid soils** are a clear example of this. Introduction of Al-resistance genes alone has been shown to increase efficiency of P uptake in barley due primarily to improved root growth and soil exploration (Delhaize *et al.* 2009). However, the best yield outcomes are achieved when lime applications are combined with the use of Al-resistant cultivars to overcome constraints associated with surface and subsurface soil acidity in cropping (Scott *et al.* 1997) and pasture systems (Scott *et al.* 2000). This is most probably because soil acidity inhibits the root hair and rhizosheath development of cereals irrespective of their Al-resistance status and this continues to affect the plant's ability to capture soil nutrients under acid soil conditions (Haling et al. 2010).

Root diseases also impact directly on the efficiency with which a plant can capture nutrients. This is most dramatically demonstrated by the large increase in wheat yields for Australia that accompanied the introduction of canola and improved break crops (Kirkegaard et al. 1997; Angus 2001). Breaking root disease cycles allowed yield responses to N-fertilisers that had previously only given irregular benefits (Passioura 2002). Persistent and widespread root diseases still plague annual crops (Harvey et al. 2001; 2008) and are endemic in perennial farming systems where break crops are not a practical option (Barbetti et al. 2007). Resolving these issues will also improve P-use efficiency and may do so more effectively than many other interventions because of the direct impact of poor root health on capacity for efficient nutrient acquisition.

Many other approaches to increasing productivity per hectare will also improve P-use efficiency. New grass **cultivars that tolerate high grazing pressure** and enable higher stocking rates per hectare (Culvenor et al. 2009) or improved animal genetics (e.g. **better feed conversion** efficiencies; Arthur et al. 2004; Hegarty et al. 2007) are examples of innovative options for yield improvement, at least one step removed from soil fertility management, that will nevertheless improve P-use efficiency.

Targeted use of P-fertilisers

Fertilising soils to levels in excess of the critical P requirement for a crop-soil system delivers no advantages for yield (e.g. Fig. 4) and reduces profitability. From a P-balance efficiency perspective, the rate of organic-P additions to soil are expected to increase more or less linearly with yield but not to increase when soil P fertility beyond the critical P requirement of the crop. By contrast, accumulations of sparingly-available phosphate, losses due to leaching, erosion and runoff, and accumulations due to uneven distribution of excreta will continue to increase, at soil fertility levels beyond critical P, because their rates of accumulation or loss are P-concentration dependent.

Best practice is to set soil fertility management targets (e.g. Fig 4) and to use soil testing to manage within the logical (critical P) and sustainable (where P inputs just replace losses and removals) boundaries that such targets represent. The upper boundary for management may be less than P-critical, but it is not logical or environmentally responsible to exceed the critical P level that is appropriate to the crop-soil system being managed.

Two independent analyses of soil testing data (Table 5 and Fig. 10) have indicated that there is scope to reduce fertiliser costs associated with managing soils in excess of their expected critical P concentrations. The results suggest that some industries may have a more widespread high soil-fertility culture than others but the issue exists across the industries examined (dairy, beef-sheep grazing and wheat). Consequently there is also scope to reduce unnecessary P accumulations in agricultural soils. This can be achieved in many instances by using existing

Table 5. PBI profiles for soil samples in south west WA, and on Australian Dairy farms (Gourley, 2010, pers. comm.), and associated percentages of soils within each PBI group that exceed the critical Colwell P levels to achieve 95% of maximum pasture production (Gourley et al. 2007a) or 90% of maximum wheat production (Moody, 2007). (From Weaver and Wong, Appendix 2).

		PBI Profile (%)		% in excess of critical P level for pasture[#]		% in excess of critical P level for wheat production*
PBI group	PBI range	Australian dairy farms	South west WA	Australian dairy farms	South west WA	South west WA
1	<5	<1	10.5		23	44
2	5-10	<1	12.7		37	66
3	10-15	<1	7.9		43	79
4	15-35	<1	24.2		56	82
5	35-70	9	19.6	95	67	81
6	70-140	25.9	14.9	98	66	75
7	140-280	31.5	9.9	96	59	61
8	280-840	29.8		80		
9	>840	2.3				

[#] Critical P to achieve 95% of maximum pasture production (Gourley et al. 2007a)

* These percentages assume the critical levels (90% of maximum production) defined by Moody (2007) for cropping apply to the south west WA dataset. However, only 1% of the samples were from cropping areas.

technology to promote a more targeted approach to P-fertiliser use (e.g. Simpson et al. 2009). However, it is of concern that the Australian Bureau of Statistics are reporting that only about 40% of southern Australian farms (ABS 2007) use soil testing as this is a primary tool in targeting and managing soil fertility.

Waste product dispersal

Nutrient cycling by grazing animals is important to the overall availability of nutrients and productivity of pasture-based systems (Haynes and Williams 1993). However, the tendency of livestock to deposit excreta disproportionately in "camps", under shade, or close to water and feeding points is also a component of poor P-balance efficiency in grazing enterprises. On flat and low slope areas, 25% - 47% of sheep dung, for example, may be deposited in only 5% - 15% of the total area of a paddock (Hilder 1966; Williams and Haynes 1992). A proportion of the P deposited in camps is returned to the rest of the paddock, but over long periods of time the uneven dispersal of P can lead to significant accumulations of P in a small area (Williams and Haynes 1992) rendering this P less available for pasture growth. Where P audits of paddocks have been conducted, the accumulations are of the order 1 - 2 kg P/ha/year (typically 5% - 7% of the annual P input in fertilised systems: Williams and Haynes 1992; Metherell 1994; McCaskill and Cayley 2000). The absolute rate of accumulation is proportional to the stocking rate for obvious reasons, and to the rate of P-fertiliser input because it influences the P concentration of herbage and, consequently, of excreta (Rowarth et al. 1988). On steep hill country, livestock camp predominantly on flat areas of paddocks and substantially higher proportions of P are transferred from steep slopes to flatter areas because higher proportions of excreta (e.g. 55% - 60% of urine and dung) are deposited in the camp area (Haynes and Williams 1993). Uneven

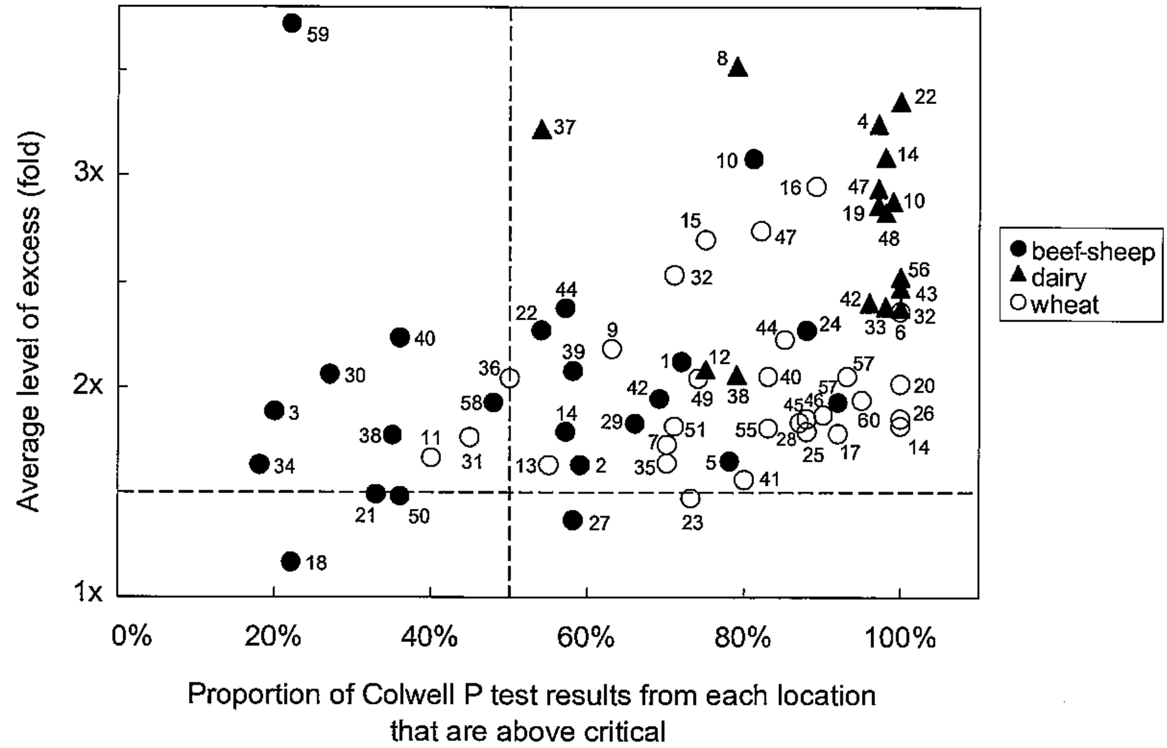

Figure 10. Proportions of soil test results from 58 farming districts of south-east Australia that exceed the expected critical extractable-P level (Colwell 1963) for the soil test sample (determined using the PBI-critical Colwell P relationship from Gourley et al. 2007) and the average levels of excess (fold) in these 'high' soil test results for beef-sheep, dairy or wheat enterprises. Wheat and legume-based pastures were assumed to have similar critical P requirements (Ozanne et al. 1976). Farming districts were identified by their Australian postcode. Each district was assigned an arbitrary identification number; where numbers are the same, more than one farming enterprise was represented in that district. The results are for soil samples that had been submitted for commercial soil testing (data supplied by J Laycock and C Walker; Incitec Pivot). Only results clearly identified by enterprise type and for soils with pH<7($CaCl_2$) were used. This is an imperfect sample of agricultural soils because soil testing is used by only 40% of southern Australian farms (ABS 2007) and it is presumed that the sample therefore reflects the situation for farmers highly motivated to use P-fertilisers. In addition, soil test values do not indicate the management reactions that they may evoke. For example, a high soil test value cannot always be regarded as indicating excessive fertiliser use if the reaction to it, is to moderate P-fertiliser inputs. For these reasons generous margins (dashed lines) were used to interpret the information and only district average results where more than 50% of samples from a district were >1.5-fold above the expected critical value (top right hand box) were regarded as indicating excessive soil P fertility. Although only three farming enterprises were examined, the data indicated that industry-related cultures may be influencing fertiliser practice (e.g. all dairy locations fall into the 'excessive' category), and there was no enterprise type that was predominantly in the lower soil fertility categories (From Simpson et al. Appendix 5).

distribution of nutrients across a farm is also not unusual, but is most often associated with regular patterns of stock movement. This is a particular issue on dairy farms, for example, where nutrient concentrations are often highest in paddocks closer to milking sheds (Lawrie et al. 2004).

Although it has been suggested that rotational grazing instead of continuous grazing can reduce camping effects (Haynes and Williams 1993), there is little evidence that increasing the frequency of rotational grazing has any further benefit for even distribution of nutrients in paddocks (Mathews et al. 1999) or on the P-balance of the grazing system (Chapman et al. 2003). In contrast, stocking rate does influence the distribution of excreta with lower stocking rates having a disproportionately high deposition of excreta in camps (Hilder 1966; Williams and Haynes 1992). Any impacts of paddock subdivision or rotational grazing on the distribution of excreta will reflect the change in short-term stocking rate achieved by such interventions.

Zone management and precision agriculture
Productivity gradients in paddocks whether a result of nutrient (N, P and K) gradients created by grazing animals (e.g. Matthews et al. 1994; Gillingham and During 1973) or as a result of topography, aspect, botanical composition, grazing preference or differences in soil type and depth (Murray et al. 2007), can result in ineffective use of P when it is applied uniformly across the landscape. The situation is analogous to uneven yield distributions in cropping paddocks which, when managed using variable rate technology, can significantly improve the net profitability of the crop (e.g. Passioura 2002). Hackney (2009) has shown that as P-fertiliser prices increase, differential fertiliser applications combined with grazing management to ensure pasture is utilised adequately, will increasingly deliver economic benefits from paddocks that have uneven productivity (Fig. 12). Whilst yield mapping of crops is now an accessible technology and its use is increasing rapidly, it is more difficult in pasture-based systems to assess the existence of productivity gradients. Where large and easily identified differences in nutrient requirement can be identified (such as camp areas) differential fertilisation is easy and commonplace (e.g. Gillingham and During 1973). However, more complex or fragmented productivity patterns can now also be determined using 'passive' or 'active' ground level, airborne or spaceborne canopy reflectance sensing devices with or without pasture modelling backup (e.g. Fig. 12; Hill et al. 1999; Murray et al. 2007; Trotter et al. 2010). The resolution being achieved with these technologies now far exceeds that needed for zone management in pastures (e.g. Berni et al. 2009). When combined with GPS technology, productivity maps should enable variable rate fertiliser delivery in grazed landscapes. However, because the plant-available nutrient status of soils cannot be mapped remotely, the spatial mapping of nutrient gradients (e.g. Kozar et al. 2002) to underpin variable fertiliser rate decisions is a potentially expensive and rate-limiting step in the application of this technology for fertiliser management.

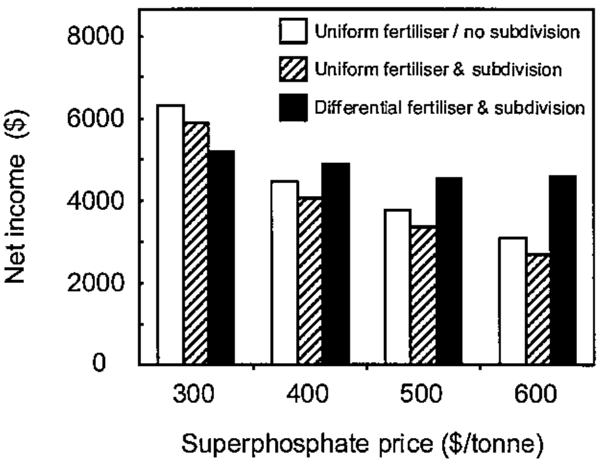

Figure 11. Anticipated net income from sheep grazing a hilly grassland at Barraga, NSW with a fragmented productivity distribution that was associated with differences in slope, aspect, soil chemistry and depth when superphosphate fertiliser is applied uniformly, applied uniformly with fencing to manage grazing patterns, or applied differentially according to nutrient responsiveness and fenced to manage grazing patterns (Hackney 2009)

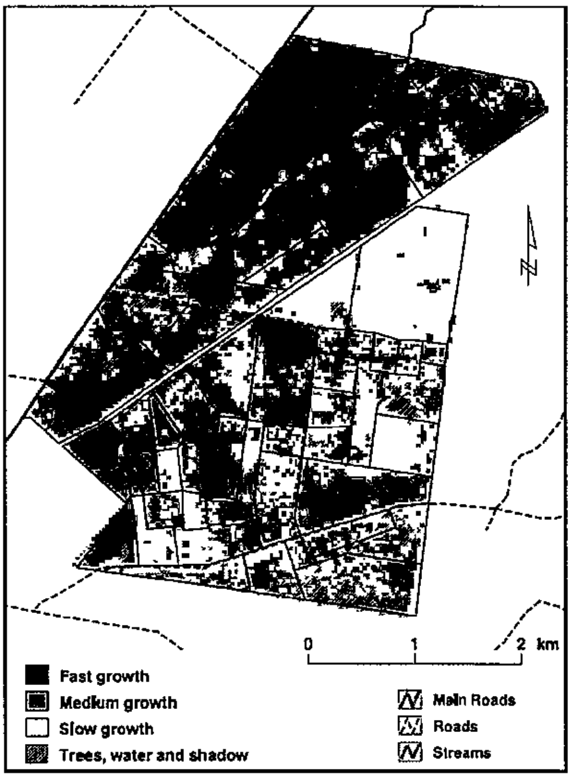

Figure 12. Pasture growth rate map from classified Landsat^{TM} imagery for spring 1993 showing productivity gradients on a farm near Armidale, NSW (from Hill et al. 1999).

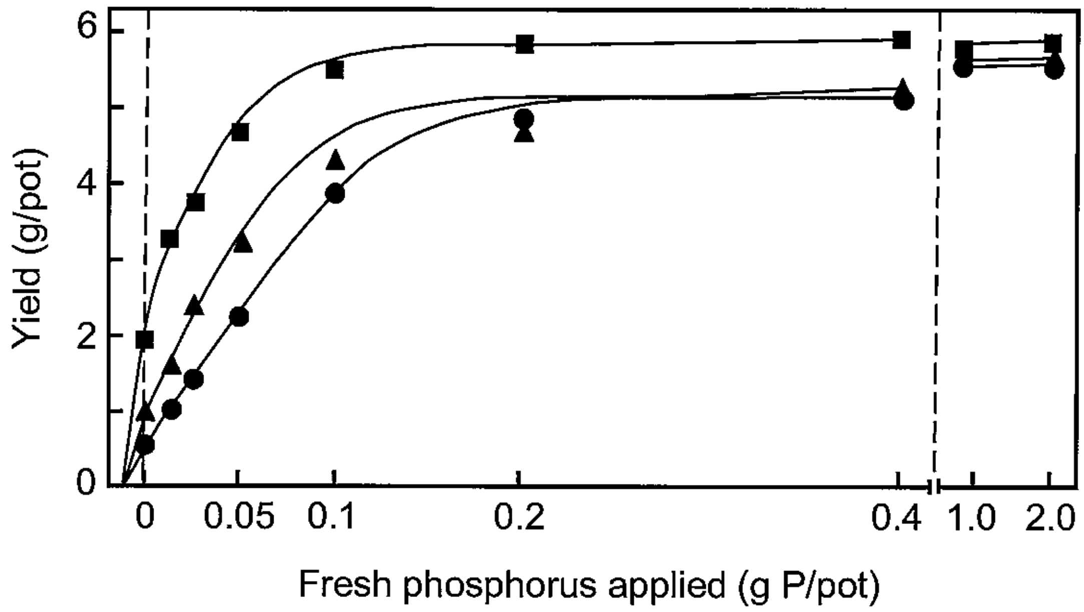

Figure 13. Effect of phosphate applied 20 years earlier on the response of wheat to newly applied phosphate. The original rates were: 0 kg P/ha (circles); 86 kg/ha (triangles); and 599 kg/ha (squares). Lines are fits to the Mitscherlich equation and are extended to the horizontal axis to indicate the amounts of P available from the original application. (Redrawn from Bolland and Baker 1998.)

Low P farming systems

The agronomic interventions mentioned so far, serve to improve current practice by eliminating waste or unguided use of P-fertilisers. However, these practices will still only bring farming systems up to the levels of P-balance efficiency currently being achieved in the most productive agricultural enterprises with P export being in the range 15% (sheep grazing) - 50% (cropping) of P input. The development of farming systems that are productive at low soil-P concentrations is a strategy likely to provide both environmental (lower P-losses) and efficiency (less P-accumulation) benefits.

(1) Impact of prior fertiliser use

It has been clearly demonstrated that previous applications of phosphate lower the P-sorption capacity of soil (Barrow et al. 1998; Bolland and Allan 2003; Burkitt et al. 2008) and increase the availability of subsequent fertiliser applications (Fig. 13; Bolland and Baker 1998). The implication is that continued P-fertiliser use will gradually lead to reduction in the critical P value of the crop-soil system and thus a decline in the available P concentration at which the agricultural enterprise can operate without compromising productivity. For these benefits to be realised, it is critical that farmers adopt a targeted approach to fertiliser use and monitor P-sorption capacity of soil over time. It is also important that single-step sorption capacity tests that are not "corrected" for current extractable-phosphate concentrations (e.g. phosphorus retention index, Bolland and Allen 2003; phosphorus buffering index, Bolland and Allen 2003; Burkitt et al. 2008) be used for this purpose as the 'corrected' versions of the test do not detect the change in P-sorption capacity. However, the large quantities of P-investment required to underpin substantial changes in P buffering capacity mean that this is not a management path that will achieve a rapid improvement in farm-gate P-balance.

(2) Biologically-fixed N versus fertiliser N
Legume-based pastures underpin the productivity of a majority of grazing and cropping enterprises in temperate Australia and New Zealand (Moore 1970; White et al. 1978; Puckeridge and French 1983) and are used to a lesser extent elsewhere in the world. Inputs of N via biological N-fixation are economically favourable, particularly in water-limited, extensive agriculture, but tend to be less favoured in well-watered environments with more intensive, high-value production systems. Increasingly fertiliser-N can become the preferred N source in these systems (e.g. Mundy 1996; Eckhard et al. 2003). The productivity of legume-based pastures thus depends on adequate nutrition of the legume and, in many cases, this translates to adequate supply of P. Forage legumes typically have the highest P-requirements of the plants that comprise a pasture system (e.g. Fig. 4; Hill et al. 2005; 2010; Haynes 1980). Figure 4b demonstrates how it would be feasible to shift to N-fertilised pastures to achieve a substantial reduction in the critical soil P fertility levels necessary for pasture production. The final target levels for soil P management would then be determined by the requirements of the major grass species. A change such as this has already occurred in the dairy industry of southern Australia which was traditionally based on white clover (*T. repens* L.) -perennial ryegrass (*Lolium perenne* L.) pastures with N-fixation estimated to provide about 70% of the N necessary to achieve potential production (Mundy 1996). However, as N applications have increased it is now more likely that white clover will comprise 10-25% of the pasture mix and provide <20 kg N/ha/year (McKenzie et al. 2003). Unfortunately, the potential improvements in P-use efficiency that could accompany such a major change in nutrient management on dairy farms has not been appreciated and indeed, the indications are that soil P-fertility has often been increased well beyond where it needs to be for a legume-based system, let alone an N-fed, grass-based system (Fig. 10, Table 5, Lawrie et al. 2004; Burkitt and Coad 2006).

The feasibility of shifting to N-fertilised pastures to gain improvements in P-balance efficiency will rest on the future relative costs of P- and N-fertilisers and the prices obtained for commodities produced in such systems. It is highly likely that N-fertiliser prices will increase as it is expected that the costs of energy and compliance with potential carbon emissions constraints are expected to rise. In addition, the use of N-fertilisers will bring new environmental challenges. Losses of N from N-fertilised dairy systems, for instance, have emerged relatively quickly as a major environmental issue (Ledgard et al. 1996; Ledgard et al. 1999; Eckard et al. 2003) and have been a significant issue in N-fertilised systems of Europe and North America for many years (e.g. Bussink and Oenema 1998).

(3) Farming systems that utilise soil organic P
The cycling of organic P underpins productivity and P-availability on all farms in every year. For example, the organic P cycle is estimated to contribute ~52% of the P used annually for pasture growth in a grassland production system at Bookham, NSW (Simpson et al. 2007). Although, opportunities to increase the rate of organic P cycling are not easily accommodated in Australian broadacre agricultural systems, soil organic matter is often used strategically as a nutrient resource. In cropping systems, soil organic matter (organic P) levels oscillate between accumulation and mineralisation across the pasture and crop phases of farming systems (White et al. 1978). This is clearly illustrated by ley-farming where soil organic matter concentrations are increased during clover-based pasture phases (e.g. Grace et al. 1995; Dalal et al 1995; Helyar et al. 1997) and nutrients are mobilised from soil organic matter and used during crop phases, bare fallows and continuous cropping (e.g. White et al. 1978; Dalal and Mayer 1986; Dalal and Chan 2001). Although the focus of soil organic matter management is usually transfer of N from the pasture (legume) phase to the crop phase, phosphorus supply to the crop is also a consequence of this form of resource management and some part of the generally better P-balance efficiency of cereal crops (Fig. 6) is attributable to net mineralisation of P from soil organic matter during the crop phase.

(4) Intercropping and phase farming

The ability of particular grain legumes to mobilise sparingly-available P has stimulated research to examine the possibility that P-efficient plants may be used to improve the availability of P from other crops by (i) mixing P-efficient with inefficient species in either crops or pastures (intercropping) or (ii) utilising the residues of the P-efficient crops for subsequent P-inefficient crops (crop rotation). The sorts of species that have been examined in this context include organic acid secreting crops such as white lupin (Gardner and Boundy 1983; Hocking and Randall 2001; Cu et al. 2005), pigeon pea (Ae et al. 1990), faba bean (Li et al. 2007) and chickpea (Veneklaas et al. 2003) which are considered capable of accessing sparingly-available phosphate, or species thought capable of mobilising P from organic sources (e.g. chickpea (Li et al. 2003; Li et al. 2004) and cowpea (Makoi et al. 2010). The principle that P-mobilising species can enhance growth and P uptake by cereals when intercropped or rotated in P-deficient soil is well established. However, the majority of evidence comes from pot experiments where the crops were not grown to maturity and periods between 'rotations' are short. Enhanced growth and P uptake was demonstrated for wheat in pots intercropped with chickpea (Li *et al.* 2003), lupin (Cu *et al.* 2005; Kamh *et al.* 1999) and faba bean (Song *et al.* 2007), or by exploiting residues of white lupin and pigeon pea (Hocking and Randall 2001), faba bean and lupin (Nuruzzaman *et al.* 2005a; 2005b) as if in a rotation. Other evidence of positive responses by cereals in pot experiments include maize (Li *et al.* 2004) and barley (Gunes *et al.* 2007) intercropped with chickpea, and maize rotated after groundnut (El Dessougi *et al.* 2003).

Horst *et al.* (2001) considered that of the two management options, intercropping should lead to most efficient transfer of P because the opportunity for re-sorption of mobilised phosphate would be less. However, field results have been mixed. There is clear evidence that cereals can gain P that would otherwise not have been accessible (Gardner and Boundy 1983; Li *et al.* 2007), but in many cases the component species have poor yields because of interspecific competition (Gardner and Boundy 1983; Härdter and Horst 1991; Härdter *et al.* 2008). In some cases, beneficial outcomes have been attributed to factors other than P-transfer, such as improved N nutrition and reduced allelopathy (Horst and Härdter 1994). Henry *et al.* (2010) have examined the impact of 'intercropping' different lines of the same species (i.e. 'multilines' of common bean, *Phaseolus vulgaris* L) which differed in root architecture as a way of reducing the agronomical challenges of intercropping and achieving improved uptake of P and water. However, they found that root growth in competition varied with both soil treatment and genotype mix. The multilines did not suffer yield penalties but, against expectations, the root architecture differences were often not sustained and differences in P or water uptake, and yield advantages were only observed in a few cases. No work has been done to assess the potential of this strategy for improved P-efficiency in natural "intercrop" situations such as pastures.

Using phase farming to exploit the residues of P-efficient grain legumes for subsequent cereal crop(s) is considered likely to hold more promise (Hocking and Randall 2001; Richardson *et al.* (2009). However, it is not clear whether P extracted by plants in one phase of a rotation will be transferred successfully to a subsequent crop under field conditions. Positive responses have been reported from rotating maize after high P-efficiency genotypes of cowpea and soybean, but not after less P-efficient genotypes (Jemo *et al.* 2006). However, gains to maize P nutrition following P-efficient grain legumes in African studies were small and not considered sufficient to substitute for fertiliser application, particularly on high P-fixing soils (Horst *et al.* 2001; Kamh *et al.* 2002).

Research is required to extend the promising glasshouse experiments to the field where crops are grown to maturity and translocation of P to the grain occurs. It is necessary to determine the size of any potential P nutrition benefit under practical farming conditions and how long the residual P benefit from organic acid-secreting crops can persist in the field. Limited work to date has shown that organic acid secretion and P uptake by chickpea and lupin was variable across a range of low P soils from WA, secretion being higher in low P-sorbing soils (Veneklaas *et al.* 2003). In another study and contrary to expectation, faba bean and chickpea grown in other low P soils from WA were not found to mobilise P from sparingly-soluble soil pools, pointing to a need for a better understanding of how and when these crops gain access to sparingly-available P (Rose *et al.* 2010).

(5) Pasture plants with low P-requirements
Phosphorus-efficient plants are required for two sorts of grassland farming system:
(a) low P-input systems in marginal or low rainfall environments (e.g. low-rainfall farming, Western Australia, Pang et al. 2010a; extensive grazing systems of northern Australia, McIvor and Probert review Appendix 3) where plants need to be as productive as possible given that soil will be maintained in a relatively low P-fertility condition because other constraints limit the production system as a whole.
(b) fertilised systems in well-watered environments, where productive plants with low critical-P requirements could contribute to improved P-balance efficiency without compromising productivity per hectare.

The agronomic potential of Australian native herbaceous legumes has been examined in recent years in an effort to harness their natural adaptation to low P environments prone to drought stress (Ryan *et al.* 2008; Dear and Ewing 2008; Ryan *et al.* 2009; Bennett *et al.* 2010; Bell *et al.* 2010). This work has shown that native species have few consistent advantages and there is no justification for focusing solely on native plants despite their adaptation to low P soils. Some exotics and some natives grew well in low P conditions. When soil P was very low, P uptake was typically correlated with root surface area and total root length. Plant growth under low-P conditions was also correlated with physiological P-use efficiency (plant DW/ plant P content).

Table 6. Species recognised for reasonable productivity in low P soils and low rainfall environments

Species	Herbage type	Attribute(s)	Reference
Ptilotus polystachyus (Gaudich.) F. Muell.	short-lived native perennial herb	shoot weights greater than chicory (*Chicorium intybus* L.) in low P soil	Ryan et al. 2009
Kennedia prorepens F.Muell., *K. prostrata* R.Br. *Glycine canescens* F.J.Herm	Australian native legumes	good growth relative to lucerne in low P soil but does not tolerate high P soil	Pang et al. 2010a; 2010b
Lotononis bainesii R.Br.) *Bituminaria bituminosa* (L.) C.H.Stirt. var. *albo-marginata*	exotic legumes	good growth relative to lucerne in low P soil	Pang et al. 2010a; 2010b
Cullen australasicum (Schltdl.)	Australian native legume	relatively tolerant of dry conditions; presently being developed as pasture species for the low rainfall wheatbelt	Suriyagoda et al. 2010; Dear et al. 2007; Hayes et al. 2009
Lotus uliginosus Schkuhr		good tolerance of low P soil	Balocchi and Phillips 1997; Kelman 2006
Trifolium ambiguum M.Bieb	Caucasian clover	good tolerance of low P soil	Virgona and Dear 1996

Table 7. Studies of the intra- or interspecifc differences in the external P requirement of keystone legumes used in temperate and Mediterranean pastures.

Species	**Number of lines examined**	**Significant variation found**	**Notes**	**Source**
Intraspecific variation				
Trifolium subterraneum L.	10	Yes	Differences in response to P present even among lines of similar shoot weight but much of the data confounded with physiological stage of development. All cultivars outclassed.	Jones et al. 1970 (Agron J 62, 439-442)
	2	Yes	More efficient cultivar at low P also more prone to toxicity at high P suggesting difference in P uptake. Interaction with Zn levels; differences between cultivars not observed at excess Zn. Not confounded by size, maturity differences. Solution culture, outclassed cultivars	Millikan 1963 (Aust J Agric Res 14, 180-205)
Trifolium repens L.	7	Yes	Natural populations from high and low P soils. Populations from high P soils showed much larger decline in growth at low P. Differences were due to P uptake ability. Sand culture, deliberately harvested at approx. similar shoot size over a 17 day period. Probably indicative of variation present naturally in this species.	Snaydon and Bradshaw 1962 (J Expt Bot 13, 422-434)
	2	Yes	No difference in growth at low P but one cultivar was more responsive and had higher critical P. Low P soil in pots.	Scott 1976 (Proc NZ Grassl Assoc 38, 151-159
	26	No?	Ecotypes from NZ and Europe, some from field stands of cultivars. Only very small variation observed although slight suggestion that some may exist. Low P soil in pots.	Caradus et al. 1980 (NZ J Agric Res 23, 211-217)
	7	Yes	Available cultivars plus naturalised strains from low, medium and high P soils. Low P soil in pots.	Godwin and Blair 1991 (Aust J Agric Res 42, 531-540)
	11	Yes	European and NZ cultivars grown in low P soil in pots. Clear differences due to selection for high and low response to P.	Caradus et al. 1992 (Plant & Soil 146, 199-208)
	37	No	Field study on lines selected for differences in response to P in glasshouse. Concluded that selection for tolerance to low P should be conducted in field.	Caradus and Dunn 2000 (NZ J Agric Res 43, 63-69)
	2	No?	Two lines selected for long, fine roots or short, thick roots conducted in low P soil in pots. Claimed that long, fine root plants displayed higher efficiency of P use. Did grow more and take up more P but this was at higher P levels. Both lines similar at low P. Critical external P was higher for the long, fine root plants.	Crush et al. (2008) (NZ J Agric Res 51, 279-285)

Intraspecific variation (*continued*)

Trifolium ambiguum M. Bieb.	8	No	Soil and solution experiments. Complicated by big differences in size.	Spencer et al. 1980 (NZ J Agric Res 23, 457-475)
Trifolium hirtum All.	6	Yes	Differences claimed but confounded by plant size and physiological stage of development. Only small differences among vegetative plants of similar size.	Jones et al. 1970 (Agron J 62, 439-442)
Medicago truncatula Gaertn.	2	Yes?	Complicated by large difference in size. Soil in pots	Jones et al. 1970 (Agron J 62, 439-442)

Interspecific variation

T. subterraneum vs *T. hirtum* vs *T. cherleri*	1 cultivar of each species	No for vegetative growth. Yes at flowering.	*T. subterraneum* had lower requirement than other *Trifolium* species at flowering. Soil in pots.	Ozanne et al. 1969 (Aust J Agric Res 20,809-818)
T. subterraneum vs *T. glomeratum vs Ornithopus compressus*	1 line of each species	No	Complicated by large difference in size. Claimed that *T. subterranuem* and *O. compressus* more efficient than *T. glomeratum* but this seemed to be due to more growth overall. Difference in relative responsiveness or P requirement was not obvious.	Blair and Cordero 1978 (Plant & Soil 50, 387-398)
T. repens & *T. ambiguum* from low P soils	Mean of 8 lines of each species	Yes? in soil	Comparison in soil complicated by differences in size. There was a possible difference between species when compared at same size. Noted that *T. ambiguum* had much larger roots relative to shoots so likely to be able to scavenge P in field better than *T. repens*.	Spencer et al. (1980) (NZ J Agric Res 23, 457-75)
	1 cultivar of each species	Yes in solution	Compared at same shoot size. *T. ambiguum* had lower requirement.	
T. subterraneum, T. vesiculosum, M. polymorpha, M. intertexta, M. truncatula, Lotus pedunculatus, O. compressus, Vicia dasycarpa	1 cultivar of each species	Yes	Soil in pots. *O. compressus* had lowest requirement.	De Ruiter 1981 (NZ J Agric Res 24, 33-36)

T. subterraneum, T. incarnatum, T. hirtum, M. hispida, 3 *Trifolium sp.* native to California, *Lotus purshianus*	1	Yes	Soil in pots. Interaction of response with temperature.	McKell et al. 1982 (Agron J 54, 109-113)
T. repens vs *Stylosanthes hamata*	1 cultivar of each species	Yes?	Solution culture. Stylo extracted P better from low P concentration and grew slightly better but responses were rather similar otherwise	Chisolm and Blair 1988 (Aust J Agric Res 39, 807-816)
T. subterraneum vs *M. polymorpha* L. vs *Ornithopus compressus*	1 cultivar of *Ornithopus*, 2 of other species	Yes	Soil in pots. *O. compressus* had lowest external requirement and *M. polymorpha* the highest. Due to uptake differences. No intraspecies differences.	Paynter 1990 (Aust J Exp Agric 30, 507-514)
T. subterraneum, M. polymorpha, M. murex, O. compressus, O. perpusillus, O. pinnatus	1 cultivar of each species	Yes	Field experiments. Comparative requirements varied with harvest at last partly because the species had different maturity times. *Ornithopus* generally had lower P requirement. *M. polymorpha* may have required less P than *T. subterraneum* on neutral soils but not on acid soils.	Bolland and Paynter 1992 (Fertilizer Res 31, 21-33) Paynter 1990; 1992
T. subterraneum vs *M. polymorpha* L. vs *Ornithopus compressus*	2 cultivars of *M. polymorpha*, 1 of other species	Yes	Field experiments. *O. compressus* had lowest external requirement and *M. polymorpha* the highest although *M. polymorpha* and *T. subterraneum* similar for seed production.	Paynter 1992 (Aust J Exp Agric 32, 1077-1086)
T. subterraneum vs *T. michelianum* Savi *(var. balansae)*	1 cultivar of each species	No	Pots and field. Concluded that *T. michelianum* probably requires slightly more P.	Bolland 1993 (Aust J Exp Agric 33, 307-18)
M. truncatula, M. murex, M. polymorpha	3 cultivars of M. polymorpha, 1 cultivar of other species	Yes	Field experiment. Differences between species and within species that changed with time. Difference within *P. polymorpha* smallest by the last harvest.	Bolland 1997 (J Plant Nutr 20, 1029-1043)

Species recognised for reasonable productivity oln low P soils in low rainfall environments are described in Table 6.

Productive species with low critical-P requirements have also been identified for higher rainfall environments. Numerous pasture grasses fit this category of plants including most, if not all of the productive-volunteer and cultivated grasses used in temperate grasslands (e.g. Hill *et al.* 2005). Amongst the grasses are a few species with exceptionally low critical P requirements (e.g. ryegrass (*Lolium rigidum* Gaud.), silver grass (*Vulpia bromoides/myuros*): Hill et al. 2010), grasses noted for vigorous growth in acid, infertile soils (cocksfoot (*Dactylis glomerata* L.): Lolicato and Rumball 1994) and some native perennials with capacity to capture phosphate from less soluble sources (e.g. *Austrodanthonia* spp.: Barrett and Gifford (1999); *Austrostipa* spp.: Marschner et al. (2006)). Unfortunately, P-efficient grasses do not have any impact on the poor farm-gate P-balance of Australian temperate pasture systems. Grasses generally have low critical P requirements because they have fine-roots with long root hairs which explore soil efficiently, whilst subterranean clover (*Trifolium subterraneum*) and white clover (*T. repens*), the key legumes in these grasslands, have course roots and short root hairs and are the least P-efficient species (Hill et al. 2006; Ozanne *et al.* 1969; 1976; Haynes 1980). Clover-based pastures are fertilised with phosphate to meet the requirements of the clover because it is the source of biologically-fixed N and this drives overall productivity. The grasses in these systems experience luxury P-fertility conditions. To improve the P-balance efficiency of clover-based pasture systems, it will be necessary to shift the legume component to a lower critical-P position.

There are few reliable studies of the variation in P-use efficiency of the keystone legume species used in temperate pastures (Table 7). Although, intraspecific variation has, in some cases, been claimed to be as large as interspecific differences (e.g. Curll 1983; Gartrell and Bolland 1987), close examination of the evidence does not support these claims. In short, there has been insufficient investigation of most species and the work that is reported for some species involves cultivars that are now outclassed. However, there are examples of differences in the external P requirements of some of the keystone legumes (Table 7); enough to indicate that further investigation would be warranted. In addition, yield improvement for some legumes (e.g. subterranean clover) has been impressive (e.g. Sandral et al.1998; Nichols et al. 2007) and this alone means that gains in P-use efficiency are being made. The fact remains that there are no *Trifolium* or *Medicago* spp. cultivars that are recommended on the basis of improved P-use efficiency. The most consistent effort has been applied to improving the P-efficiency of white clover (*T. repens* L.: Caradus 1994) but results to date have been disappointing. P-efficiency, measured as response to a given level of applied P, was shown to be heritable under glasshouse conditions (Caradus *et al.* 1992). However, differences in response under field conditions proved to be minimal (Caradus and Dunn 2000).

Currently, the only substantive attempt being made to improve the P-use efficiency of the keystone temperate legume species is further work with white clover where the emphasis is on selection for root traits such as long, fine root systems that are likely to influence P uptake from soil (Crush et al. 2008). In Australia, where agricultural productivity is highly dependent on use of P-fertiliser and a limited number of key pasture legume species, it is remarkable that there is not a continuing effort to examine the potential for improving P-use efficiency. Subterranean clover (*Trifolium subterraneum*), is currently the focus of a large research project which aims to produce a QTL map for six important traits in two populations and a core collection (Ghamkhar et al. 2009). Recombinant Inbred Line (RIL) populations are also being developed. This provides an invaluable resource for efforts to improve P-efficiency traits. Root traits have not been examined to date, but promising preliminary results have been reported in a similar exercise with white clover (*T. repens*) (Jahufer et al. 2008).

Adoption of some alternative legumes to the commonly-used *Trifolium* and *Medicago* species appears to also hold some promise for developing more P-efficient pasture systems. The critical P requirement of yellow serradella (*Ornithopus compressus* L.) was most often ~55%-65% of that required by subterranean clover (*T. subterraneum* L.) in field experiments in Western Australia (Paynter 1990; Bolland and Paynter 1992; Paynter 1992). Subterranean clover, in turn, had a lower critical requirement than burr medic (*M. polymorpha* L.var. *brevispina*). The lower critical P requirement of serradella is attributed to it having longer, finer roots (Paynter 1990; 1992). Serradella is recommended primarily for acid, infertile sandy soils in WA (Anon. 2007) and NSW (Zurbo 2006). However, the same rates of P application are still recommended for serradella and subterranean clover despite the higher P-efficiency of serradella (Paynter and Bolland 2006).

Many other new legume species have been released as cultivars in the last 15 years in response to the need for attributes such as adaptation to difficult soils and other niche environments, higher levels of hardseededness, deeper root systems, length of growing season and ease of seed production (Nichols et al. 2007). A number of these may potentially offer higher P-use efficiency. For example, *Biserrula pelecinus* L., a deep-rooted species also adapted to acid sandy soils, is claimed to have higher P-efficiency than subterranean clover and burr medic (Howieson et al. 2000). However, it is clear that for the benefits of lower P-use efficiency to be realised, it is necessary to evaluate the P requirements of new legumes under field conditions and to release them with revised guidelines for soil fertility management. More commonly the P-requirements of new species are ill-defined and there has been no demonstration that farming systems (grass-legume pasture, ley farming, etc.) can be highly productive at lower soil P fertility levels when P-efficient legumes are used.

(6) Plants with low P-requirements for cropping systems
As is the case for pasture species, there have been numerous comparisons of the P-use efficiency of key crop species (Simpson et al. Appendix 5) and many claims of significant differences in P-use efficiency. Intraspecific variation in the P-use efficiency of major crops is important because the option of using an alternative species will in many cases not be realistic. With the possible exception of the white lupin (*Lupinus albus*), however, few if any crops or crop varieties are promoted as low-P plants.

It has been reasonably well established that there are significant differences in the critical P requirements of some of the mainstream crop varieties used in temperate cropping rotations. For example, comparisons of wheat (*Triticum aestivum* L.), narrow-leaf lupin (*L. angustifolius* L.), canola (*Brassica napus* L.) and the pasture legume, subterranean clover (*T. subterranean* L.) indicate that the critical P-requirements of the narrow leaf lupin are marginally (10%; Bolland and Brennan 2001;) or considerably greater (70%+; Ozanne et al, 1976; Bolland 1992) than the critical requirements of wheat or subterranean clover (Ozanne et al. 1976), which are, in turn, 25-60% greater than the critical requirement of canola (Bolland 1997; Brennan and Bolland 2001; Brennan and Bolland 2009). The rankings are very consistent and indicate that better (targeted) management of soil P-fertility should be possible across cropping rotations than is practiced currently. However, occasionally experimental results indicate wide fluctuations in the critical P requirements of crops (Bolland 1992) suggesting that factors such as root diseases may alter P-requirements and may need to be considered when developing management guidelines.

3.3.4 Fertiliser technology and strategies [f]

Evaluation of the efficiency of P fertilisers using isotopic techniques under field conditions has been carried out in Australia mostly on alkaline cropping soils, and has not been adequately studied on other soil or farming system types. Two studies in alkaline soils using isotope techniques have reported that P uptake in the year of application is less than 12% of the P applied, with most of P uptake coming from residual P (presumably from previous fertilisers applications assuming low concentrations of available geogenic P (McLaughlin *et al.* 1988a; Dorahy *et al.* 2008). This means that nearly 90% of added P enters phosphate or organic-P cycles where it is exposed to reactions that slowly result in it becoming sparingly-available to plants. Many of the strategies to improve the efficiency of fertiliser P are, therefore, aimed at increasing the proportion of P that is taken up by plants in the year of application.

Why is the P-recovery efficiency of added P so low in the year of application? P-recovery efficiency is affected by the volume of soil to which the fertiliser is applied (i.e. as shown by the difference in effectiveness of banded vs broadcast fertiliser), poor root interception and uptake of P in bands, soil reactions which reduce P availability, and variable soil moisture in the field. Under glasshouse conditions where P is uniformly mixed with soil, and soil moisture conditions and root exploration are optimised, P-uptake determined by the direct method can be up to 60-70% in Australian soils (Bertrand *et al.* 2006).

Placement to improve P-recovery efficiency

Since P moves primarily to the root zone through diffusion and the P diffusion coefficients are very small in soil (10^{-12} to $10^{-15}/m^2/s$; Marschner 1995), a readily available supply of P in soil near the root zone is necessary to optimise plant uptake, especially during the most active growth period. Therefore, banding of P fertiliser near the root zone is the best placement option for most cropping systems (Mitchell 1957). Banding will improve P-recovery efficiency where sorption reactions dominate, but where precipitation reactions are dominant, banding may actually reduce P-recovery efficiency. For pasture systems, broadcasting has been the predominant fertiliser placement method due to cost considerations, although subsurface placement has shown potential to increase P-recovery efficiency (Scott 1973), likely through interactions with soil water (see below).

Soil water plays a significant role in P-recovery efficiency through the interaction with soil chemical reactions, and the diffusion of P to the rhizosphere. Dry conditions may exacerbate P precipitation reactions with the solid phase in fertiliser bands by increasing the concentration of P around the point of application. When water is inadequate, P diffusion is also reduced due to reduced water-filled porosity and increased tortuosity of water-filled pores. Therefore, the efficiency of P use in soils with adequate water is much higher than in dry soils and the placement of P (i.e. surface or subsurface) may be critical in determining P-recovery efficiency (Pinkerton and Simpson 1986; Cornish and Myers 1977; Scott 1973; Officer *et al.* 2009; Jarvis and Bolland 1991). In any cropping season, soil moisture appears to affect the availability of residual P in soil more than that of the applied fertiliser in that year (Bolland 1999; Officer *et al.* 2009).

Deep placement in the subsoil may also increase P-recovery efficiency on some soils. Research in both southern and northern Australia has shown that enormous yield increases are possible when fertilisers are applied to infertile subsoils (Graham and Ascher 1993; Singh *et al.* 2005). Graham and Ascher (1993) measured 3.6-fold yield increases when N, P and trace element fertilisers were mixed into the subsoil, compared with surface fertiliser application. Residual benefits from subsoil fertilisation were measured for seven years. Similarly large increases in

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[f] Information drawn primarily from the draft review by McLaughlin et al. (Appendix 4).

crop production were observed by Singh *et al.* (2005) in northern Australia. Unfortunately the difficulty of applying fertilisers to subsoils limits the use of this technology, but if effective subsoil fertilisers could be developed, large increases in crop production could be achieved in many soils.

Bypassing the soil

Due to the low P-recovery efficiency of P applied to soil, it is reasonable to expect that foliarly applied P might have a higher efficiency. In general, P uptake by leaves is either via cuticular pores or via the stomata. The dissociated species $H_2PO_4^{2-}$, which dominates at pH 2-3, is absorbed more readily than the undissociated form H_3PO_4 (Wittwer and Teubner 1959). However, the foliar application of acidic solutions may cause damage to leaf tissues. There no consensus in the literature on the agronomic and P-recovery efficiencies of foliar application of P; it has been reported to either increase, decrease, or have no effect on P uptake in comparison to soil-applied P (Noack et al. 2010). Absorption and translocation of P applied to the leaves is very rapid and this may translate into an early season P response but may not be sufficient to supply P need unless several foliar applications are performed throughout the growing season (Silberstein and Wittwer 1951).

Linking P supply to plant demand

For optimal yield of most crops, a readily available P pool above the critical value is required to meet the plant demand. Phosphorus demand differs for different crop species and even for different genotypes within species with most of the differences attributed to root architecture (Marschner 1995). Annual crops demand P earlier during their growth while perennial tree crops require P supply slowly over several seasons (Benzian, 1965; Johnson 1980; Rahmatullah *et al.* 2006). Therefore, for annual crops, fertilisers with high P solubility are essential in meeting the crops requirement. On the other hand, a slow release P fertiliser will be more suitable for slow growth perennial species. Furthermore, slow release P fertilisers can improve the P-balance efficiency of pastures growing in high-rainfall areas and/or on coarse-textured soils where dissolved P can be lost via leaching (Lewis *et al.* 1987; Yeates *et al.* 1984).

Fertiliser formulations to improve P-recovery efficiency

The scientific literature suggests that fertiliser effectiveness may be improved by technologies that either alter the pH around fertiliser granules (Owino-Gerroh and Gascho 2004), slow the release rate of P from fertiliser granules (Pauly *et al.* 2002) or increase P solubility (Babana and Antoun 2006; Holloway *et al* 2001; Rudresh 2005). The most applicable technology will depend on the source and speciation of the P source used and the main cause of poor P-recovery efficiency, which is soil dependent.

As soil pH has a major influence on the reactions that remove P from soil solution, methods have been developed to increase P solubility by modifying the pH around fertiliser granules. Elemental sulfur (S^0) and ammonium salts have been co-granulated with phosphates to reduce soil pH on neutral and alkaline soils. Silicate compounds have been used to increase soil pH on acidic soils and reduce P retention by Al and Fe oxides. These technologies are not new. Elemental S has been co-granulated with phosphate fertilisers since the late 1940's (Mitchell et al. 1952). A net release of protons results from the oxidation of S^0 into sulfate, which may reduce soil pH and increase P solubility. Mitchell et al. (1952) found that S^0 co-granulated with dicalcium phosphate and MAP significantly increased fertiliser P uptake by wheat in the glasshouse using non-sulfur responsive soils (Fig. 14). However, there was no improvement in P availability under field conditions (Mitchell et al. 1952). Since then, there have been a large number of dual P and S^0 fertilisers made available to farmers, such as SF45 (Incitec Pivot Ltd.), Super M (Hi-Fert Pty Ltd.), Super and Sulfur (Clarkson et al. 1989), MicroEssentials (The Mosaic Company) and Granulock (Incitec Pivot Ltd.). However, most published studies have focussed on the nutritional value of S in these products, rather than the effect of S on P solubility (Clarkson *et al* 1989;

McCaskill and Blair 1989; McLaughlin and Holford 1982). More recently, Evans and Price (2009) found that ground S^0 applied with ground phosphate rock increased Olsen-extractable P in five out of eleven soils compared with phosphate rock applied on its own. However, very high rates of S^0 (up to 400 kg/ha) were applied. The lowest rate of S^0 (100 kg/ha) significantly increased Olsen P on four soils and decreased Olsen P on one site. The average increase in Olsen P was only 0.9 mg P/kg with a S^0 application rate of 100 kg/ha.

On alkaline and neutral pH soils, P solubility can also be increased by co-application of ammonium salts. Rahmatullah *et al.* (2006) found that the application of ammonium-sulfate nitrate (ASN) with phosphate rock increased P concentrations in maize shoots, from 1.0 mg P/g to 2.1 mg P/g. However, even with ASN, P uptake was less than half of that achieved with single superphosphate due to the poor solubility of the rock phosphate. The authors concluded that ammonium application reduced soil pH, from pH 7.1 to pH 6.7, which improved P solubility. The authors did not state whether the soil was S responsive. It may also be possible to increase P solubility by co-granulating ammonium sulfate with phosphates; however, no studies were found in the literature that tested this hypothesis.

Silicon compounds have also been used to modify soil pH and reduce P retention in soils. Application of sodium silicate to an acidic sandy-clay soil reduced P sorption and increased P concentrations in maize shoots, from 0.55 mg/g to 0.91 mg/g (Owino-Gerroh and Gascho 2004). The authors concluded that P solubility was improved by an increase in soil pH and reduced precipitation with Al or Fe, rather than the substitution of silicates for phosphates on soil binding sites. Smyth and Sanchez (1980) also measured a reduction in P sorption to an acidic Oxisol following $CaSiO_3$ application and an associated small increase in soil pH. Duque and Samonte (1990) also claimed that $CaSiO_3$ increased P-recovery efficiency on an acidic clay soil. The effect was also associated with a small increase in soil pH, however statistics for fertiliser P-recovery were not provided in this study.

Fluid fertilisers

Recent studies have shown that fluid fertilisers can improve P-recovery efficiency on some soils in southern Australia. On calcareous soils granular P-fertilisers are very ineffective. Only slight yield responses to P were observed even at application rates as high as 100 kg P/ha (Holloway *et al.* 2001). Holloway et al. (2001) found fluid P fertilisers were up to 15 times more effective than granular sources at equivalent P application rates. Subsequently, Lombi et al. (2004) observed that fluid P sources significantly increased P diffusion and availability (measured by isotope dilution) in calcareous soils compared to granular sources (Fig. 15). By contrast, soluble calcium from the soil diffused into the granular fertilisers and precipitated phosphate as apatite-like minerals (Lombi et al. 2004; 2006). The increased diffusion measured with fluid P reduced P concentrations at the point of application, which in turn reduced P precipitation (Lombi et al. 2006). To date, however, improvements in agronomic and P-recovery efficiency from the use of fluid fertilisers have been limited to calcareous soils and some alkaline non-calcareous soils (McBeath et al. 2005).

Slow-release coatings

Slow release coatings may also increase P-recovery efficiency. Nyborg *et al.* (1998) simulated the effect of slow release P by making small periodic additions of P to soil. Compared to a large single addition of P, smaller periodic additions increased P uptake in barley by 12.2%, 25.8% and 19.4% when MAP, DAP and ammonium polyphosphate were applied, respectively. Subsequently, Pauly et al. (2002) coated MAP and DAP fertilisers with synthetic polymers to slow the rate of P release from the fertilisers. In barley, the slow release polymer significantly increased P uptake from MAP by 9.7% and 10% on the silty loam and sandy clay loam soil, respectively. However, the polymer did not increase the P uptake from DAP. Other studies have found no significant benefits from slow release coatings. Garcia et al. (1997) coated lignin and rosin onto DAP and triple superphosphate. The fertilisers were supplied to ryegrass grown on a highly calcareous soil. Phosphorus uptake from the DAP-treated soil was significantly higher than from TSP and the P-free control (Garcia et al. 1997). However, the coatings did not affect P uptake by ryegrass.

Sparingly-soluble P sources, such as magnesium ammonium phosphate and reactive rock phosphates, also have slow release characteristics. These compounds may be effective P fertilisers for slow growing perennial species where soluble salts are rapidly lost by leaching (Benzian, 1965; Johnson 1980). However, they may be relatively ineffective when supplied to annual crops that have a high P demand over a short time period (Rahmatullah et al. 2006).

Coatings claimed to reduce precipitation or "fixation" reactions

A review of the patent and scientific literature reveals that a number of products have been designed to either enhance the efficiency of applied P or unlock P already retained in the soil. Two recent technologies that appear in the patent literature, but not the scientific literature, include the use of polymers to complex cations that might otherwise precipitate P following application to soil (e.g. US 6,515,090) and the use of silicon based compounds to reduce P fixation (e.g. WO 2005/097947). The use of silicates is also mentioned in the scientific literature but the mechanism attributed to the silicate effect is different (Owino-Gerroh and Gascho 2004).

Fertiliser technologies intended to increase the availability of accumulated P reserves in soil

To this point we have addressed reactions of added P to soil systems, their form and strategies to increase the availability of those additions to plants in the short term. Here we address strategies to increase the availability, through fertiliser design, of added P after it has transformed to more recalcitrant soil P forms (inorganic and/or organic). More commonly fertiliser design strategies focus on placing P in an available form in the soil and limiting the rate at which it reacts with soil constituents.

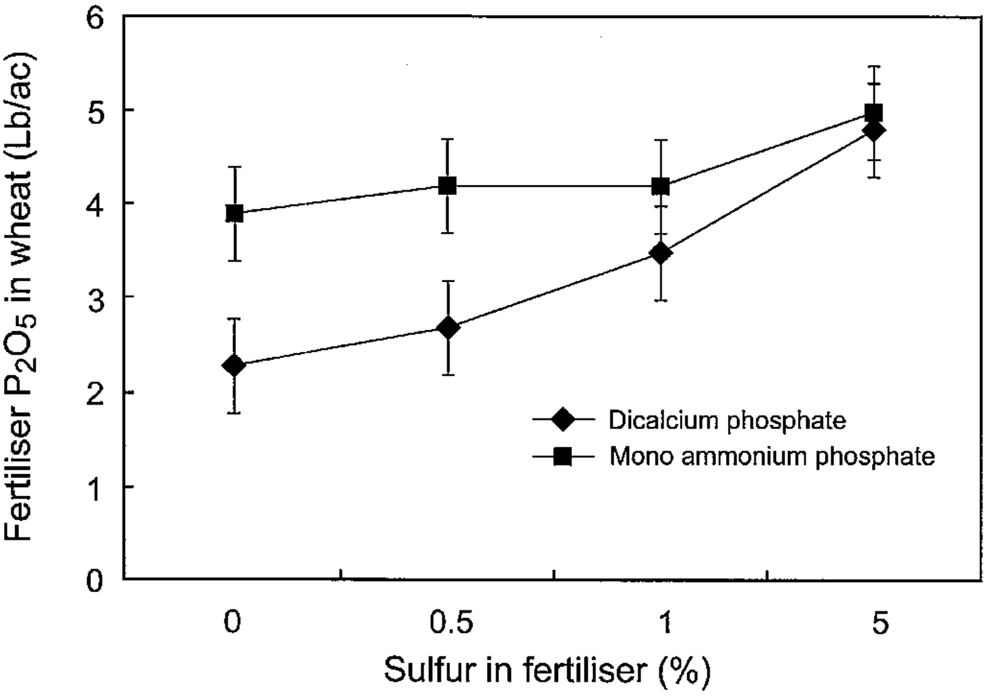


Figure 14. Effect of elemental S on phosphate uptake by wheat (adapted from Mitchell et al. 1952).

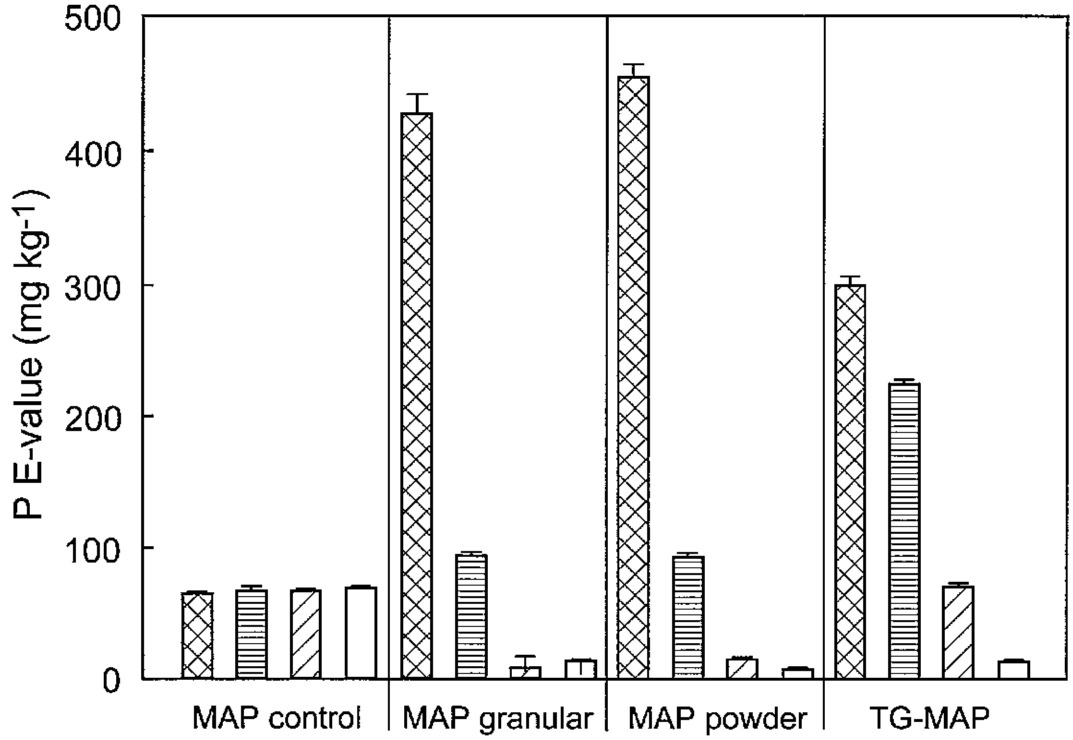


Figure 15. Diffusion of labile P from granular MAP and fluid MAP (TG-MAP) away from the point of application on a grey calcareous soil (redrawn from Lombi *et al.* 2004). Total available P from fluid MAP was significantly greater than granular MAP ($P \leq 0.05$).

A comprehensive literature search revealed very little mainstream research effort has addressed application of products to increase the availability of existing recalcitrant P sources. However, internet (Google^{TM}) searching of this topic reveals enormous amounts of literature referring to products claiming to do just that. Unfortunately, the quality and intent of the majority of this literature is aimed at sales of the products. Some products and claims raise questions regarding potential mechanisms by which the availability of recalcitrant P sources might be increase but most of the information is speculative, unsupported by solid evidence.

What product marketers have correctly identified is that in terms of available P resources, more than half of P in soil exists in forms that are difficult to extract chemically (Cross and Schlesinger 1995). Consequently, products that target existing P sources rather than adding new P sources into the soil have considerable potential. Whilst acid extractable P reserves are most likely insoluble inorganic phosphorus compounds, it is less clear what proportion of the residual P pool in fractionation schemes is organic or inorganic. Certainly, the use of concentrated acids has been suggested to liberate P from the soil "bank" in calcareous soils (Ryan and Stroehlein 1979), but even then difficulty in handling and expense has prevented this from being a commercial reality.

It is clear that further research is needed to understand the nature of the residual P fractions in soils prior to investing considerable effort in developing strategies to mobilise or render this fraction "bio-available".

3.3.5 Plant and microbial strategies

There are three potential approaches by which plant and microbial strategies may be able to improve P-balance efficiency:

(i) strategies that slow the rate of P-accumulation into sparingly-available pools,
(ii) strategies that enhance the desorption or mobilisation from sparingly-available P,
(iii) plants that produce more dry matter per unit of P uptake.

In each case the efficiency with which fertiliser P is used when building soil fertility will also be improved by these strategies. Prospects and/or progress in development of plant or plant-microbial strategies to realise P-efficiency gains are now discussed. For progress to be made the adoption of any particular strategy must also consider ecological context of the farm system or soil environment in which it is to be employed.

There are numerous examples at various levels of system organisation that illustrate the importance of understanding the ecophysiological context of P nutrition for P-efficiency gains. Attempts to improve P-efficiency by breeding white clovers with longer root hairs proved ineffective because the root hair lengths achieved by breeding were not long enough to acquire more P than already provided by mycorrhiza (Carradus 1981). Traits such as root hairs and root exudates are potentially synergistic with root architectural traits, which locate root axes in soil domains with varying P availability and the interactions of some root traits can be very positive. P acquisition by *Arabidopsis thaliana* is the interaction of 4 distinct root hair traits whose combined effect on P acquisition is estimated to be 371% greater than their additive effects (Ma et al. 2001b). However, root architectural traits may also interact to alter the extent of inter-root competition, which is also an important component of overall root foraging efficiency (Ge et al., 2000; Rubio et al., 2003; Rubio et al., 2001; Walk et al., 2006). An important tradeoff associated with topsoil foraging in beans has been increased sensitivity to drought stress (less deep roots) (Ho et al., 2005). George et al. (2010) demonstrated that the P-efficiency of spring and winter barley cultivars was modified by tillage practices. Likewise it is logical to expect fertiliser placement strategies may interact with plant-efficiency traits. For example, it is unclear whether deep placement of fertiliser to avoid surface soil drying (section 3.3.4) would compliment, or counteract the P-efficiency benefits of plants developed with enhanced topsoil foraging roots (3.3.6). Finally, it is critical that plant improvement strategies be directed at keystone species. There is, for example, little point improving the P-efficiency of pasture grasses in clover-based pasture systems because it is the inefficiency of the clover that determines how much P is applied to the pasture (e.g. Hill et al. 2010).

3.3.6 Slowing the rate of P-accumulation into soil pools (traits conferring lower critical P requirements)

Topsoil foraging
Phosphorus bioavailability is typically greatest in the topsoil, so root traits that enhance topsoil foraging enhance phosphorus acquisition (Lynch and Brown, 2001). Substantial differences exist for Architectural traits that can enhance topsoil foraging within and among species inclduing: shallower growth angles of axial roots, enhanced adventitious rooting, and greater dispersion of lateral roots (Lynch, 2007).

Shallower root growth angle
In maize, bean, and soybean, shallower growth angles of axial roots (basal roots in legumes, seminal and crown roots in maize) result in greater topsoil foraging and thereby P acquisition. Variation in root growth angle among closely related genotypes is associated with up to 600% increase in P acquisition and 300% increase in yield in bean (Bonser et al., 1996; Liao et al.,

2001) (Fig. 16), and 100% increase in P acquisition in maize (Zhu et al. 2005a). Quantitative trait loci (QTL) controlling root growth angle in bean, co-segregate with yield under P stress in the field (Liao et al., 2004). Direct phenotypic selection for root growth angle has been successfully used breed P-efficient beans for low fertility soils of Africa and Latin America, and soybean breeding in China (Lynch, 2007).

Adventitious rooting
In many dicot crops, adventitious roots emerge from the subterranean portion of the hypocotyl and grow horizontally through the topsoil. Substantial genetic variation for adventitious rooting is present among bean genotypes, it is under strong genetic control (Ochoa et al., 2006) and is associated with growth and P acquisition in a low P soil in the tropics (Miller et al., 2003; Ochoa et al. 2006). The adventitious roots have greater specific root length, lower tissue construction cost, more aerenchyma, and less lateral branching than other axial roots (Miller et al. 2003). These traits are advantageous by reducing the metabolic costs of soil exploration (Lynch and Ho 2005). However, *SimRoot* modelling (Lynch et al. 1997) indicates that excessive adventitious rooting may be counterproductive for plant P acquisition by diverting carbohydrates from lateral branches of basal roots (Walk et al., 2006), thereby decreasing total soil exploration.

Lateral branching
Low phosphorus availability changes the distribution of growth among various root types. In bean and maize, growth of axial roots is maintained under low P, while initiation of lateral roots is reduced and lateral root density declines (Borch et al., 1999; Mollier and Pellerin, 1999). Maize genotypes with increased or sustained lateral rooting under P-deficiency had up to 100% greater P accumulation and relative growth rate than closely related genotypes with less lateral branching (Zhu and Lynch, 2004).

Root hairs
Root hairs are important for the acquisition of immobile nutrients such as phosphorus (Clarkson 1985; Jungk 2001; Peterson and Farquhar 1996; Gahoonia and Nielsen 1998). Genotypic variation in root hair length and density in maize and common bean is controlled by several major QTL (Yan et al. 2004; Zhu et al. 2005c), suggesting that this trait could be selected in crop breeding programs through marker aided selection as well as through direct phenotypic screening. Root hairs are particularly important for P acquisition in non-mycorrhizal plants, since mycorrhizal hyphae fulfil some of the same functions as root hairs. However, genotypic variation in root hair length and density is important for P acquisition regardless of the mycorrhizal status of the plant (Fig. 17; Miguel 2004). Root hairs are attractive targets for crop breeding programs because there is large genotypic variation, substantial effect of this variation on P acquisition, regardless of mycorrhizal status, relatively simple genetic control, and opportunities for direct phenotypic selection (Gahoonia and Nielsen 2004; Lynch 2007).

3.3.7 Arbuscular mycorrhizal symbioses

Arbuscular mycorrhizal (AM) symbioses infect many agricultural species (exceptions include Brassica spp, and Lupinus spp.), and are particularly prevalent in pastures. They have an important role in improving the P nutrition of some species (e.g. clovers) in low P soils. Research into AM symbioses has mainly focused on plants that have positive mycorrhizal growth response at low available soil P. For example, in pasture legumes with short root hairs and barley lacking root hairs, mycorrhizas compensate for the limitations associated with short or absent root hairs and substantially improve the ability of the plant to acquire P under low P conditions (Caradus 1981; Jakobsen et al. 2005). However, the P-uptake advantage diminishes with improving soil P nutrition and there is little advantage to be observed at soil fertility levels necessarily for near-maximum pasture growth rates (e.g. Hill et al. 2010). Fungal hyphae are known to extend further from roots than root-hairs (centimetres compared with millimetres) and the larger soil volume hat can be exploited by AM plants is speculated to enable greater P uptake via the mycorrhizal pathway. Despite this, plants with long root hairs and extensive finely-branched root systems tend to show little or no positive mycorrhizal growth response even in low-P soils (e.g. Schweiger et al. 1995), whereas plants selected for longer root hairs show improved root foraging and P-uptake capacity (Fig. 17; Miguel 2004; Gahoonia and Nielsen 2004). Because of the extent of external AMF hyphae and their relatively small diameter, it is not intuitively obvious why this should be the case. It may be relevant that non-mycorrhizal controls in experiments can have higher root hair frequency and length compared with the AM plants, and also change their root architecture (e.g. Kothari et al. 1990).

Positive mycorrhizal growth responses decrease with increasing plant-available soil P. At a given P level this effect varies greatly among plant genotypes (Baon et al. 1993 - barley cultivars; Hetrick et al. 1996 - wheat cultivars) and also AMF fungal genotypes (e.g. Thomson et al. 1986). Similarly, the proportion of root-length that is colonized also tends to decrease with increasing soil P. This is often taken to mean that the plant is suppressing the AM symbiosis, but colonization per plant does not necessarily decrease until soil P levels are very high (e.g. Thomson et al. 1986). Studies in southern Queensland have shown that crops grew poorly when AM fungal propagules were depleted by long fallow (Thompson 1987, 1991). However, AM symbioses have poor reputation as a means of improving crop growth because under high soil P AM fungi (AMF) provide little nutritional benefit to crops and may have "parasitic" effects that reduce yield. Consequently, it has been suggested that there may be benefits for production in having less AMF colonization either by selected crop rotations or targeted breeding (Ryan and Graham 2002; Ryan et al. 2005). However, supply of ^{32}P or ^{33}P to external hyphae of AMF has shown conclusively that, as with plants showing positive mycorrhizal growth responses, the mycorrhizal path for P uptake operates in wheat, barley and other plants with no or negative mycorrhizal growth responses and in such plants the direct (plant root) path for P uptake is suppressed (e.g. Li et al. 2006). This has also been demonstrated qualitatively with wheat in the field (Schweiger and Jakobsen 1999). Thus, lack of a positive mycorrhizal growth response may not mean that AMF are not involved in the P nutrition of a plant.

From an agronomic perspective, AM roots are the rule rather than the exception in those species that become infected. Root architecture is the scaffold for AMF colonization and although P nutrition can improved by altering root architecture and root-hair length and density (Lynch 2007), few opportunities exist presently to manipulate the symbiosis to enhance P uptake. It is not intuitively obvious why mycorrhiza on plants with long root hairs (which are expected to be able to exploit a larger volume of soil than plants without mycorrhiza) provide little if any P-uptake advantage in low-P soils (e.g. Schweiger et al. 1995). It is also unclear why P uptake by the direct and mycorrhizal paths for P-uptake are not additive, so giving a positive mycorrhizal growth response in every case.

3.3.8 Reducing the metabolic costs of soil exploration

Root metabolic costs are an important component of plant growth under low P availability (Lynch and Ho, 2005). Variation for root costs is associated with P acquisition among closely related genotypes of maize and bean (Lynch and St.Clair 2004; Nielsen et al. 2001; Nielsen et al. 1998; Zhu and Lynch 2004; Zhu et al. 2005b; Zhu et al. 2009). Various root traits alter the relationship of root growth and cost:

(i) Root architecture alters the carbon cost of soil exploration by regulating the extent of root competition within and among root systems (Ge et al., 2000; Rubio et al., 2003; Rubio et al., 2001).

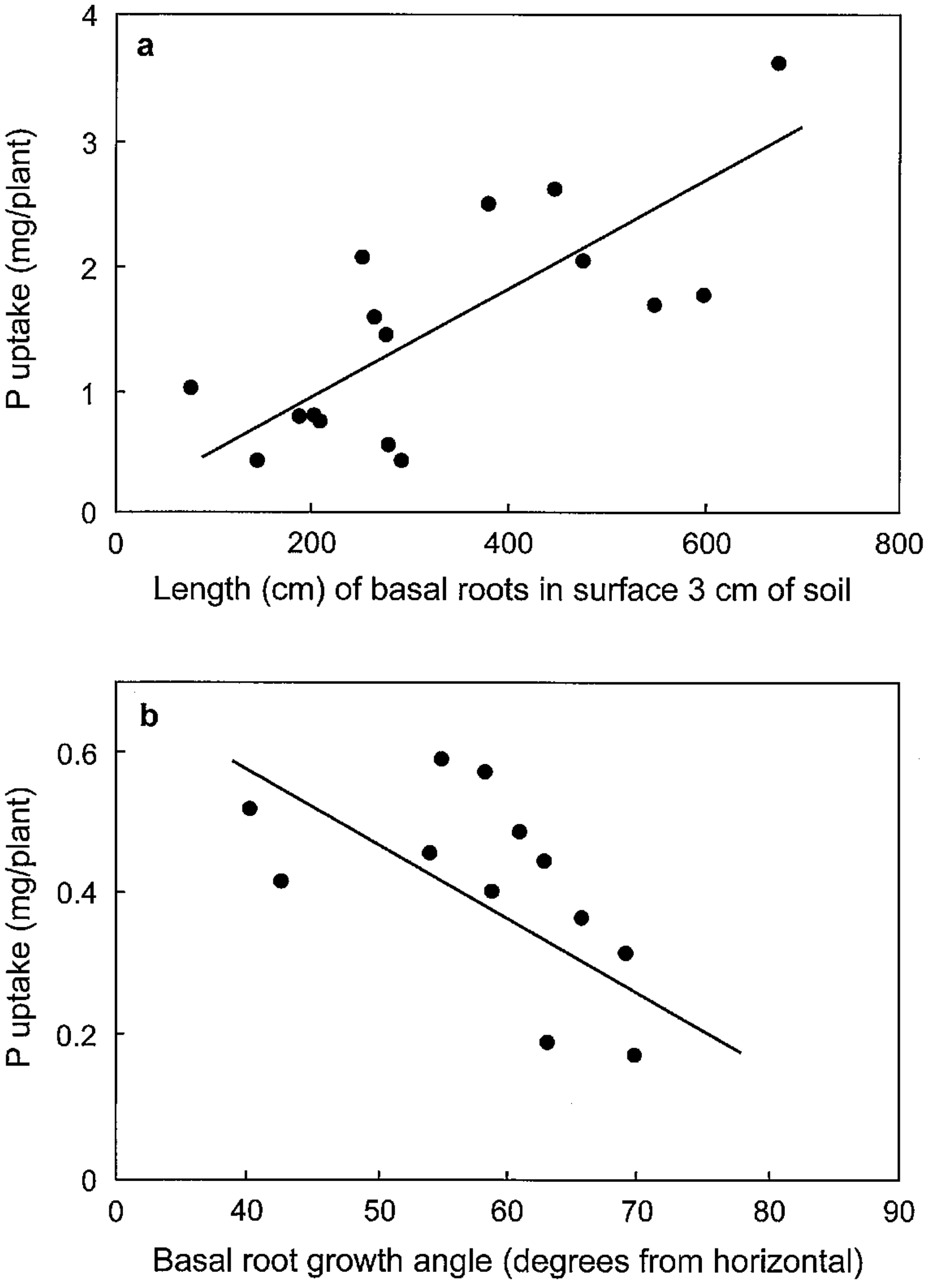
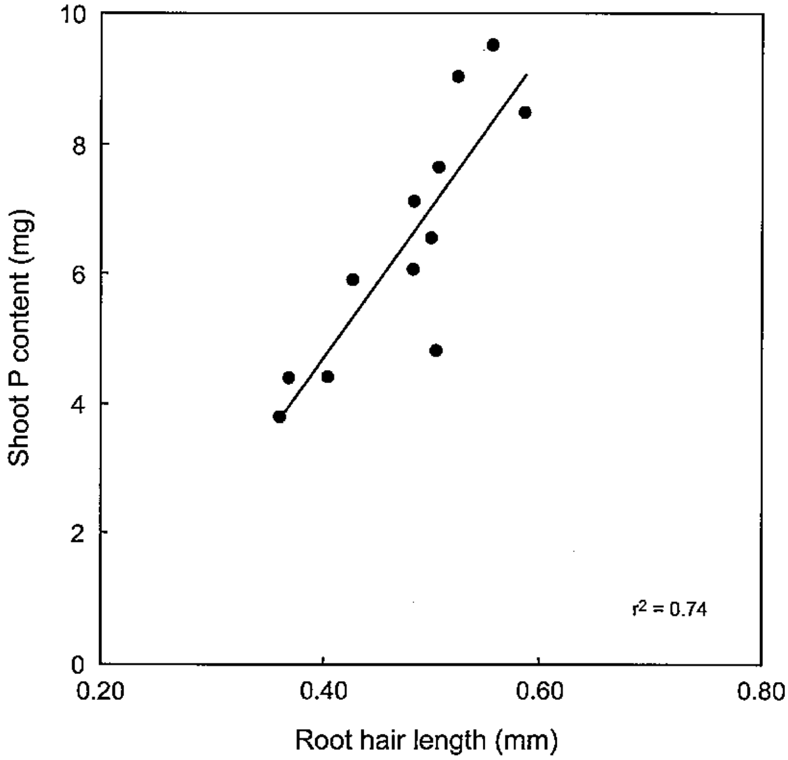


Figure 16. Relationship between root shallowness and (2a) phosphorus uptake and (2b) relative yield of contrasting genotypes of common bean growing in low-P soil. (From Bonser et al 1996 and Liao et al 2001).

Figure 17. Effect of root hair length on phosphorus content of common bean genotypes. Plants were grown for 35 days in low-P soil in the field in Costa Rica. Each point is the mean of 4 replicates of one genotype; the set of genotypes are six recombinant inbred lines having long or short root hairs. Miguel and Lynch, unpublished.



(ii) Biomass allocation to root classes that are less metabolically demanding per unit of P acquisition, notably adventitious roots, reduce overall root system cost (Miller et al. 2003).

(iii) Morphological traits such as root hairs enhance P acquisition at minimal root carbon cost (Bates and Lynch, 2000a; Bates and Lynch, 2000b; Ma et al. 2001a).

(iv) Anatomical traits such as root cortical aerenchyma and delayed root etiolation (reduced secondary development and expansion in favour of root elongation) are associated with P acquisition in low P soil by roots with low metabolic costs. Aerenchyma formation in maize is strongly related to root P content and lower respiration and root growth maintenance in low P soil (Fan et al. 2003).

3.3.9 Enhancing the desorption or mobilisation of P from sparingly-available pools in soil

'P-mining' by specialist root structures and carboxylate-secreting roots

In soils with extremely low available P, including many Australian soils under native vegetation, clustering of rootlets with abundant root hairs is a prominent root specialisation. Proteaceae and a number of phylogenetically unrelated species have proteoid (cluster) roots, while dauciform and capillaroid roots are found in Cyperaceae and Restionaceae respectively (Lambers *et al.* 2006). The concentration of rootlets in small soil volumes, rather than exploring larger soil volumes, is clearly not the optimal morphology for scavenging low concentrations of diffusely available P. Instead, the cluster root morphology is consistent with a mining strategy (Lambers *et al.* 2006). Species with cluster roots are particularly abundant on severely weathered soils where recycling of P from aboveground litter and belowground root turnover is virtually the only source of P, and on strongly P-sorbing soils that do have reasonable amounts of total P but where this is not available to plants that do not have a specialised mechanism to extract this resource (Lambers *et al.* 2006). Root clusters are positioned in soil horizons or patches that have above-average total P but low levels of plant-available P (e.g. Pate et al. 2001), are rich in organic matter, or are positioned under decomposing litter (Lamont 1973; Gaxiola and Veneklaas, unpublished). They mobilise unavailable P through alteration of soil chemistry. The mechanism involves root exudates including carboxylates, enzymes, phenolic acids and protons with carboxylate secretion usually regarded as a primary factor in the mobilisation of sparingly-available P.

While cluster roots, dauciform roots and capillaroid roots are most abundant in Proteaceae, Cyperaceae and Restionaceae on severely P-impoverished soils, their presence is not limited to these phylogenetic groups nor are they limited to extremely infertile soils (Skene 1998). *Lupinus albus* is an established crop species that has cluster roots indicating that the specialised root structures can be used in agricultural production systems. However, because increasing soil P availability reduces investment in cluster roots of all species to almost zero (Reddell *et al.* 1997; Shane *et al.* 2003a; Shane *et al.* 2003b; Shane *et al.* 2006 Abdolzadeh *et al.* 2010), the P-acquisition traits of these plants may not be expressed in all cropping situations. This will tend to reduce their effectiveness when being deployed to mobilise P for use by other crops or as part of a strategy to reduce the accumulation of sparingly-available P in fertilised soils.

Considerable plasticity in cluster root investment, placement and activity has been demonstrated in Australian perennial legumes (Adams *et al.* 2002) and in *L. albus* (Shu *et al.* 2007a, 2007b). Both studies exposed different parts of the root system to different levels of P, and showed that while overall investment in cluster roots is suppressed when more P is available, cluster roots preferentially grow in the P-enriched parts of the soil, even when enriched with inorganic P. Moreover, rhizosphere carboxylate concentrations were enhanced when the added P was iron phosphate or hydroxyapatite (Shu *et al.* 2007a, 2007b). Split root experiments indicate that the response of cluster root species to locally-enhanced P can also differ markedly. When one side of the root system experienced higher P concentration in hydroponics, *Hakea prostrata* and *H. trifurcata* produced less cluster root mass on that side than on the low P side. In contrast, *Lupinus albus*, *L. mutabilis* and *Grevillea crithmifolia* produced more cluster root mass on the high P side (Shane and Lambers 2005). The adaptive deployment of the cluster roots leads us to conclude that it may be feasible to encourage more efficient P acquisition in agriculture by using cluster root species in combination with banded fertiliser placement where the concentrated fertiliser bands allow adequate fertility for high production but also a patchy distribution of P suitable for expression of the P-mining attributes of cluster roots.

Alteration of rhizosphere chemistry is not limited to species with root clusters. In the *Lupinus* genus, species that do not form cluster roots have similar rhizosphere pH and carboxylate concentrations to those that do (Pearse *et al.* 2006). High rhizosphere carboxylate concentrations have also been reported in other grain legume crops such as pigeon pea *Cajanus cajan*, chickpea *Cicier arietinum* and field pea *Pisum sativum* (Ae *et al.* 1991; Veneklaas *et al.* 2003; Nuruzzaman *et al.* 2005a; 2005b; Pearse *et al.* 2006), as well as a range of Australian and exotic herbaceous perennial legume species (Pang *et al.* 2010a). In many species, exudate concentrations are responsive to plant P status and are reduced at higher levels of soil P fertility. In some species, exudation appears to be constitutive, sometimes at high rates (e.g. chickpea, Wouterlood *et al.* 2005).

There is good evidence that cluster roots enable plants to access soil P pools that are not available to species that do not have this mechanism (e.g. Hocking *et al.* 1997). It is less clear if exudation of carboxylates from plants that do not have the cluster root morphology also increases their access to sparingly-availble P. For example, Pearse et al (2007) found that wheat took up more P from $AlPO_4$ than three lupin species. So it should be remembered that even though diffuse fine root systems may not be effective in mobilising poorly-soluble P, there will always be small amounts of P in solution and these may be scavenged by such roots. It was also noted that field pea and chickpea were unable to access $AlPO_4$ or $FePO_4$ in sand culture despite releasing carboxylates into the rhizosphere (Pearse *et al.* 2007). However in a separate study, P uptake by chickpea from 11 different soils did correlate with rhizosphere carboxylate concentrations (Veneklaas *et al.* 2003).

Can the release of organic anions from roots alone mobilise soil phosphorus ?
Carboxylate exudation from roots has been embraced widely as a likely mechanism for improving the access to sparingly-available P by agricultural crops. The observations of P nutrition in species that naturally secrete carboxylates indicate that that the process(es) by which these plants extract sparingly-available P, regulate cluster root formation and release carboxylates is reasonably complex. This raises the question: can enhanced carboxylate release from roots of agricultural species deliver the promise of improved P-use efficiency in agricultural systems by mobilising fixed pools of Pi into the soil solution? It is thought that organic anions may occupy sorption sites on soil minerals that might otherwise bind Pi, and can replace Pi in the sparingly-soluble complexes that form with aluminium, iron and calcium.

In addition to the observations of cluster-root forming species, the idea is based on many studies reporting: (i) the release of citrate, malate and oxalate from roots of certain species increases with the onset of P deficiency (Jones 1998; Vance *et al.*, 2003; Ryan *et al.*, 2001; Neumann and Martinoia 2002) and (ii) organic anion treatment of soil can liberate more Pi into soil solution than similar treatments with water (Fox *et al.*, 1990; Gerke 1992; Jones 1998; Khademi *et al.*, 2010).

Organic anion efflux from roots has now been reported in many different species in response to P deficiency and Al toxicity. Although comparing anion release between different species is difficult due to the range of units employed the highest rates appear to occur in white lupin and members of the Proteaceae which show ~3 μmol g^{-1}FW h^{-1} for citrate efflux (Roelofs *et al.*, 2001). Despite an extensive literature implicating root exudates in P mobilisation, the evidence that organic anions perform any of these interactions sufficiently to impact plant nutrition is modest.

Precautionary comments: Support for this hypothesis typically comes from studies that compare genotypes grown in hydroponics, artificial media, or occasionally P-deficient soils and associate physiological differences with their growth responses. When some better performing plants release more citrate efflux than the others this is offered as an explanation for their improved performance in P-limited conditions. These studies usually do not consider whether the magnitude of efflux is sufficient to influence Pi availability and nor do they explore whether other plant responses occurring in parallel also contribute to nutrient efficiency. Even the seminal studies on white lupin (*Lupinus albus*), the species upon which the hypothesis was largely based, provide indirect evidence for the hypothesis only. For example, while organic anion efflux from white lupin roots is among the highest recorded from any species it occurs concomitantly with other exudates including phosphatases, protons and secondary metabolites all of which have the potential to contribute to P nutrition as well (Neumann and Martinoia 2002; Lambers et al. 2006). Furthermore, all these compounds are released from specialised roots structures called cluster roots that develop in response to P deficiency (Dinkelaker *et al.*,1989; Neumann and Martinoia 2002). Dissecting the contribution of the organic anions in mobilising Pi in isolation from the other exudates and in isolation from the enormous increase in root surface area afforded by the cluster roots is a daunting task. Recent data suggests that organic anion efflux does not explain the variation in P efficiency among different landraces of white lupin (Pearse *et al.*, 2008). Therefore it may be misleading to conclude that organic anions are the main player conferring the remarkable P-efficiency in these and other species.

Evidence in favour of a role for organic anions: *In vitro* studies have demonstrated that the local injection of citrate and oxalate into the rhizosphere can mobilise Pi and increase Pi uptake by plants (Strom *et al.*, 2002; Khademi *et al.*, 2010). Furthermore the presence of these carboxylates can increase the diffusion coefficient of Pi in the soil solution by two or three orders of magnitude (Gerke 1994). Lastly a series of models generated on varying soil types and with different species support a role for organic anions in mobilising P bound by metal ions (Kirk 1999). While not compelling in themselves these results provide proof-of-principle that organic anions have the capacity to enhance Pi availability in soil. A key question is whether the magnitude of this response in natural systems is sufficient to impact plant nutrition, or indeed, whether plants can be bred or engineered to do so.

Soluble organic anion concentrations measured in a range of soil types are generally <50 µM. Their concentrations in the rhizosphere are usually greater than the bulk soil. Values of 5 to 50 µmol citrate g^{-1}soil around the cluster roots of white lupin (Dinkelaker *et al.*, 1989; Gerke 1992) likely correspond to soluble citrate concentrations of 1 to10 mM which are consistent with recent measurements using ceramic suction caps (Dessureault-Rompre *et al.*, 2007). These concentrations are substantial and likely to benefit plant nutrition because *in vitro* studies estimate >1 mM citrate or oxalate can mobilise Pi in some soils (Gerke 1994; Kirk 1999; Jones *et al.*,2003; Khademi *et al.*, 2010). What remains unclear is whether these localised increases in organic anion concentration affect a sufficiently large volume of soil to provide meaningful supply of Pi to the plant.

In principle, standard physiological methods of study should be able to answer to these questions. However, in practice, soil properties are difficult to measure accurately at the scale of the rhizosphere and spatial heterogeneity and uncertainties with soil chemistry further complicate interpretation. While soils rich Al- and Fe-(hydr)oxides and allophone generally have greater sorption capacity (Jones and Brassington 1998) the time constants that govern these reactions are unknown. Yet these constants determine the rate with which Pi and organic anions are removed and replaced from the soil solution. Sampling scale is also important because organic anions released from roots are unlikely to diffuse farther than a few millimetres, with most remaining much closer to the root surface. The exception appears to be white lupin where the high efflux increases organic anion concentrations >6 mm from the cluster roots (Dessureault-Rompre et al 2007). In any case soils sampled too far out from the root will underestimate the true concentration in the rhizosphere. Even careful measurement on soil closely adhering to the root might underestimate the local concentrations in microscopic water-filled spaces near the root surface by orders of magnitude (Jones *et al.*, 2003). Diffusion of organic anions in a soil is influenced by its bulk density, water content and ion-exchange capacity.

Other variables that will influence the efficacy of organic anions to mobilise soil P include their longevity in soil and the accompanying ion fluxes that balance anion release from root cells. Efflux of organic anions from cells must be accompanied by an equal efflux of cations or an equal influx of anions to satisfy electroneutrality. These counterions are important because they can influence the effectiveness of the ligand-exchange reactions. Citrate and malate efflux from white lupin is balanced, at least in part, by H^+ efflux because the rhizosphere around cluster roots becomes significantly more acidic than the bulk soil (Dinkelaker *et al.*, 1995; Yan *et al.*, 2002). Although pockets of low pH might assist in mobilising Pi, especially in alkaline soils, organic anions are unlikely to be as effective in very acidic environments because a greater proportion will carry smaller net charge. For instance, the pKa's of malic acid are 3.4 and 5.11 which means that at pH 3.4 approximately half the malate is present as malic acid and half as H:(malate)$^-$. Neither of these species will bind with Fe, Al or Ca ions as well as the divalent anion malate^{2-} which is more prevalent at higher pH. However acidification would suit the activity of acid phosphatases also released from these cluster roots (Zinn *et al.*, 2009) and perhaps retard the degradation of organic anions by microorganisms (see below: Khademi *et al.*, 2010). However, proton efflux is not the only ion movement helping to balance the charges. The efflux of a large range of organic anions from cluster roots of several members of the Proteaceae is not associated with acidification (Roelofs *et al.*, 2001). Even in white lupin there is evidence that K^+, Na^+ and even Mg^{2+} efflux help maintain electroneutrality (Zhu *et al.*, 2005d). Malate efflux from Al^{3+}-resistant wheat roots is accompanied by K^+ and not H^+ efflux, at least over the first few hours (Ryan *et al.*, 1995). In fact the pH around those root apices of wheat increases (Wherrett *et al.*, 2001) which would be expected as malate equilibrates in the apoplasm and a proportion of the divalent anions bind with protons to become monovalent anions. These fluxes are likely to show significant temporal variation as well.

The rhizosphere generally supports a larger microbial biomass than the bulk soil because organic anions and other root exudates represent a ready carbon source. The persistence of organic anions in soil depends to a large extent on size and vigour of these communities as well as the physical properties of the soil. *In vitro* estimates for the half-lives of organic anions varies from less than 0.5 h for malate in a Cambisol to more than 24 h for oxalate in a Podsol (Jones and Darrah 1994; Kirk 1999; Oburger *et al.*, 2009). Decomposition of organic anions can be slower on soils with high sorption capacity perhaps indicating that anions bound to mineral surfaces are less likely to be degraded by microorganisms (Oburger *et al.*, 2009).

Definitive evidence
Two approaches are likely to provide the best opportunity for quantifying the influence of organic anions on plant nutrition. They are:

(i) to exploit natural genotypic variation to generate populations that segregate for the trait of interest (eg. recombinant inbred lines, doubled haploid lines or F_3 families etc). Scoring individuals in these populations for organic anion efflux and P-efficiency enables the association between PUE and organic anion efflux to be assessed. Segregating populations can also be used to identify quantitative trait loci (QTL) by developing framework maps of molecular markers between the parental lines. This works best for traits controlled by relatively few genetic loci. An alternative method, and one with advantages over bi-parental populations, is association or disequilibrium mapping. This approach also requires a framework map of molecular markers but it allows traits to be finely mapped among a wide range of genotypes or ecotypes. These genetic approaches provide a means of assessing the relative contribution of individual traits independently of other characters that may be contributing to the same phenotype.

(ii) to use molecular genetics to engineer plants with novel traits that can be assessed in isolation from other factors. Success requires cDNAs from candidate genes, a suitable expression system and sufficiently strong phenotypes in the transgenic lines. Several groups have already attempted to engineer plants with greater organic anion efflux by over-expressing genes controlling organic anion synthesis or organic anion efflux.

Progress in the engineering plants for organic anion efflux
Attempts to genetically engineer enhanced organic anion efflux from plant roots can be broadly divided into strategies that aim to alter biosynthesis and those that focus on transport processes. For an organic anion to be secreted by roots requires a biosynthetic pathway with the capacity to generate and maintain sufficient amounts during periods of peak efflux. However, the organic anions considered to be effective in mobilising mineral P (citrate, malate and oxalate) exist as anions in the cytoplasm and do not readily move unassisted across the plasma membrane to the external medium. Transport of these organic anions is facilitated by specific transport proteins embedded in the membrane and in many cases it is the transport of organic anions and not their biosynthesis that appears to be the rate limiting step for their secretion. Nevertheless, in the absence of cloned genes for transport proteins the earliest attempts at enhancing organic anion efflux focussed on biosynthetic pathways for which many of the genes were readily available for genetic manipulation.

The most spectacular success claimed for modifying organic anion biosynthesis came from tobacco engineered to express a bacterial gene for citrate synthase. Originally designed to enhance citrate secretion as a means of conferring aluminium (Al^{3+}) resistance on acid soils (de la Fuente et al. 1997), the same plants genetically engineered to express a citrate synthase gene from *Psuedomonas aeruginosa* showed a greatly enhanced ability to mobilize soil P from an alkaline soil and, under restricted P nutrition, yielded more seed than a control (Lopez-Bucio et al. 2000). The transgenics had about 2.5 fold greater citrate synthase activity in roots than the control and this resulted in an over 4-fold increase in citrate efflux from roots. White powdery deposits were found on roots of transgenic plants grown on the alkaline soil and these were interpreted to be precipitated calcium citrate (Lopez-Bucio et al. 2000) reminiscent of similar deposits found around roots of white lupin (Dinkelaker et al. 1989). However, this interpretation is questionable in view of the relatively small amounts of citrate secreted by the tobacco when compared to white lupin. Reports showing that overexpression of citrate synthases of mitochondrial origin in Arabidopsis and carrot cell cultures conferred similar phenotypes and, although somewhat attenuated, appeared to support the notion that enhancing the biosynthesis of organic anions could increase the efflux of organic anions from roots to enhance P nutrition (Koyama et al. 1999; Koyama et al. 2000). The transgenic Arabidopsis plants with the greatest citrate synthase expression had larger rosettes and accumulated more P in their leaves compared to sibling null lines and the wild type parental line when grown with limiting P on an andosol (Koyama et al. 2000). The increase in citrate efflux was only two-fold and whether these effects can be attributed to enhanced dissolution of soil P by the citrate is not certain.

Subsequent attempts to repeat the findings with the citrate synthase genes from *P. aeruginosa* or a mitochondrial citrate synthase gene from tobacco were unsuccessful (Delhaize et al. 2000; Delhaize et al. 2003). Indeed, despite generating tobacco plants with 100-fold more citrate synthase protein than the original report by de la Fuente et al (1997) as well as using the same plants from that study, enhanced citrate efflux was not detected (Delhaize et al. 2000).

It is doubtful whether engineering plants with citrate synthase genes is a reliable strategy for enhancing organic anion efflux. Despite this, Knoop et al. (2003) reported that *Brassica napus* engineered to express a mitochondrial citrate synthase gene from Arabidopsis had enhanced Al^{3+} resistance (associated with increased citrate efflux). Citrate efflux was increased in the absence of Al^{3+}, however, efflux from both wild type and transgenics was increased 8 to 10 fold when roots were exposed to Al^{3+} so it is unlikely that the relatively small fluxes found in the absence Al^{3+} would have been beneficial for P nutrition. Overexpression of malate dehydrogenase but not phosphenolpyruvate carboxylase (PEPC) has also been claimed to enhance efflux of a range of organic anions from roots of lucerne (*Medicago sativum*) and the enhanced P nutrition of the transgenic plants when grown on acid soil was attributed to the greater efflux of organic anions (Tesfaye et al. 2001). However, organic anions were collected from roots under non-sterile conditions over 24 hours and it is likely that microbial degradation could have confounded the results. Enhanced Al^{3+} resistance (Tesfaye et al. 2001) and changes in microbial communities around roots of the transgenics grown in soil (Tesfaye et al. 2003) provided indirect evidence that organic anion efflux had been enhanced. If Al^{3+} resistance was enhanced then the effect on P nutrition was more likely to have been indirect due to more vigorous root growth in the acid soil. In contrast to lucerne, overexpression of PEPC in rice enhanced oxalate efflux from roots but the effect that this may have had on the P nutrition of plants grown in soil was not assessed (Begum et al. 2005).

The cloning of genes encoding proteins that transport organic anions provided an alternative means of enhancing efflux. These proteins belong to two distinct families of membrane proteins named the MATE and ALMT families (Delhaize et al. 2007, Ryan and Delhaize 2010). Initially all the cloned genes encoded transport proteins that were Al^{3+} activated and responsible for Al^{3+} resistance mechanisms. For instance, barley genetically engineered with the *TaALMT1* gene from wheat showed at least a 20-fold greater Al^{3+}-activated malate efflux than controls and this conferred greatly increased Al^{3+} resistance (Sasaki et al. 2004, Delhaize et al. 2004). When grown on an acid soil, the transgenic barley had improved P nutrition. This due mainly to improved root growth allowing better exploration of the soil (Delhaize et al. 2009).

Subsequently, genes encoding members of both the MATE and ALMT families were cloned that transported organic anions in the absence of Al^{3+} activation. When overexpressed ectopically, AtFRD3 from Arabidopsis (Durrett et al. 2007) and HvALMT1 from barley (Gruber 2009) confer organic anion efflux that is independent of Al^{3+}.but any effects on P nutrition have not been assessed (Durrett et al. 2007, Gruber 2009).

In summary, although there is evidence that altering organic anion biosynthesis can change internal concentrations of the major organic anions the resulting effects on efflux appear small and the impacts claimed for plant P nutrition are, to date, arguable. The more recent cloning of genes encoding transport proteins is a promising strategy for increasing organic anion efflux but whether efflux of organic anions from roots at levels required for improved P nutrition remains to be established. To achieve efflux of organic anions to levels approximating those found in white lupin may require that both transport and biosynthetic capacity be engineered in concert.

Phosphatases and utilisation of soil organic phosphorus by plants
Organic forms of P in soil constitute a significant component of total soil P (often about half) and contribute substantially to the overall operation of the soil P cycle. Cycling of P through organic pools is important in natural ecosystems, lowly-fertilized grasslands and well-fertilised systems. Substantial flows of P occur between inorganic and organic pools of soil P through immobilization and mineralization processes mediated largely by the activity of soil microorganisms (Richardson, 1994; Oberson and Joner 2005).

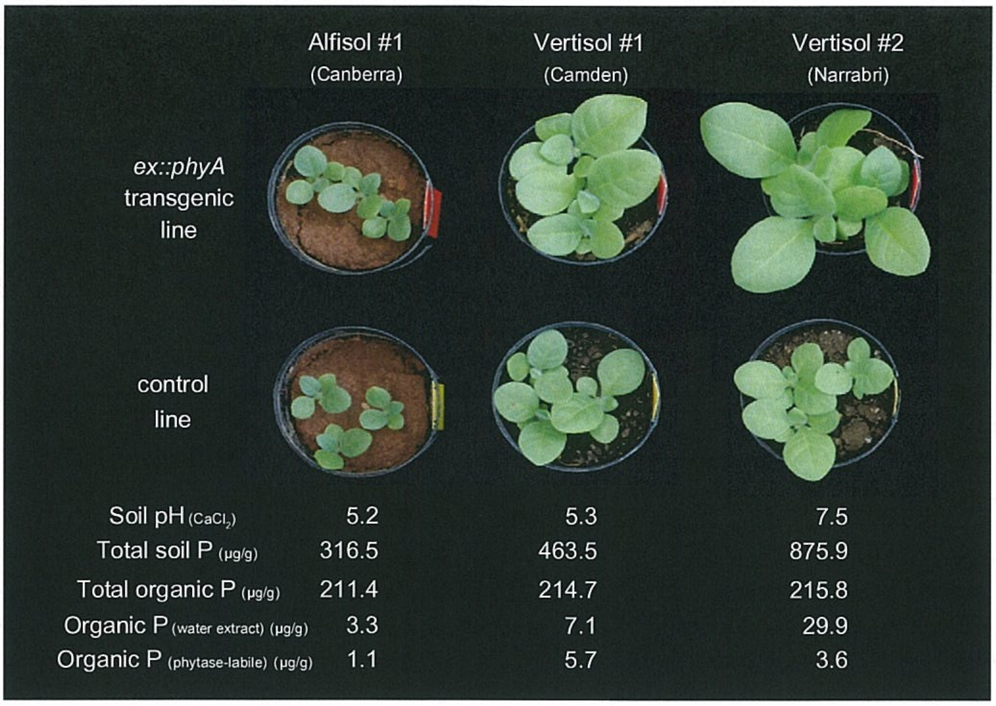
Mineralization of organic P occurs through the activity of phosphatase enzymes. Soils have demonstrable phosphatase activity and substantial increases in activity have been shown to occur in the rhizosphere of plants, with many studies showing this to be associated with a depletion of soil organic P (Asmar *et al.*, 1995; Gahoonia and Nielsen, 1992; Chen *et al.* 2002; George *et al.* 2002; Tarafdar and Jungk 1987). However, the relative contribution of different phosphatases, derived from either plant or microbial origin (including those from mycorrhizas), to this process is poorly understood along with knowledge of the chemical nature of the organic P substrates that are utilized. There is need to link studies of the identity of organic P forms in soil (e.g., through fractionation and extraction procedures, or by direct analysis of extracts using NMR) with work that aims to understand the biological availability of P pools and forms. Recent studies using *in vitro* assays with excess concentrations of different phosphatase enzymes indicate that, depending on soil type and fertilizer history, significant amounts of orthophosphate can be released from soil extracts/suspensions (George *et al.*, 2007; Bünemann, 2008). Greater understanding of the factors that limit such P release under field conditions and the role of specific phosphatases in mediating the hydrolysis of different sources of organic P in soil is needed.

From a 'P-use efficiency' perspective the challenge exists as to whether the utilization of organic P by plants can be managed or manipulated for agronomic gain. In the broadest sense, this will need to be able to be achieved through modifications to agronomic practice or by germplasm selection. For any strategy to be effective it will require either: a) an increase in the net rates of P cycling through organic pools so that more P from organic sources contributes to the annual or temporal requirements of crops and pastures; or b) increased mobilisation of specific forms of organic P that accumulate in soil and are poorly available (or unavailable) to plants and microorganisms. For example, mineralization of organic P is enhanced by cultivation (Condron *et al.*, 1990; Magid *et al.*, 1996) but this is only useful in systems where cultivation can be accommodated environmentally, economically and sustainably. It is also possible to increase the cycling of P and its net availability to plants by manipulating microbial processes (e.g. increased organic mater inputs, use of legumes in pastures, etc). However, these options must also be practical and provide a sufficient agronomic and economic gain to be useful. Underpinning any intervention to enhance the availability of p from organic sources, is the need to better understand the factors that contribute to the stabilization and turnover of soil organic matter pools in relation to the mineralization and subsequent availability of organic P to plants.

Organic forms of P may also accumulate in soil independently of soil organic matter. For example, the inositol phosphates (isomers and lower order derivatives of inositol hexakisphosphate), which constitute a significant component of the total organic P in soils (Turner 2002; Turner 2007), are readily adsorbed to soil particles and, depending on pH, react with cations (e.g., Fe and Al in acid soils, and Ca in alkaline soils) to form poorly soluble precipitates (Anderson *et al.*, 1974; Shang *et al.*, 1992; Celi and Barberis, 2005). Reactions of inositol phosphates in soil that lead to reduced availability as a substrate for phosphatases can, therefore, be analogous to the processes that lead to declining availability of phoshate for plants. Strategies to either 'intercept' the initial deposition or formation of inositol phosphates in soil or to mobilize P from accumulated pools of inositol phosphate in soil represents an alternative approach for improving P-use efficiency of plants (Richardson *et al.*, 2007). Plants generally have limited capability to access P directly from this source (Hayes *et al.*, 2000; Richardson *et al.*, 2001). This is attributable to various factors including, poor availability of substrate, low extracellular phosphatase (i.e., phytase) activity in roots and low efficacy of enzyme-substrate interactions (Richardson *et al.*, 2007). Moreover, in soil the availability of inositol phosphates to plants is influenced primarily by the presence and activity of soil microorganisms that possess phytase activity, and their interactions within the rhizosphere (Richardson *et al.*, 2001; Unno *et al.*, 2005).

Variation in phosphatase activity of plants and the potential for genetic improvement

It is recognized widely that extracellular phosphatase activities of plant roots varies considerably across different species and that significant within cultivar variation exists for a wide range of agricultural plants (e.g.., Tadano *et al*, 1993; Li *et al.*, 1997; Gilbert *et al.*, 1999; Hayes *et al.*, 1999). In most instances it has been shown that various phosphatase activities are also highly responsive to plant growth under P deficient conditions and are a key component of the plants general response to 'P starvation' (Richardson *et al.* 2005). Phosphatases are thus proposed to play a number of roles in improving plant P nutrition including; enhanced recycling of internal P, efficient capture of organic P compounds that may be lost from roots and to provide greater access to organic P substrates in soil (Barrett-Lennard *et al.*, 1993; Duff *et al.*, 1994). It is a common belief, therefore, that enhancement of phosphatase activity in roots may be an effective strategy for improving plant P-use efficiency. Despite this, there is little evidence to support this notion and there are few examples where selection (or genetic modification) of a species for enhanced phosphatase activity has been of clear benefit. For example, George *et al.*, (2008) reported significant variation in the activities of various intra- and extra-cellular phosphatases (measured against a range of model and actual organic P substrates) for different wheats, but this did not account for any differences in plant P nutrition when plant growth was assessed over a range of soils. Therefore any benefits in organic P utilization derived from root phosphatases were considered to be common to all genotypes. That is not to say that extracellular root phosphatases and enhanced activity in the rhizosphere do not play an important role in plant nutrition. The question is, whether or not the function of plant phosphates is already 'optimized' for utilization of soil organic P, is negated and/or complimented by the activities of soil



	Alfisol #1 (Canberra)	Vertisol #1 (Camden)	Vertisol #2 (Narrabri)
Soil pH $_{(CaCl_2)}$	5.2	5.3	7.5
Total soil P (µg/g)	316.5	463.5	875.9
Total organic P (µg/g)	211.4	214.7	215.8
Organic P (water extract) (µg/g)	3.3	7.1	29.9
Organic P (phytase-labile) (µg/g)	1.1	5.7	3.6

Figure 18. Growth of transgenic tobacco (*Nicotiana tobacum*) in three Australian soils that differ in phosphorus availability. Shown are transgenic tobacco plants (*ex::phyA*) that express constitutively a phytase gene from *Aspergillus niger* and release it from roots as an extracellular enzyme and a control transgenic line without phytase expression. Chemical characteristics of the soils (represented by an Alfisol and two Vertisols) from Canberra (ACT), Camden (NSW) and Narrabri (NSW) are shown as pH (1:5 w/v 0.1 M $CaCl_2$), total soil P and total organic P (as determined by the ignition-extraction [550°C; 0.5 M H_2SO_4]), organic P extractable in water (1:5 w/v) and the portion of water-extractable organic P that was amendable to hydrolysis by purified phytase. Source: George, Richardson, Simpson et al. (*unpublished*).

microorganisms (i.e., is functionally redundant), or is simply limited by the availability of substrate in soil (Tarafdar and Claassen, 1988).

Phosphate activities in the rhizosphere of some plant species (e.g., agro-forestry and *Pinus* spp., as reported by George *et al*., 2002; Chen *et al*. 2004, respectively) have however, been reported to confer a significant benefit to plant P nutrition when compared along side agricultural plants. Other species, such as chickpea, also appear to increase the mineralization of organic P in soil, and when intercropped with wheat or maize is reported to enhance plant P nutrition when grown under controlled conditions (Li *et al*., 2003; Li *et al*., 2004). Whether enhanced utilisation of organic P occurs as a direct consequence of root phosphatases, or as an indirect effect due to other factors, such as root growth or exudation of organic anions, remains unclear. Similarly it is unknown if these species are able to access forms of organic P that are otherwise unavailable to other plants. Indeed the capacity of white lupin to mobilize P in soil may be a consequence of a range of mechanisms that include the release of both phosphatases and organic anions (Gilbert *et al*., 1999; Weisskoph *et al*., 2006).

Genetic modification of plants to over-express phosphatase genes has been investigated as a potential means for improving the utilization of soil organic P with a specific focus on accessing P from inositol phosphates. Richardson *et al*., (2002) first showed that arabidopsis plants engineered for extracellular release of a microbial phytase showed enhanced P nutrition when supplied with inositol phosphates. A range of plants have subsequently been developed that over-express different sources of phytases and/or phosphatases (e.g., Lung *et al*., 2005; George *et al.*, 2004; Wasaki *et al.*, 2009; Ma *et al.*, 2009; Wang *et al.*, 2009). Collectively these studies have shown greater P nutrition for engineered plants (compared to control lines) when supplied with organic P sources, albeit generally under controlled growth conditions only and without limitations to substrate availability. In contrast, limited success has been observed when the plants have been evaluated in soils or in growth conditions where the availability of substrate is restricted irrespective of its total supply (George *et al.*, 2005a; George *et al.*, 2005b; Lung and Lim, 2006). George *et al.* (2005; 2007) showed that interactions between phytases and soil (e.g., deactivation of enzyme activities through either adsorption or degradation reactions) may further influence the efficacy of enzyme interactions with substrates. They also demonstrated that the efficacy in soil of different phytase enzymes differs markedly and success in enhancing phytase activity will depend on a well-informed choice of the enzyme isomer. Transgenic plants that release phytase from their roots have been shown to be effective in some soils, particularly those with relatively high water-extractable organic P (Fig. 18). Once adsorbed to soil mineral or clay constituents inositol phosphates cannot be easily hydrolysed (Giavano *et al.*, 2009). More detailed understanding of how such interactions might be manipulated to enhance the capacity for hydrolysis of inositol phosphates in soil or to increase the availability of organic P is needed. For example, organic anions have been shown to enhance the enzyme-lability of soil organic P, including inositol phosphates (Hayes *et al.*, 2000; Tang *et al.*, 2006), and further work to investigate their capacity to mobilize organic P and interact with phosphatases in soil environments is warranted.

Microbial inoculants

Rhizosphere microbial inoculants have been proposed as a promising component of intergrated nutrient management (Adesemoye and Kloepper 2009; Harvey *et al.* 2009; Khan *et al.* 2010) and there is a considerable history in their promotion and potential application to increase crop P-availability (Gerretsen 1948; Kucey *et al.* 1989; Bowen and Rovira 1999, Jakobsen *et al.* 2005). Inoculants and inoculant mixes intended to aid plant nutrition or stimulate root growth or both (excluding *Rhizobium* spp. for N-fixation by legumes) are also available for application to pastures (e.g. www.yladlivingsoils.com.au; www.microbials.com.au; www.ausmin.net.au; www.biofarmag.com.au). Strong claims are made for some of these products, some have unknown microbial composition, others are comprised of microorganisms known to have beneficial attributes, but there is little scientific literature that examines the efficacy of such inoculants in pastures. The symbiotic association between plant roots and arbuscular mycorrhizal fungi has long been recognised as an important plant-microbial association by which plants acquire P (Smith and Read 1997, Jakobsen *et al.* 2005) but the inability to readily culture AMF in artificial media and their establishment of host plant-specific associations limits their development as rhizosphere inoculants. From a practical point of view, it has been suggested that research should be directed at the introduction of free-living beneficial microbes that form non-specific associations with a range of plant hosts, can be mass-produced and have increased potential to persist in the environment (*e.g.* prolific sporulators; Bowen and Rovira 1999; Harvey *et al.* 2009; Khan *et al.* 2010).

Microorganisms play a fundamental role in the biogeochemical cycling of inorganic P in the rhizosphere and detritusphere (Whitelaw 2000; Jakobsen *et al.* 2005; Harvey *et al.* 2009; Khan *et al.* 2010) with 15 and 5 % of the total culturable bacterial and fungal communities respectively reported to have P-solubilising activity (Kucey *et al.* 1989; Bowen and Rovira 1999). Most research into the development of microbial inoculants to enhance P availability and root uptake has centred on soil microflora capable of solubilising inorganic P sources (Kucey *et al.* 1989; Whitelaw *et al.* 1999; Wakelin *et al.* 2004; Leggett *et al.*, 2007). Bacteria (most commonly *Bacillus* and *Pseudomonas*: Babu-Khan *et al.* 1995; Richardson and Hadobas 1997; Tye *et al* 2002; Taurian *et al.* 2010), actinomycetes (El-Tarabily *et al.* 2008) and fungi, (primarily *Penicillium* and *Aspergillus*: Kucey 1983; Wakelin et al 2004; Kucey *et al.* 1989; Whitelaw *et al.* 1999; Wakelin *et al.* 2004), have all been identified as being able to liberate phosphate from inorganic and organic substrates under laboratory conditions by releasing organic anions, protons, phytases and cation chelating compounds. However, the main effort to improve P availability using microbial inoculants has focused on P-solubilising fungi and in particular *Penicillium* species (Kucey, 1988; Whitelaw *et al.* 1999; Leggett *et al.* 2007; Wakelin *et al.* 2007b). *Penicillium* are considered as key functional components of P cycling in soils, generally attributable to the release of organic anions (*e.g.* gluconate, oxalate, citrate) that can directly dissolve P precipitates, or chelate P-precipitating cations with the concomitant release of P into solution (Cunningham and Kuiack 1992; Whitelaw *et al.* 1999). Whilst *Penicillium* are known to mineralise organic forms of P (Yadav and Tarafdar 2003), little is known of the relative importance of extracellular phosphatases in providing plant-available P compared with inorganic P-solubilisation. *Penicillium* species do not exhibit specific plant or soil associations, having been isolated from the rhizospheres of diverse agricultural and natural plants (Kucey 1983; Hocking *et al.* 1998; Wakelin *et al.* 2004; Babana and Antoun 2006), indicating potential to select and develop inoculants for a broad range of agro-ecological conditions.

P. bilaiae has been shown to solubilise P (Cunningham and Kuiack 1992; Takeda and Knight 2006) and improve plant P uptake (Kucey 1988; Chambers and Yeomans 1990) with inoculated wheat obtaining up to 18% of its P from sources unavailable to non-inoculated plants under glasshouse conditions (Asea *et al.* 1988). *P. bilaiae* does not produce any known toxic secondary metabolites (Savard *et al.* 1994) and is reported to stimulate production of root hairs (Gulden and Vessey 2000) and increase overall root growth (Vessey and Heisinger 2001). Inoculation with *P. bilaiae* has improved growth of many crop species including wheat (Kucey 1987; Kucey 1988; Anstis 2004), canola (Kucey and Leggett 1989) and grain (Kucey 1987, Gleddie 1993) and pasture legumes (Beckie *et al.* 1988, Rice *et al.* 2000) and a commercial inoculant product based on *P. bilaiae* (JumpStart^{TM}, Novozymes Biologicals Pty Ltd) has been used in North America for at least 15 years.

Strains of *Penicillium* capable of solubilising highly recalcitrant forms of inorganic P have been isolated from Australian cropping soils (*P. radicum*, Whitelaw *et al.* 1997; *P. bilaiae*, Wakelin *et al.* 2004). The strain with the greatest P-solubilisation efficacy (Wakelin *et al.* 2004) and plant-growth promotion (Wakelin *et al.* 2007b) was identified as a novel genotype of *P. bilaiae* (P.R. Harvey, unpublished). Although *P. radicum* was selected for its ability to solubilise inorganic P and improve plant growth (Whitelaw *et al.* 1997; Whitelaw *et al.* 1999), further studies showed that the P-solubilisation efficacy of the *P. radicum* inoculant was significantly lower than other *Penicillium* strains, including *P. bilaiae* (Wakelin *et al.* 2004). The major mechanism of plant-growth promotion by *P. radicum* may be related to production of plant growth hormones (Anstis 2004), compounds known to increase proliferation of fine root hairs and enhance a plants ability to capture available nutrients, whilst not increasing nutrient availability *per se*. Opportunities also exist to develop novel 'multifunctional' microbial strains as inoculants, such as P-solubilising and N-fixing strains of *Mesorhizobium mediterraneum* (Peix *et al.* 2001) and disease bio-control strains of *Trichoderma harzianum* with capacity to solubilise P (Altomare *et al.* 1999). Similarly, enhanced plant nutrition and growth may be achieved by using mixtures of PGP microbes. Positive synergistic responses have been observed when inoculating cereals (Kucey 1987; Babana and Antoun 2006) and legumes (Osorio and Habte 2001) with *Penicillium*-VA mycorrhizae and legumes with *Penicillium-Rhizobium* (Downey and van Kessel 1990; Rice 2000), the latter also being used in a commercial product (TagTeam^{TM}, Novozymes Biologicals Pty Ltd).

Although, positive responses to non-symbiotic inoculants are often observed in controlled (laboratory and glasshouse) environments, they are less consistently observed in field trials. The results obtained from some broadly-based field trials have been described as inconsistent, not significant, or 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 of introduced rhizosphere microbes 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). Improved efficacy and on-going successful adoption of rhizosphere inoculants to improve access to P will require rigorous ecological and genetic analysis of the interactions between the inoculants (*e.g. Penicillium, Pseudomonas*), soil-borne microbial communities with which they compete and their plant hosts, in both a spatial and temporal context. A thorough understanding of the rhizosphere ecology, genetic stability and mechanisms associated with enhancing P-availability in soils will assist selection and deployment of inoculants across phases of the cropping system, thereby improving field efficacy and ensuring greater consistency of performance.

The adoption of hierarchical molecular ecological approaches in microbiological research (Anderson and Cairney 2004) has significantly advanced our understanding of the impacts of environmental factors and management practices on the structure and function of soil microbial communities (Xu 2006; Edel-Hermann *et al.* 2008). Application of these methods provides opportunities to define the impacts of rhizosphere inoculants on specific root-microbe interactions critical for P cycling and plant growth and soil microbial communities in general. Application of molecular markers will enable an ecological understanding of their interactions with crop roots, other rhizosphere microbiota and the impacts of management practices on their survival. This will be essential for predicting field efficacy and manipulating inputs to maximise inoculant colonisation, survival and function, defining the most appropriate conditions to achieve consistent performance and adoption by industry.

The efficacy of P-solubilising or P-mineralising inoculants depends also on their competitive abilities in soil environments and their capacity to colonise, survive and multiply in the rhizosphere (Van Veen et al., 1997; Gyaneshwar et al. 2002). Extensive DNA sequence data bases have assisted with the development of DNA-based diagnostic tools and real-time quantitative assays (Q-PCR) for taxonomic groups of soil-borne bacteria (Costa et al. 2006) and fungi (Haugland *et al.* 2004, Sampson *et al.* 2004; Seifert *et al.* 2007) involved in enhancing P availability. Application of these techniques will enable studies of the rhizosphere competence (i.e. colonisation and survival) and population dynamics of inoculants at the genus or species level, but need to be refined to differentiate specific inoculants from related taxa present in natural soil communities.

3.3.10 Plants that produce more dry matter per unit of P uptake.

Plants with low internal P requirements (low plant P concentrations) for growth may potentially also provide gains in P use efficiency either because they can achieve similar yields by taking up less soil P or because for a given level of production/ha, less P will be exported. On face value this strategy is attractive, but there are a few counterintuitive observations that may indicate that the predicted gains in phosphorus efficiency may not be realised. In addition, reduced concentrations of P in plant tissues may impact of the downstream use of the plant material.

Low internal P concentrations are a commonly observed characteristic of plants adapted to low P soils and these species appear not to be seriously disadvantaged in that they often have high photosynthetic rates per unit leaf area and per unit of leaf P (Lambers et al. 2010). Indeed, Hill et al. (2005) observed that among pasture grasses, two native Australians species (*Austrodanthona richardsonii* and *Microlaena stipoides*) had internal critical P concentrations that were 30-45% less than a range of alternative introduced pasture grasses. However, across all of the grasses examined there was no relationship between the critical external P concentrations (a relative measure of the P-fertiliser requirements) and their critical internal P concentrations. This is not an uncommon observation and is considered to reflect the higher importance of root size, growth rate and morphology for soil exploration and P acquisition (Nye 1973, Silberbush and Barber 1983), at least at an interspecific level.

The other counterintuitive observation is that low farmgate P-balance efficiency is almost invariable associated with agricultural industries that export relatively low P amount in products (Fig. 6). This may reflect the fact that accumulations in soil in both Po and Pi forms dominate the P-balance of agricultural systems on soil with high P-sorption capacity.

With these provisos in mind it is nevertheless possible to make a case for modifying the concentrations of P in grains with the aim of reducing the P_{export} component of the farmgate P-balance (Equation 4).

P-efficient crops and crop systems
There is clear evidence for variation in the P-use efficiency of growth and in the efficiency of P acquisition in a variety of crops, under both glasshouse and field conditions. However, a number of studies indicate that ability to acquire P may be more important to high yields that P-efficiency *per se*.

A very large fraction of P in leaves of plants grown at a high P supply tends to be inorganic P, e.g. 75% in barley leaves (Chapin and Bieleski 1982), mostly located in the vacuole (Foyer and Spencer 1986). It is therefore expected that leaves function equally at significantly reduced leaf P concentrations. Indeed, tomato plants exhibit the same relative growth rate (RGR) at 5 mg P g^{-1} DM as at 10 mg P g^{-1} DM (De Groot *et al.* 2001). At lower leaf P concentrations, leaf area ratios (LAR) and net assimilation rates (NAR) decline, with changes in LAR being more important at a mild P limitation and those on NAR and photosynthesis (De Groot *et al.* 2003) more important at more severe P limitation. Similar effects of severely limiting P supply on photosynthesis have been found for spinach (*Spinacia oleracea* L.) (Brooks 1986) and barley (Fay *et al.* 1996). The increase in leaf starch concentrations at mild P limitation shows that reductions in RGR and LAR are due to an effect on leaf area expansion, rather than a limitation by assimilate supply (Brooks 1986; Rao and Terry 1989; De Groot et al. 2001).

In a comparison of 14 *Brassica* cultivars, grown at a range of P supplies in hydroponics, a two-fold difference was found in total biomass production at both low and high P supply (Akhtar *et al.* 2008). P-efficient cultivars produced most shoot and total biomass and the lowest shoot P concentrations. If these results can be validated under field conditions and if there are no penalties associated with greater P-use efficiency it would appear a desirable strategy to pursue. A much broader comparison was made of 355 *Brassica oleracea* accessions: 74 commercial cultivars and 90 doubled haploid mapping lines grown at a minimum of two P concentrations (Hammond *et al.* 2009 found that shoot yield was a major factor driving P-use efficiency in *Brassica*; i.e. for the same amount of shoot P, higher shoot biomass can be obtained. Similarly, a glasshouse evaluation of 73 bread and durum wheat genotypes grown in a P-deficient calcareous soil found that shoot dry weight and shoot P concentration tended to be negatively correlated (Ozturk *et al.* 2005). These studies and that of Vesterager *et al.* 2006 (21 genotypes of pigeon pea (*Cajanus cajan* (L.) Millsp.) indicate there is variation in P-use efficiency in crop species, however, the correlations observed between absolute shoot dry weight and shoot P content under P-deficient conditions suggests that P acquisition is more important for yield than biomass production per unit shoot P (i.e. P-use efficiency).

Alternatively, the P efficiency ratio of grain production (grain yield to total P in shoots) differs substantially between the major field crops used in Australia and this may potentially be exploited to manage P removals from a cropping system. For instance, canola has a P efficiency ratio (grain yield to total P in shoots) less than half that of wheat when grown with or without P fertiliser; field peas were intermediate (Ryan and Angus 2003). The low P efficiency ratio of canola reflects a high concentration of seed P and a low harvest index. Adding P fertiliser or growing crops on soils naturally high in P tends to reduce the P efficiency ratio. Batten and Khan (1987) screened a large number of wheat genotypes over 3 seasons and 3 levels of fertiliser and found that P efficiency ratio varied by as much as 100%. A large component of the differences was variation in harvest index, but differences were also present between genotypes with a similar harvest index. They concluded, however, that negative relationships between grain P concentration and both P efficiency ratio and harvest index indicated that breeding had already made some progress indirectly, in improving the internal P-utilisation efficiency in wheat.

Potential to reduce P export in grain

Crop plants concentrate P in seeds and fruits, with little remaining in straw and roots (Rose *et al.* 2007). Indeed, the P-harvest index (proportion of total shoot P in the grain at maturity) is usually >50%, and sometimes up to 90%, for field-grown crops in Australia (Batten and Khan 1987; Zubaidi *et al.* 1999; Santonoceto *et al.* 2002; Ryan and Angus 2003), although it can be reduced by factors that reduce harvest index such as a dry spring or disease (Zubaidi *et al.* 1999). The P-harvest index differs between the major temperate crop species. For instance, at a field site near Temora, New South Wales, wheat (*Triticum aestivum* L.) and field peas (*Pisum sativum* L.) had a P-harvest index of 82–84% compared with canola (*Brassica napus*) at 87–89% which reflects the higher P concentration of canola seed (Ryan and Angus 2003). The P-harvest index was little affected by addition of P fertiliser and P nutrition has been reported elsewhere to have only minor impacts on the harvest index for yield (Elliot *et al.* 1997). Santonoceto *et al.* (2002) reported a P-harvest index of 63% for linola (*Linum usitatissimum*), 76% for Indian mustard (*B. juncea*) and 78% for canola (data from Dirnaseer site, averaged across years and N application levels). In a glasshouse, canola had a lower harvest index than wheat and narrow-leafed lupin (*Lupinus angustifolius* L) Bolland and Brennan (2008). The above P-harvest index does not consider P in roots. However, a substantial proportion of plant P at crop maturity may remain in roots and is therefore not removed from the system. For instance, Rose *et al.* (2007) reported roots at maturity contained 6–11% of plant P for 3 canola cultivars and 22% for wheat. For wheat, prior to anthesis, the proportion of plant P in roots was 14% less in P-starved than in P-sufficient plants (Elliot *et al.* 1997).

Due to the high P-harvest index of the major crops, large amounts of P are removed from farms in grain. This contributes to the more favourable farmgate P-balance of crop systems (Fig. 6). The P concentrated in the seed of crops is mostly in the form of phytate; a mixed cation salt of

Table 8. Concentration of phytic acid (PA), the proportion of grain P stored as phytic acid and the Ca × PA:Zn molar ratio, an indicator of Zn bioavailability, in whole-grain wheat grown with and without P fertiliser in a trial near Temora in southern New South Wales (data averaged across 4 precrop treatments) (Ryan *et al.* 2008).

P applied (kg/ha)	Phytic acid (g/kg)	Phytic acid (% of grain P)	Ca × PA:Zn ratio*
0	5.8	65	259
20	6.9	67	404

* A Ca × PA:Zn ratio >200 may indicate poor Zn availability to humans

phytic acid (Raboy 2003). The high phytate content of grains and fruits contributes to a number of nutritional issues including poor availability of essential micronutrients, such as zinc, calcium and iron, to humans due to chelation by phytic acid (Kumar *et al.* 2010). For example, Ryan *et al.* (2008) found zinc bioavailability in whole-wheat grain was low, and became extremely low when P fertiliser was used (due to a higher phytic acid and a lower Zn concentration) (Table 8). It is likely that reducing the phytic acid concentration in Australian grains would result in benefits for human health as sections of the population, even in developed countries such as Australia, have an inadequate dietary intake of zinc (Record *et al.* 1985; Watt *et al.* 2001). An additional problem with high phytate grains is that they do not provide adequate P for some intensive animal industries (e.g. pigs, poultry) (Raboy 2009).

A substantial effort has been made to select low-phytic acid grain crops. This research has recently been reviewed by Raboy (2009) and Rasmussen *et al.* (2010). Mutations in 7 genes involved in the metabolism of phytic acid have been identified and characterised among plant species, including maize (*Zea mays* L.), rice (*Oryza sativa* L.), potato (*Solanum tuberosum* L.) and soybean (*Glycine max* L.(Merr)) (Rasmussen *et al.* 2010).

The agronomic traits of low-phytate mutants still require attention, although, seedling emergence has been increased for low-phytic acid soybean lines through backcrossing (Spear and Fehr 2007; Trimble and Fehr 2010). Some low-phytate barley (*Hordeum vulgare* L.) mutants have been registered as cultivars (Rossnagel *et al.* 2008). Also requiring consideration are reports of a range of health benefits for humans from current levels of phytate, especially in protection against a variety of cancer and heart-related diseases, diabetes mellitus and renal stones (Kumar *et al.* 2010).

A significant problem with the current low phytic acid mutants is that their seed P concentration is generally little changed from their high phytate parents due to seed phytate being replaced by inorganic P (Raboy 2009). For instance a low-phytic acid wheat mutant had 43% less phytic acid in the bran, but the bran total P concentration was reduced by only 12% and total P in other milling fractions actually increased (Guttieri *et al.* 2004). However, the development of numerous low-phytic acid mutants gives hope that other seed P characteristics can be manipulated. Raboy (2009) speculates that an alternative way to address the development of low grain P crops could be to aim for plants with low total seed P, but no change in the proportion of seed P that consists of phytate. It is not known if selecting for plants with a low total seed P will result in plants with higher P-use efficiency or a low P-harvest index due to retention of P in straw and roots. If P is simply retained in straw this could markedly change on-farm P cycling due to the input of large quantities of organic P.

In Australia, seed P content has been repeatedly shown to be positively related to seedling vigour, especially under P-limiting conditions (Bolland and Baker 1988; De Marco 1990; Thomson and Bolger 1993) and it would almost certainly be necessary to overcome this problem in low-P seeds; for example, by soaking seeds in a potassium phosphate solution to enrich their P content prior to sowing (Sekiya and Yano 2010).

Prospects for low internal-P plants in grazing systems

The potential for selecting pasture plants with lower internal P requirements has been examined on a number of occasions and it is generally agreed that there is a reasonable prospect for reducing the P-concentration of herbage by breeding (e.g. Godwin and Wilson 1976). In addition, some native Australian pasture species (e.g. *Austrodanthonia* spp., *Microlaena stipoides*) already have relatively low internal P concentrations (e.g. Hill et al. 2005). For legume-based pastures, the target for improvement must be the legume component for all of the reasons outlined previously (e.g. Section 3.3.3). However, the critical P concentrations of pasture herbage are already relatively close to the P-concentrations needed in ruminant feeds for growing and lactating animals (Table 9), and that of senescing and dead herbage or unfertilised pasture is often less than required for grazing ruminant production (e.g. Ozanne 1980; Freer et al. 2007). This castes serious doubt on the wisdom of attempting to improve P-efficiency by selecting for herbage with lower internal P concentrations.

Table 9. (a) Recommended P allowances for sheep and cattle and the derived concentrations of P needed in herbage intake for various livestock classes and (b) critical P concentrations of whole shoots for maximum growth by some keystone pasture species. Lower P concentrations are found in herbage when soil fertility is below optimum levels for maximum pasture growth rates, in older plants, in dry soil and when pasture is drying off or dead. Higher concentrations are found in young leaves, and may be found when growth rates are constrained by some other factors (e.g. low temperatures).

(a) Recommended P allowances for sheep and cattle*

Animal	Weight (kg)	Weight gain (g/d) or other condition as specified	Intake (kg DM/d)	P intake (g/d)	P concentration of diet required (g/kg DM)
Growing weaner sheep	20	100	0.61	1.28	2.1
	20	200	0.95	2.37	2.5
	40	100	0.97	1.53	1.6
	40	200	1.45	2.66	1.8
Adult sheep	50	0	0.69	0.6	0.9
Pregnant ewe	50	week 21 of gestation	0.96	3.99	2.0
Lactating ewe	50	1.7 kg milk/d	1.77	5.31	3.0
Growing weaner calf	150	500	2.9	6.2	2.2
	150	1000	4.1	10.9	2.7
	400	500	5.7	8.5	1.5
	400	1000	7.5	13.2	1.8
Adult cow	500	0	4.4	4.3	1.00
Lactating cow	500	18 kg milk/d	9.0	34.5	3.8
	500	32 kg milk/d	16.8	62.3	3.7

(b) Critical** internal P concentrations (whole shoots) - key temperate pasture species (g/kg DM)

Medicago murex / polymorpha / truncatula	annual medics	2.6 - 3.5
Trifolium repens / subterraneum	white clover / subterranean clover	2.5 - 3.2
Medicago sativa	lucerne	2.1 - 2.6
Phalaris aquatica	phalaris	1.8 - 2.0
Lolium perenne	perennial ryegrass	2.0 - 2.5
Stylosanthes spp.	stylo	1.3 - 1.7

* Source: Freer et al. (2007)

** P concentration required for maximum growth of plants during active growth prior to flowering (Pinkerton et al. 1997)

4 Impact on meat and livestock industry

4.1 Phosphorus - a critical input for high productivity

4.1.1 A significant input cost

Phosphorus is an essential input for farms on low P soils. Even in low-input agriculture it is essential to at least replace P removals to protect the sustainability of production. However, for most commercial farms, it is also essential for high production per hectare which allows a business to minimise overhead costs per DSE and to maximise profitability and return on investment.

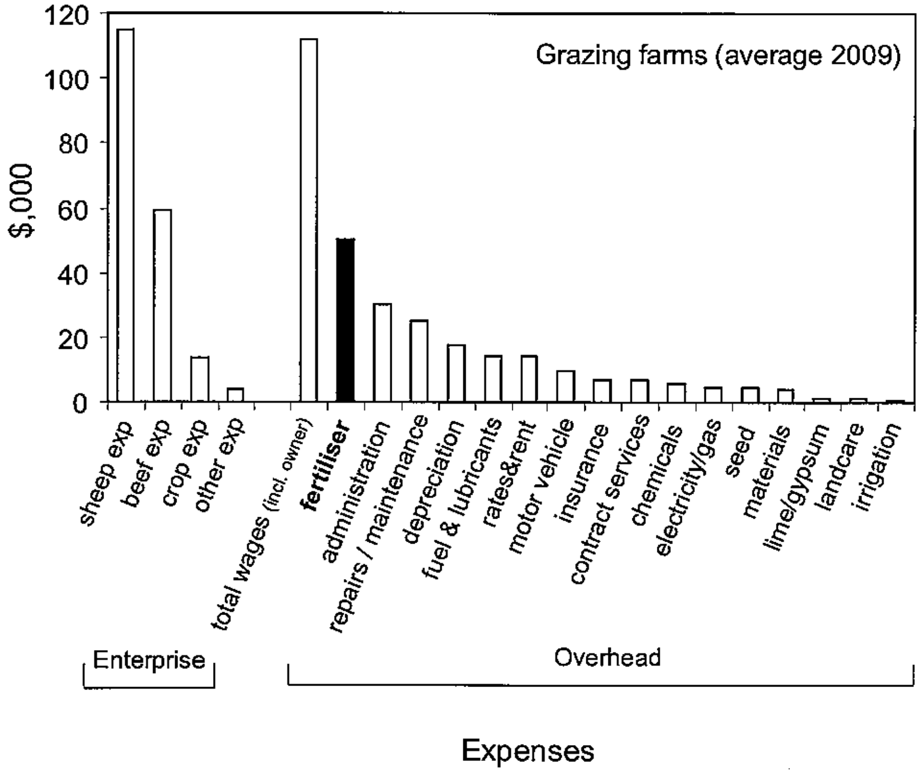


Figure 19. Average expenses incurred by grazing farms in the Holmes Sackett Pty Ltd and Principle Focus benchmarking groups (Source: Holmes Sackett 2010).

Presently, P-fertiliser inputs account for about 10% of all expenses (including wages) (Fig. 19) on 'average' grazing farms (Holmes Sackett benchmarking group; Homes Sackett 2010).

Although Holmes Sackett treats fertiliser as an overhead cost for their accounting purposes, it is more often regarded as a direct cost of production. As such, it amounted to 21% of total enterprise costs in 'average' and 'top-20%' farms, and 26% of enterprise costs in 'bottom-20%' farms.

4.1.2 Impact of increasing P costs on business risk

Phosphorus remains a profitable investment for a grazing business. However, increases in fertiliser cost reduce profitability as shown in the example illustrated in Figure 20 where cash

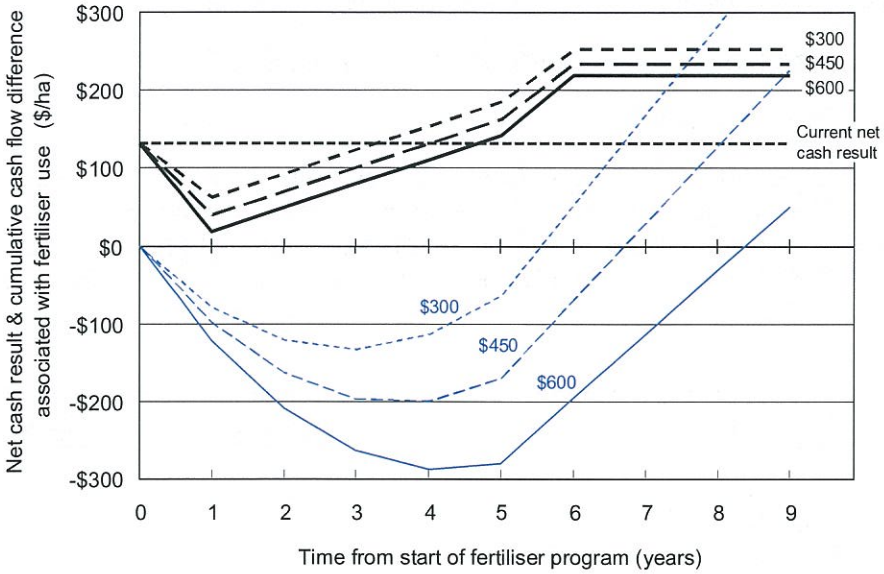


Figure 20. Impact of fertiliser prices ranging between $300/tonne and $600/tonne on profit per hectare (net cash results; black lines) and pay back periods (cumulative net cash differences which include interest on debt; blue lines) for a Merino wether enterprise grazing previously unfertilised pasture at Bookham, NSW. The payback period is indicated by the time it takes for the cumulative net cash difference to return to zero. The investment in fertiliser in this example allows stocking rate to be raised from 6 to 13 wethers/ha over a 5 year period.

flows associated with lifting soil fertility for a pasture with a low soil fertility base are shown. Because the pasture was not being fertilised prior to the implementation of the new soil fertility strategy, the livestock enterprise had been slowly exploiting soil P reserves. The new fertiliser plan to lift stocking rate and improve income per hectare must now cover both maintenance and capital P-fertiliser applications.

Whilst high fertiliser prices directly reduce profitability (see: net cash results [black lines]), they also have a significant impact in business risk by lengthening the pay back period (cumulative cash flow differences [blue lines]) for a fertiliser investment. This can substantially reduce the attractiveness of an investment. In this example, it is expected to take between 8 and 9 years to break even when the fertiliser price is $600/tonne, compared with between 5 and 6 years for fertiliser at $300/tonne. The payback periods for lifting soil fertility from low levels are similar in duration to those required for pasture improvement. All of the cost, however, is not associated with the fertiliser itself; often about half of the cost or more is associated with the extra livestock needed to utilise the extra pasture that is grown.

4.2 Threats to the meat and livestock industry

4.2.1 Sources of P for agriculture in Australia

Presently Australia sources about half of its annual P requirements domestically and half from overseas sources. The majority is used in agriculture with a P-balance efficiency of only 25%. About 90% of the P in agricultural products is exported, the rest is consumed domestically (Fig. 3). In some countries, global P-shortages would result in increased emphasis on recovery and recycling of P from waste streams. For some countries, this will go close to covering P needs. However, in Australia recycling will cover only 5-10% of the annual P requirements of agriculture

(Fig. 3, Table 1a). While these is no doubt that there will be an increasing role for P-fertilisers derived from waste streams, the major avenue for addressing pending increases in P-fertiliser costs in Australia will be through improved P-use efficiency in agriculture. Significant opportunities exist to lift the profitability and sustainability of agricultural production and to improve the environmental credentials of farming, if the efficiency with which P is used in agriculture can be improved.

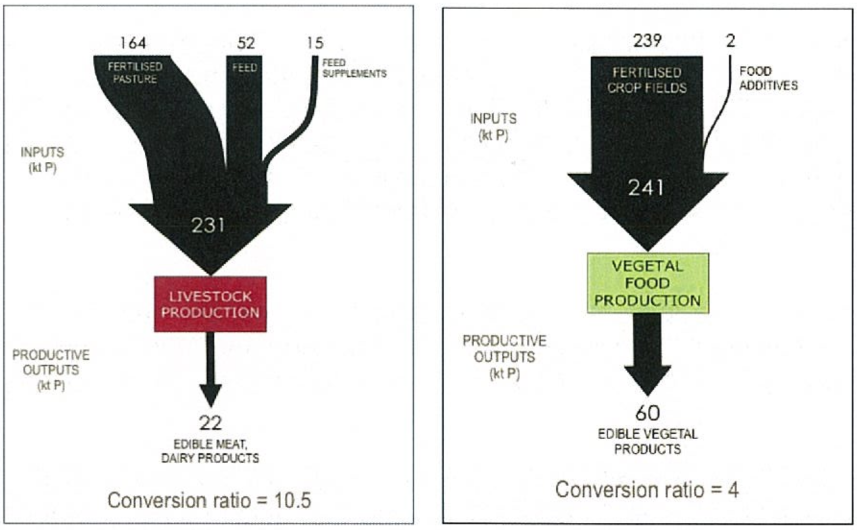
4.2.2 Threats to production, profitability and sustainability

Global reserves of phosphorus are unlikely to be entirely depleted in the foreseeable future but high-grade sources of P are finite and are being depleted. This is resulting in steady expansion of mine capacity to include sources that are of lower grade or harder to mine. The cost of P-fertiliser is also rising steadily. If predictions of peak P by 2033 are correct, it is anticipated that fertiliser costs will rise dramatically. The immediate problem is that 25 years is a very short timeframe for the industry to position itself to achieve substantive improvements in P-use efficiency.

Even if predictions of the timing of the peak in P supply prove to be inaccurate, most commentators agree that there will be increasing upward pressure on fertiliser prices which will contribute further to the declining terms of trade for agriculture. The large inefficiency associated with P use in agriculture and the grazing industries in particular, represents a substantial opportunity to reduce costs by promoting a targeted approach to soil fertility management and by researching and developing P-efficient farming systems.

4.2.3 Potential threats to Australian meat as a global commodity

It is believed by a number of commentators that amongst a range of efficiency options in the food production and consumption chain that one of ways to rationalise P use globally is to promote change in human diets. More specifically, to reduce the consumption of meat (e.g. Cribb 2010) which, on face value, has a poor P-efficiency "footprint" (e.g. Fig. 21).



(a) (b)

Figure 21. Embodied phosphorus in a) meat-based and b) vegetal foods produced in the Australian food system. Units are in kt/a of P. Conversion ratios indicate the P in phosphate rock used to produce edible foods. *Note: 1. a substantial fraction of the final products (or their intermediates, such as live sheep, or wheat) are exported, 2. The*

outputs represent edible products, not actual food consumed. The latter is approximately half, losses occurring during retailing, storage, food preparation and food consumption stages. (From White et al. Appendix 1).

Based on global averages and assumptions which include, a high reliance on feedlot livestock production, meat-based diets have been calculated to result in the depletion of approximately 2-3 times as much phosphorus as a vegetarian diet (Cordell et al. 2009a; Cordell et al. 2009b).

These sorts of calculations are intended to highlight issues but suffer from the fact that they gloss over a variety of details which are, in fact, important to understanding how efficient or inefficient food production may be. For example: feedlot production represents only 14% of livestock production in Australia; the assessment of P embodied in meat-based foods does not account for the fate of by-products removed as carcasses are rendered down to saleable meat products (some by-products are used as animal feeds, others are used in clothing and other industrial applications, and some is returned to agriculture in fertiliser products); and finally a major proportion of Australian red meat production is sourced from Northern grazing systems (Section 3.2.3) which generally have negative P-balances (not necessarily a good outcome; see Table 3) but may in some cases be lifted to a 'near perfect' P-balance efficiency by solving issues associated with P supplementation. The calculations also do not consider that meat production often uses non-arable land, or is produced from pasture leys necessary for soil fertility improvement and crop disease control, or has other social consequences (landuse efficiency, jobs, nutrition, etc) both here and across the world.

The calculations do, however, highlight the threat that P-supply issues may create for meat as a commodity that is traded globally.

It is recommended that the P-efficiency footprint of Australian meat production systems be quantified along with other aspects of the industry's environmental footprint so that the industry's position and environmental costs and benefits can be defended.

4.3 What is the potential for improving P-use efficiency and reducing the P-fertiliser costs of production?

There are now reasonable estimates of the farmgate P-balance of the major southern Australian broadacre farm enterprises (e.g. Fig 5; Table 2). Industry and enterprise outcomes vary from extremely poor (5-15%, some horticultural enterprises), through poor (20-40% for grazing industries, to average (45-60% in cropping enterprises). Only very low input-low production systems, or enterprises on very low P-sorbing soils (such as sands) approach 100% efficiency. In each case they do so at a cost (e.g. low productivity, or nutrient-leaky and environmentally problematic).

Unfortunately there is relatively little data about the nature and lability of the P that is accumulating in Australia's agricultural soils and consequently it is very difficult to estimate the magnitude of savings in P that can realistically be made by moving agriculture towards improved P-efficiency.

The few examples that are available from experiments, or studies of farming systems managed to maintain plant-available soil P (Table 4) indicate that accumulations in paddocks managed at sensible levels of soil fertility with inputs in the range 9-12 kg P/ha/year can range between 4-8 kg P/ha annually depending on enterprise and soil type. Higher levels of accumulation are expected on very high P-sorbing soils and when excessive levels of fertiliser are being used (Simpson et al. 2010). The studies summarised in Table 4 are considered likely to represent enterprises on low to moderately P-sorbing soils which are common in major agricultural areas.

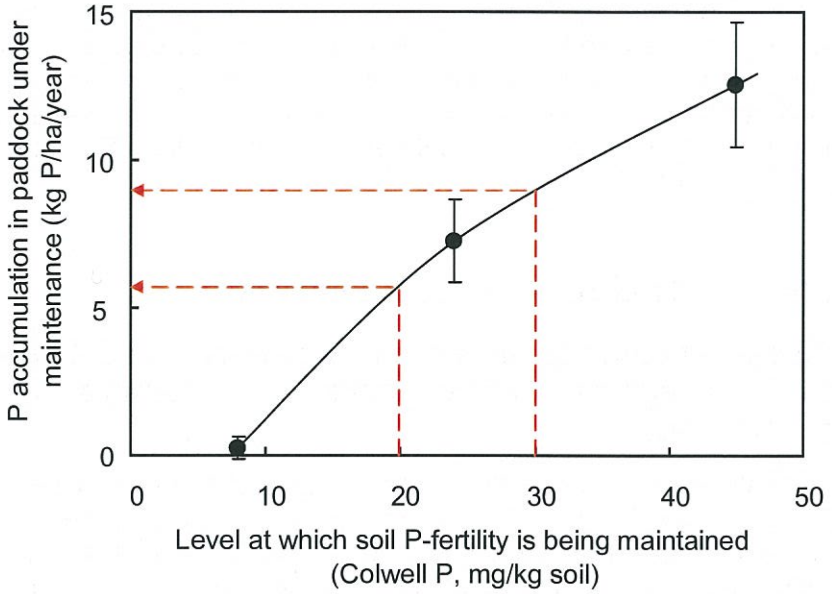


Figure 22. Estimated annual rates of accumulation of P in paddocks maintained at contrasting soil fertility levels and grazed by Merino wethers in a grazing systems experiment near Hall, ACT (from Simpson et al. 2010)

Simpson et al. (2010) have recently published estimates of the amounts of P accumulated in a sheep grazing system based on a low-moderate P-sorbing soil (PBI = 50). Data derived from this experiment permits an estimate of the potential annual savings in P that may accrue in one soil type, by adopting a farming system capable of operating at a lower soil P concentration (Fig. 22). With current technology, a grazing system operating at near optimum soil P fertility on this soil would aim to maintain Colwell P at 30 mg/kg soil. If similar productivity could be achieved at Colwell P = 20 mg/kg, as a result of sowing a P-efficient pasture legume, the recurrent saving in P fertiliser is estimated to be ~3.2 kg/ha/year as a result of a lower rate of P-accumulation in the paddock (Fig. 22). This is a 29% saving in fertiliser (presently worth about $12.40/ha/year; Sept 2010).

The maintenance fertiliser requirement at Colwell P = 30, is estimated to be ~11.9 kg P/ha and the grazing system would have a farmgate P-balance efficiency of about 24%. If the system were able to operate at Cowell P = 20, annual fertiliser inputs would be 8.7 kg P/ha with a P-balance efficiency of 32%.

Currently, many farms appear to be operating at soil fertility levels in excess of the level necessary for maximum production (Fig. 10), so savings of this magnitude or greater can be achieved simply by encouraging adoption of current best practice. However, it is suggested in this report that it will be necessary to prove by demonstration, that soil fertility can be managed in a targeted manner using critical P values suitable for the farming system. On the basis of the limited available data, there appears to be either a lack of understanding, or a lack of confidence in the application of critical P values to guide fertiliser decisions. In addition, it will be necessary to prove that low-P systems based, for example, on alternative P-efficient legumes can reduce the magnitude of P fertiliser inputs even further.

Efficiencies derived by lowering the soil P concentration at which a farm can operate, are obtained because the rate of P accumulation in sparingly-available soil P is slowed at the lower P concentration (Fig. 9). It is possible that larger savings in P-fertiliser may be made if novel plants are found, or developed with traits that also enable solubilisation or extraction of P already accumulated in sparingly-available soil pools (e.g. organic acid secretion from roots; access to organic P [e.g. Fig. 18]). Such plants would establish new P accumulation equilibria in soils and should reduce the net accumulation of P. However, it is difficult to estimate the magnitude of the potential benefits of such traits because there are few examples of plant-based systems from which the estimates may be determined.

5 Conclusions and recommendations

5.1 RD&E opportunities to underpin improvements in the productivity, profitability and sustainability of livestock systems as influenced by phosphorus use.

Achieving substantial improvements in the P-balance of Australian agriculture will not be an easy task despite the clear imperative and obvious production and environmental benefits that could be realised. P is such a universally important input in Australia that changes would already have implemented were there easy solutions available. Despite this, there are some very obvious immediate goals that will deliver benefits with relatively little effort and there are a variety of options for improving the efficiency with which P fertilisers are used, for developing lower-P farming systems, and for reducing the rate at which P is accumulated in agricultural soils. Most of the latter options will take a committed RD&E investment and it is therefore essential that the benefits and feasibility of alternative options are clearly evaluated and understood.

5.1.1 Immediate priorities - soil fertility management practices

Despite nearly 60 years of widespread P use in grazing systems, it is clear that many graziers find it difficult to manage soil P fertility with confidence. Alternatively, they attempt to manage soil fertility without a clear understanding how pastures respond to P, or the relationship between soil P fertility and stocking rate. The proportion of farmers that use soil testing is believed to still be very low and, where tests are used, there is reasonable evidence to suggest that soils are often being over-fertilised.

A clear finding of this report is that there is no financial or production benefit to be gained from applying more P than is necessary to achieve the production goals of a farm. Over-use is also environmentally undesirable and in some circumstances is an irresponsible use of a scarce resource that can lead to adverse off-site impacts.

- Promote wider adoption of soil testing and its interpretation by farmers
- Develop through demonstration and extension, confidence in the use of critical soil test values and targeted use of P-fertilisers
- Continue to focus on achieving improvements in the total factor productivity of grazing systems. The most profitable use of P arises from good pasture and livestock management and use of the best-available pasture and livestock genetics.
- Develop the capability necessary for future application of variable rate fertiliser technology in pasture systems *before* fertiliser prices rise to the level that will justify this technology.

Ensuring adoption of best management practices will provide relatively easy improvements in profitability and will reduce the costs associated with inappropriate fertiliser practice. Farmgate P-balance will also be improved where over-use of fertiliser has occurred. However, for continued improvements into future, the industry needs to research the development of novel, lower-P farming systems that can provide measurable improvements in P-efficiency. If the timeframe to peak P is indeed only 25 years, this is only just enough time to develop novel pasture systems, new fertiliser technologies and/or new plants and to get them adopted. If this timeframe is found to be overly pessimistic, the same novel systems and technologies will still deliver input cost efficiencies, improved profitability and improved environmental outcomes for the industry.

5.1.2 Low-P farming systems

Operating agriculture at the correct soil P concentration for the production goals of the farm and, in the future, at lower P concentrations than are currently necessary, is a powerful way to slow the accumulations of sparingly-available P in soils. Lower P concentrations will also minimise the chances of P loss to the environment by runoff and leaching.

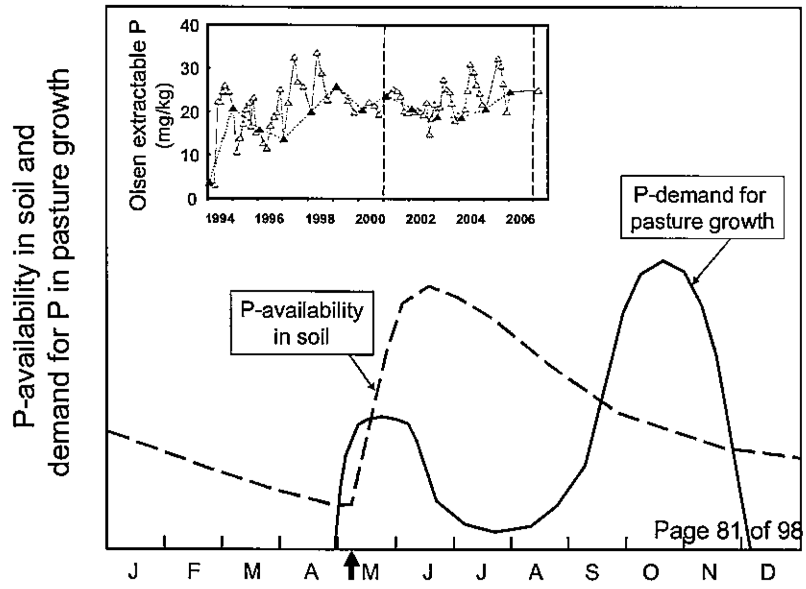
- Prove the economic and P-efficiency benefits of low-P agricultural systems that can still support high productivity
- Quantify the P-requirements of the keystone and alternative legume resources that underpin Australian pasture systems
- Develop new high productivity, low-P grazing system options

5.1.3 Fertiliser technology

Improvements in fertiliser can arguably provide the fastest improvement in P efficiency as uptake and adoption can potentially be very rapid. However, the problems of matching P supply to plant demands (Fig. 23), or minimising P sorption reactions in soil are substantial. There have been very innovative solutions addressing soil-specific P-use problems that have delivered large P-efficiency gains (e.g. fluid P fertiliser for calcareous soils). However, technology change has otherwise been relatively slow, probably reflecting the amount of research effort in this area.

- Reduce the amount of P that becomes sparingly-available in soils by developing technology or management options to control release of phosphate to soil and address the seasonal mismatch between availability of P in soil and pasture requirements for growth
- Examine fertiliser placement options to increase P availability for plants

Figure 23. Schematic illustration of the seasonal mismatch in availability of P versus plant P requirements for growth, following annual autumn applications of fertiliser. Inset shows actual patterns of P-availability in a grazing system experiment at Hall, ACT. Black dots are annual soil fertility monitoring points (February) and grey symbols show the seasonal fluctuations in P-availability. The period to 2001 was regarded as a soil fertility build-up phase, thereafter fertiliser was applied for maintenance



of soil P fertility (from Simpson et al. 2010).

5.1.4 Plant improvement

There is good evidence from crop species that a root trait-oriented approach to plant improvement can produce varieties with significantly improved P efficiency. Although it seems likely that some low-P pasture systems can be developed based on a limited number alternative, P-efficient legumes, there will still be large areas of agriculture reliant on the keystone species that carry modern Australian farming systems. Although P-efficiency may be gained by moving away from legume-based pasture to N-fed pasture, this is unlikely to be a viable option for grazing systems producing lower-value animal products and would bring substantial environmental issues as is the present experience in the dairy industry.

- Evaluate the variation in key root traits of the keystone pasture legumes; use this to select P-efficient cultivars
- Address the widespread problem of root damage on pasture legumes which may negate attempts to improve P-use efficiency and the value of improved legumes
- Position the industry to take advantage of nutrient efficiencies currently being developed in crop species using conventional and GM technology.

5.1.5 Threats

All commentators agree that it is inevitable that P-fertiliser prices will increase as the industry moves to lower grade P deposits, or sources of P that are harder to mine or process. Meat production and consumption is claimed to be very P inefficient. In a P-constrained world, the image of meat as a sustainable product will come under scrutiny. Thus, the industry may potentially face the dual threats of high prices for an input essential to productivity, and loss of market share.

- Quantify the P-footprint (paddock to plate) of the alternative meat production systems used in Australia
- Protect the export industry against simplistic evaluations of the P-cost of meat production.

5.1.6 Northern grazing systems

Australia's extensive northern rangelands are P-deficient but there are few economic options for using P-fertilisers. A desktop audit (Table 3) indicates that the systems are all likely to be slowly extracting P without replacement. In most cases, the rates of P loss are low and are not considered to be a threat to production at the present time. However, where productivity is higher as a result of introduction of exotic species (e.g. Leucaena-based systems), nutrient extraction is thought to be a factor in the effective collapse of grazing system productivity and the issues of P extraction and replacement need to be explored. Direct strategic P-supplementation of cows in extensive breeding systems is likely to lift both productivity and to bring the P-balance of these systems closer to an 'ideal' P-balance efficiency.

- Conduct a benchmark audit of P- (and other nutrients: S, N) balances of Northern grazing systems that quantifies and extends the "calculations" undertaken for this report
- Develop practical methods for identifying when P-supplements will result in livestock growth responses and assess their role in closing the P-imbalance of extensive breeder systems

- Assess N and P constraints and options for nutrient restoration in established rangeland systems considered to be experiencing nutrient exhaustion

5.1.7 Underpinning knowledge

There are still a surprising number of gaps in knowledge about the reactions of phosphate in soil and around fertilisers; especially those leading to P accumulations as sparingly-available phosphate and organic P. Relatively little is known about the P-acquisition mechanisms of P-efficient plants and the role and ecology of soil micro-organisms (including mycorrhiza) in making P available to crops and pastures. Strategic investment in new knowledge is ultimately the only way to develop innovative answers to difficult problems. Presently innovative fertiliser technologies and the development of novel plants that may access organic P in soil are potentially constrained by a limited understanding of soil P reactions and the chemical forms of organic P in soil. However, if investment in fundamental knowledge is to be contemplated it should be sensibly aligned with applied research programs to ensure a well focussed research effort. For example see: Section 5.3: "P reactions in soils - Understand the processes leading to accumulation of Po in soil and the bioavailability of Po substrates" as an example of the need for integration of fundamental and applied research.

It is always difficult to know how to most effectively make investments in fundamental knowledge because scientific breakthroughs are not predictable. However, what can be predicted is that if no investment is made, there will be no new discoveries.

- Develop a measured program of investments in the science that underpins the most intractable problems of P supply, soil P reactions and P-use efficiency by plants. Ensure that it is linked to allied, applied research and use it to train young scientists who will go on to serve the grazing industries.

5.2 A quick guide to P-efficiency RD&E opportunities that specifically address issues for Australian grazing industries.

Three levels of information about the RD&E opportunities to lift P efficiency in agriculture are provided.

The first is the a visual key to the major areas of RD&E for **grazing systems** alone, this is more detailed than the preceding summary and targets issue of particular concern to grazing businesses. It includes and indication of the likely priority areas of RD&E based on informal consideration of both urgency and feasibility.

KEY:

🟩 HIGH priority

🟨 MODERATE priority

🟥 LOWER priority

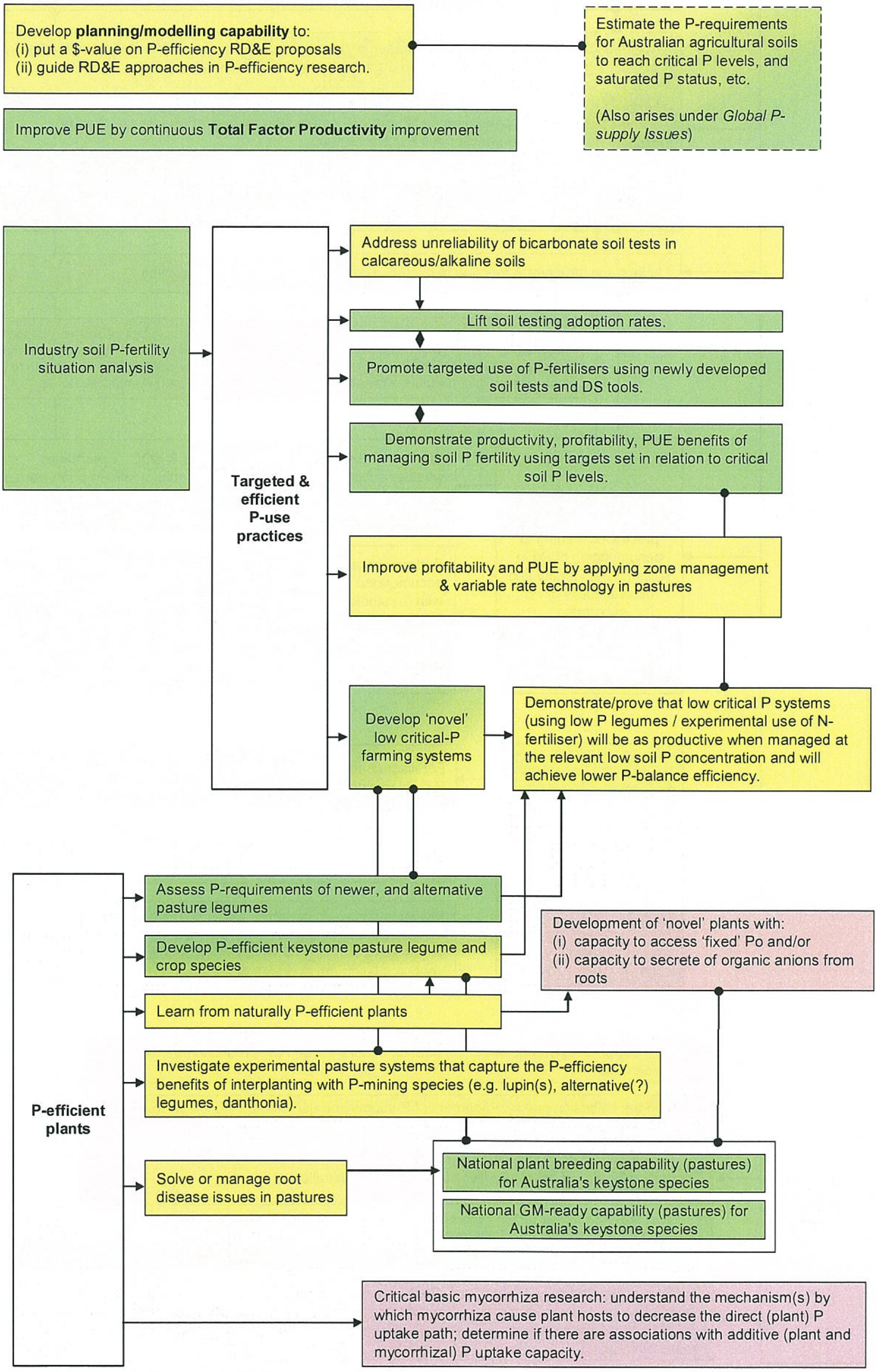
●——● linkages

——→ dependencies

This is followed (Section 5.3) by a more detailed assessment of each topic for **grazing and cropping** systems grouped into potential programs of research.

Finally, considerably more detail is provided in the body of the report which summarises reviews of the scientific literature underpinning all topics. These reviews were the basis from which the RD&E opportunities were identified.

P-efficient agriculture: temperate (southern) grazing system RD&E opportunities



Develop **planning/modelling capability** to:
(i) put a $-value on P-efficiency RD&E proposals
(ii) guide RD&E approaches in P-efficiency research.

Estimate the P-requirements for Australian agricultural soils to reach critical P levels, and saturated P status, etc.

(Also arises under *Global P-supply Issues*)

Improve PUE by continuous **Total Factor Productivity** improvement

Industry soil P-fertility situation analysis

Targeted & efficient P-use practices

Address unreliability of bicarbonate soil tests in calcareous/alkaline soils

Lift soil testing adoption rates.

Promote targeted use of P-fertilisers using newly developed soil tests and DS tools.

Demonstrate productivity, profitability, PUE benefits of managing soil P fertility using targets set in relation to critical soil P levels.

Improve profitability and PUE by applying zone management & variable rate technology in pastures

Develop 'novel' low critical-P farming systems

Demonstrate/prove that low critical P systems (using low P legumes / experimental use of N-fertiliser) will be as productive when managed at the relevant low soil P concentration and will achieve lower P-balance efficiency.

P-efficient plants

Assess P-requirements of newer, and alternative pasture legumes

Develop P-efficient keystone pasture legume and crop species

Learn from naturally P-efficient plants

Development of 'novel' plants with:
(i) capacity to access 'fixed' Po and/or
(ii) capacity to secrete of organic anions from roots

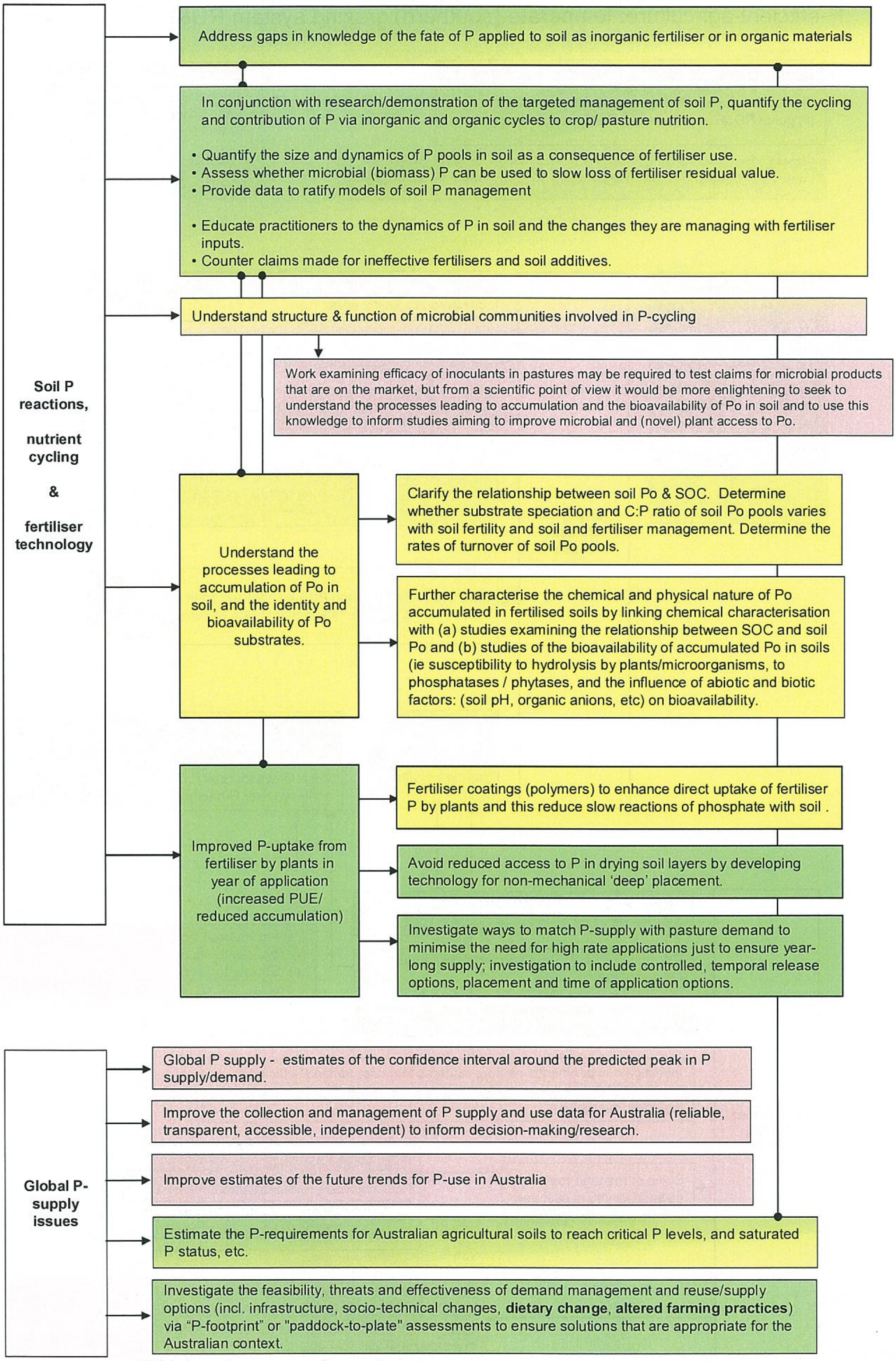
Investigate experimental pasture systems that capture the P-efficiency benefits of interplanting with P-mining species (e.g. lupin(s), alternative(?) legumes, danthonia).

Solve or manage root disease issues in pastures

National plant breeding capability (pastures) for Australia's keystone species

National GM-ready capability (pastures) for Australia's keystone species

Critical basic mycorrhiza research: understand the mechanism(s) by which mycorrhiza cause plant hosts to decrease the direct (plant) P uptake path; determine if there are associations with additive (plant and mycorrhizal) P uptake capacity.



Soil P reactions,

nutrient cycling

&

fertiliser technology

Address gaps in knowledge of the fate of P applied to soil as inorganic fertiliser or in organic materials

In conjunction with research/demonstration of the targeted management of soil P, quantify the cycling and contribution of P via inorganic and organic cycles to crop/ pasture nutrition.

- Quantify the size and dynamics of P pools in soil as a consequence of fertiliser use.
- Assess whether microbial (biomass) P can be used to slow loss of fertiliser residual value.
- Provide data to ratify models of soil P management

- Educate practitioners to the dynamics of P in soil and the changes they are managing with fertiliser inputs.
- Counter claims made for ineffective fertilisers and soil additives.

Understand structure & function of microbial communities involved in P-cycling

Work examining efficacy of inoculants in pastures may be required to test claims for microbial products that are on the market, but from a scientific point of view it would be more enlightening to seek to understand the processes leading to accumulation and the bioavailability of Po in soil and to use this knowledge to inform studies aiming to improve microbial and (novel) plant access to Po.

Understand the processes leading to accumulation of Po in soil, and the identity and bioavailability of Po substrates.

Clarify the relationship between soil Po & SOC. Determine whether substrate speciation and C:P ratio of soil Po pools varies with soil fertility and soil and fertiliser management. Determine the rates of turnover of soil Po pools.

Further characterise the chemical and physical nature of Po accumulated in fertilised soils by linking chemical characterisation with (a) studies examining the relationship between SOC and soil Po and (b) studies of the bioavailability of accumulated Po in soils (ie susceptibility to hydrolysis by plants/microorganisms, to phosphatases / phytases, and the influence of abiotic and biotic factors: (soil pH, organic anions, etc) on bioavailability.

Improved P-uptake from fertiliser by plants in year of application (increased PUE/ reduced accumulation)

Fertiliser coatings (polymers) to enhance direct uptake of fertiliser P by plants and this reduce slow reactions of phosphate with soil .

Avoid reduced access to P in drying soil layers by developing technology for non-mechanical 'deep' placement.

Investigate ways to match P-supply with pasture demand to minimise the need for high rate applications just to ensure year-long supply; investigation to include controlled, temporal release options, placement and time of application options.

Global P-supply issues

Global P supply - estimates of the confidence interval around the predicted peak in P supply/demand.

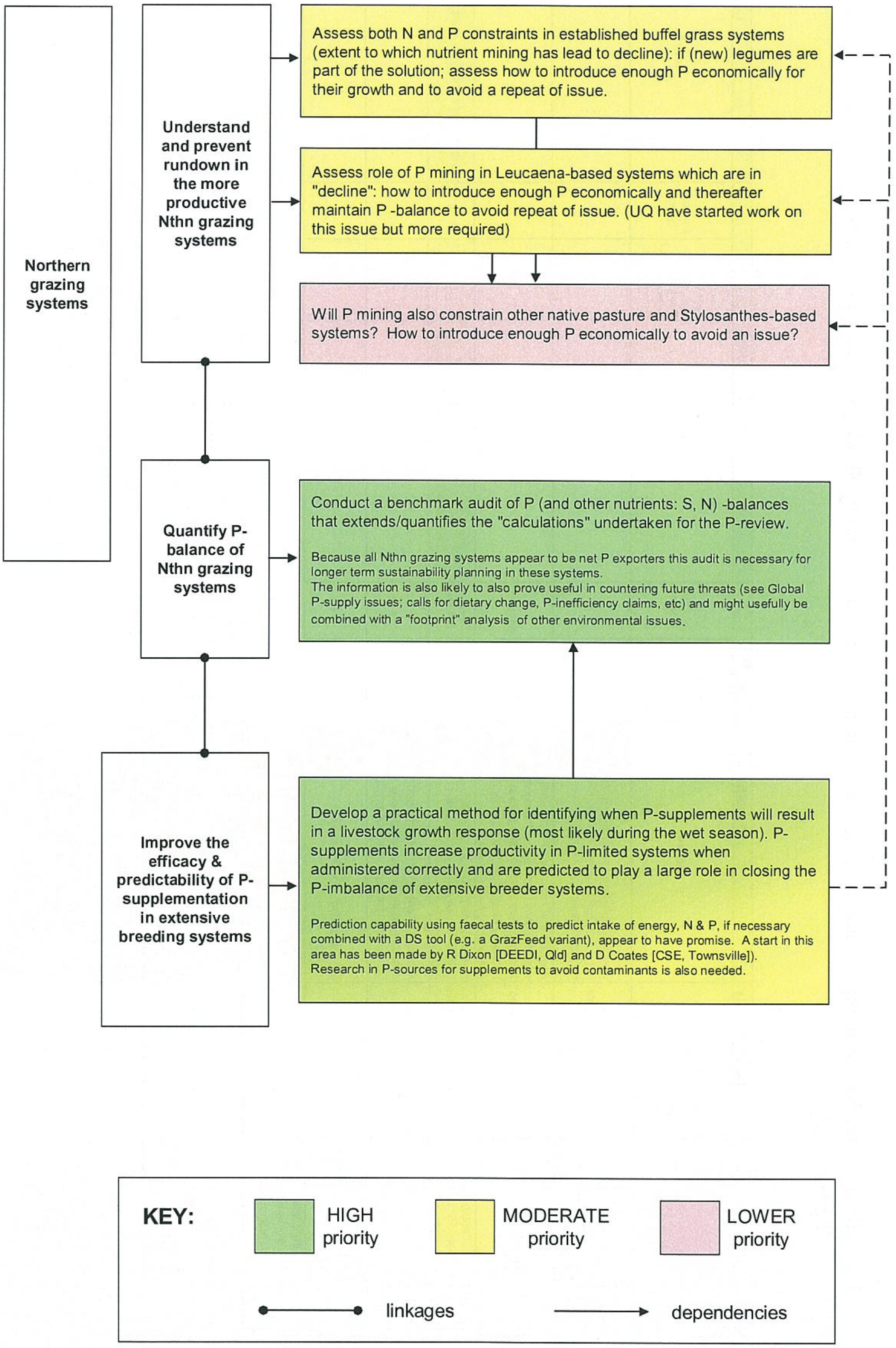
Improve the collection and management of P supply and use data for Australia (reliable, transparent, accessible, independent) to inform decision-making/research.

Improve estimates of the future trends for P-use in Australia

Estimate the P-requirements for Australian agricultural soils to reach critical P levels, and saturated P status, etc.

Investigate the feasibility, threats and effectiveness of demand management and reuse/supply options (incl. infrastructure, socio-technical changes, **dietary change**, **altered farming practices**) via "P-footprint" or "paddock-to-plate" assessments to ensure solutions that are appropriate for the Australian context.

P-efficient agriculture: northern grazing system RD&E opportunities



Northern grazing systems

Understand and prevent rundown in the more productive Nthn grazing systems

Assess both N and P constraints in established buffel grass systems (extent to which nutrient mining has lead to decline): if (new) legumes are part of the solution; assess how to introduce enough P economically for their growth and to avoid a repeat of issue.

Assess role of P mining in Leucaena-based systems which are in "decline": how to introduce enough P economically and thereafter maintain P -balance to avoid repeat of issue. (UQ have started work on this issue but more required)

Will P mining also constrain other native pasture and Stylosanthes-based systems? How to introduce enough P economically to avoid an issue?

Quantify P-balance of Nthn grazing systems

Conduct a benchmark audit of P (and other nutrients: S, N) -balances that extends/quantifies the "calculations" undertaken for the P-review.

Because all Nthn grazing systems appear to be net P exporters this audit is necessary for longer term sustainability planning in these systems.
The information is also likely to also prove useful in countering future threats (see Global P-supply issues; calls for dietary change, P-inefficiency claims, etc) and might usefully be combined with a "footprint" analysis of other environmental issues.

Improve the efficacy & predictability of P-supplementation in extensive breeding systems

Develop a practical method for identifying when P-supplements will result in a livestock growth response (most likely during the wet season). P-supplements increase productivity in P-limited systems when administered correctly and are predicted to play a large role in closing the P-imbalance of extensive breeder systems.

Prediction capability using faecal tests to predict intake of energy, N & P, if necessary combined with a DS tool (e.g. a GrazFeed variant), appear to have promise. A start in this area has been made by R Dixon [DEEDI, Qld] and D Coates [CSE, Townsville]).
Research in P-sources for supplements to avoid contaminants is also needed.

KEY:

🟩	HIGH priority
🟨	MODERATE priority
🟥	LOWER priority
●——●	linkages
——→	dependencies

5.3 More details and potential programs of research: P-efficiency RD&E opportunities for Australian broadacre agriculture.

Research Programs	Category and project alignments	Outcome/benefit	Feasibility	Priority	Immediate term			Medium term			Longer term		
			Short-term Medium term Longer term		Activity	Underpinning Research; Applied Research; Develop; Extend; Commercialise.	Duration (years)	Activity	Underpinning Research; Applied Research; Develop; Extend; Commercialise.	Duration (years)	Activity	Underpinning Research; Applied Research; Develop; Extend; Commercialise.	Duration (years)
	P-efficient systems	Capability to (i) put a $-value on RD&E proposals; (ii) guide RD&E approaches in P-efficiency research.	S	moderate	Develop modelling capability to quantify impact of RD&E intended to improve P-balance efficiency.	UR	3						
	P-efficient systems	Improved PUE through improving TFP	S	on-going	Projects that increase TFP also increase P-use efficiency (farm output for a given level of P input): increased management skills, removing constraints to production, improving pasture and livestock genetics.	AR/D/E	on-going						
	Targeted & efficient P-use practices	Address unreliability of bicarbonate soil tests in calcareous/alkaline soils	M	moderate	Evaluate need, examine alternatives (incl. GRDC-funded diffusive gradients in thin-films [DGT] test).	UR/AR	6 mths	If case is made, engage industry partner - adapt or evaluate alternative soil test	UR/AR	3	If performance and BCA adequate release via industry partner	E/C	
	Targeted & efficient P-use practices	Industry soil P-fertility situation analysis	S	high	Assess current soil fertility situation on farms; evaluate evidence that some farms continue building soil fertility well beyond critical P.	E	1 ~ 2						
	Targeted & efficient P-use practices	Increase the awareness and objective management of soil fertility.	M	high	Lift soil testing adoption rates.	E	3						
	Targeted & efficient P-use practices	Improve the profitability of P-fertiliser use; ensure environmental credentials of the industry	M	high	Promote targeted use of P-fertilisers using newly developed soil tests and DS tools.				E	3			
	Targeted & efficient P-use practices	Counter lack of understanding and confidence in use of soil testing and soil test targets for managing pastures.	M	high	Demonstrate productivity, profitability, PUE benefits of managing soil P fertility using targets that are set in relation to critical P for pastures/crops. (Well run prticipatory demonstrations similar to 'triple-P', on contrasting soil types / farm systems. Emphasis now is to guide targeted/profitable use of P, to counter overuse, and to link P use with SR and pasture utilisation. Essentialto value add by linking to other extension issues (above) and research projects. **Issue:** Soil P-fertility management targets for **pastures** have largely been determined. However, lack of understanding / confidence constrains implementation.				D/E	3 ~ 6			
	Targeted & efficient P-use practices	Develop low critical-P farming systems	S-M	high	Demonstrate/prove that new low critical P systems (using low P legumes / experimental use of N-fertiliser) will be as productive for herbage and animal production, when managed at the relevant low soil P concentration and will achieve improved PUE with lower P-balances.				AR/D/E	3~ 6			
	Targeted & efficient P-use practices	Counter lack of information and confidence that soil P-fertility of **crops** can be managed using a targeted approach using critical soil P information.	M-L	high	Establish critical soil P values for **crop/soil** systems. A GRDC project to do this is presently underway: "Making Better Fertiliser Decisions for Cropping Systems in Australia", Speirs et al. (2010) *Proc. 15th Aust. Agron. Conf.* http//www.agronomy.org.au/	D/E	2	As has occurred in pasture systems, lack of confidence is likely to contrain implemention, and there will be a need to demonstrate productvity, profitability, PUE benefits of managing soil P fertility within crop system phases using critical P targets.				D/E	3~6

Research Programs	Category and project alignments	Outcome/benefit	Feasibility	Priority	Immediate term			Medium term			Longer term		
			Short-term Medium term Longer term		Activity	Underpinning Research; Applied Research; Develop; Extend; Commercialise.	Duration (years)	Activity	Underpinning Research; Applied Research; Develop; Extend; Commercialise.	Duration (years)	Activity	Underpinning Research; Applied Research; Develop; Extend; Commercialise.	Duration (years)
	Targeted & efficient P-use practices	Improved profitability and PUE through zone management for P in pastures systems	M-L	moderate (benefit is P-cost sensitive)				Evaluate extent of problem, BCA, assess feasibility of zone management for grazing farms, develop business case. **Current situation**: (1) paddock productivity patterns can now be determined using ground, airborne or spaceborne canopy reflectance sensing devices with or without pasture modelling backup. (2) GPS technology, productivity maps should enable variable rate fertiliser delivery (3) spatial mapping of nutrient gradients to underpin VRT decision is probably rate-limiting step	AR	3 ~ 5	If BC is favourable: engage commercial partner/ develop VRT for grazed pastures	E/C	
	Targeted & efficient P-use practices	Ensure environmental credentials of the industry in farming areas where P losses are a of critical pollution.	M	Impact varies regionally **Can be very important**; priority should be determined from regional significance.	Assess environmental impact (P losses) at critical P levels for different soil types (possibly directed at low PBI soil categories; critical source areas). Assess how to minimise/eliminate environmental impact incl. changes to fertility practices (fertiliser types, targets, etc). One of the key things here is to not do small plot studies only, due to massive storage of P in the landscape. Small plot work often bears little relationship to catchment studies. Also losses can be through runoff and leaching - each of these requires a different strategy for management. This issue has become critica in some areas - GBReef and WA and is likely to spread.				D/E	Wiil be driven by urgency of environmental issues			
	P-efficient plants	Learning from naturally P-efficient plants	M	moderate-low				Plants that have natural P-efficiency traits demonstrate that improvements in PUE are possible and inform the directions of research. However, to date most studies have focussed on a narrow range of plants with extra-ordinary features. There are Australian native species that occur in grazed pastures that are considered to also be P-efficient but little is known about how this is achieved. Studying the PUE of these species will provide novel insights into PUE mechanisms.	UR (ideal PhD training)	3			
	P-efficient plants	Assess P-requirements of newer, and alternative pasture legumes	S-M	high	P-requirements of newer and alternative pasture legumes is sparsely or not documented. At least one speceis is known to be signifcantly more P-efficient that the clovers used in most pastures; others are 'suspected'. Research that quantifies the relative PUE of pasture legumes is required to assist soil fertility management and species choice.	AR	3	Extend field trialling/demostrations to districts appropriate for each species; determine contributing traits; revise soil fertility management guidelines on basis of robust results.	AR/E	3			
	P-efficient plants	Develop P-efficient keystone pasture legume and crop species	M-L	high	Assess extent of variation in key traits (see reveiw), their heritability, likely progress. Experience with crops (Lynch 2007 and white clover (NZ research) indicates a targeted root trait approach is required; initial studies in glasshouse but work must then progress beyond glasshouse comparisons. **NOTE:** good progress is being made in wheat in Australa, beans and maize in USA/ China/ SouthAmerica etc; white clover in NZ and links to these programs are essential.	UR/AR	3	Once potential for improvement is established and proof that systems can be run productively with less p-input to refelct lower critical P requirments: commence phase, 2 prove robustness of approach; continue testing of promising genotypes in field trials; develop QTL's; commence selection of elite germplasm	AR	3	Incorporate traits into elite lines; release with new/appropriate agronomic guidleines	AR/D/E	3 ~ 6

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	P-efficient plants	Reduce prevalence of root disease on keystone pasture legumes (& crops)	M-L	moderate	Address persistent issue of soil-borne, root damaging diseases which must affect the nutrient acquisition efficiency of pastures and are proven to have done so in crops. Major yield improvements associated with root disease management in crops indicate breeding solutions need to be re-examined and management alternatives also considere				AR	3~6	Develop new management systems or new cultivars with improved root disease resistance.	D/E/C	3~6
	P-efficient plants	Plants with low internal P-efficiency	L	moderate	Low P content plants have higher P-efficiency provided that equivalent production is achieved. Many native plants show this trait but not all mainatin high growth rates. In all studies of species/cultivars for P-efficiency, internal P should be routinely evaluated. Implications for production and animal nutrition neeed to be examine before expanding this line of enquiry.	UR	always considered as part of other work	Explore potential for improving P-efficiency in crops by reducing P-export through lower seed/grain P content. Seed P storage in compounds such as phytate have low bioavailability in diets and there is potential to have seeds with lower P-content. **Questons to be answered**: to what extent does p-content of seeds/grain vary naturally and does this justify this line of enquiry; what implications for human nutrition & environment; implications for P mobilisation from stalk to grain;effects on production/early growth?				UR	3~6
	P-efficient plants	Development of 'novel' plants with capacity to access 'fixed' Po	L	moderate	Well-funded program of research with cereals underway in Australia which will test hypotheses and provide proof of concept. Initially attempt to "buy-in" to gain access to results if that is still possible: e.g. fund linked projects such as a GM-ready pasture legume strategy.	UR	wait & see approach	Address barriers to access, or deficits in capability for pastures and maintain modest nationally-oreiented breeding and GM capabilities that can be expanded as needed to ensure that keystone species can be breed and / or transformed with novel genes when problems arise, technology advances and / or public acceptance is in place.	UR/AR	3 ~ 6	Move to elite cultivar development phase as appropriate. Merge with agronomic studies to ensure cultivars are released with appropriate management guidelines	AR/D/E	~6
	P-efficient plants	Development of 'novel' plants with capacity to secrete of organic anions from roots	L	moderate	Well-funded program of research with cereals is currently underway in Australia which will test hypotheses and provide proof-of-concept. Initially attempt to "buy-in" to gain access to results if that is still possible: e.g. fund linked projects such as assessment of keystone pasture legume root traits.	UR	wait & see approach						
	P-efficient plants	National plant breeding capability (pastures) for Australia's keystone species	S	high	Ensure capacity remains intact for the keystone species (particularly pasture legumes not covered by others or where access to O/S technology will be denied).	UR	on-going						
	P-efficient plants	National GM-ready capability (pastures) for Australia's keystone species	S-M	high	Assess whether keystone pasture legumes are GM-ready. Proof-of-concept research and plants with novel traits are likely to need this technology. Examine freedom to operate, etc; commence work to address limitations. Ensure capacity remains intact or is developed for the Australia's keystone species (particularly pasture legumes not covered by others or where access to O/S technology will be denied or prevented).	UR	re-start						
	P reactions in soils / Fertiliser technology	Capture additive benefits of using P-efficient plants with P-efficient fertiliser placement technology (especially for crops)	S	high	The root system characterisitics of plants that capture more P from low P soils and soil with surface P-rich layers are well documented. In cropping systems placement technology (e.g. banding) also improves P-use efficiency. Investigate the interaction of P-efficient root systems and fertiliser placement to capture additive P-use efficiency benefits	AR	3	Lift P-efficiency further by optimising the remaining agronomic variables (e.g. row spacing, plant density, offset fertiliser placement, inter-row planting and break crops for root disease control) to gain maximum benefits from P-efficient cutivars.	AR	3	Adapt this technology to farming systems (e.g. pastures) where placement technology has so far not been able to be applied or has had little impact.	AR	3

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	Fertiliser technology	Improved P-uptake from fertiliser by plants in year of application (leading to reduced accumulation in soil)	M	moderate	Re-examine strategic foliar P applications for **crops** to gain P-effic advantage thorugh by-passing soil.	AR	3	Continue with or engage commercial partner, develop new fertiliser technology or encourage technology development by third party.	D	3			
	Fertiliser technology	Improved P-uptake from fertiliser by plants in year of application (leading to reduced accumulation in soil)	M-L	moderate-high	Investigate ways to match P-supply with crop / pasture demand to minimise the need for high rate applicatons just to ensure year-long supply; options to include controlled, temporal release, placement and time of application.	AR	3	Continue with or engage commercial partner, develop new fertiliser technology or encourage technology development by third party.	D	3			
	Fertiliser technology	Improved P-uptake from fertiliser by plants in year of application (leading to reduced accumulation in soil)	S-M	moderate	Develop partnership with industry; examine feasability of fertiliser coatings (polymers) to enhance direct uptake of fertiliser P by plants and this reduce slow reactions of phosphate with soil that lead to reduced P-availability.	AR	3	Check freedom to operate, continue with or engage commercial partner, develop new fertiliser technology or encourage technology development by third party.	D	3			
	Fertiliser technology	Improve pasture and crop growth during periods of "nutrient drought" when drying soil layers inhibit access to P by deeper 'placement' to avoid drying soil.	M-L	high	Assess potential benefit to crops and pastures by modelling soil moisture and P-uptake from soil layers. Variables to include seasonal conditions and differing climatic regions: HRZ v LRZ pastures/crops; winter-rainfall vs summer-rainfall pastures/crops.	UR	6 mths	Develop partnership with industry; investigate innovative ways to achieve deep placement that avoid the high cost of mechanical placement at depth - (e.g. nanoparticle technology).	UR/AR	2~3	If research outcomes are favourable: continue with or engage commercial partner/ develop new fertiliser technology.	D	3
	P reactions in soils Fertiliser technology	Address gaps in knowledge of the fate of P applied to soil as inorganic fertiliser or in organic materials	S	moderate	Investigate the path and changing availability of P after it is applied as inorganic and organic materials and fertilisers in pasture and crop systems (incl: alkaline and acid soils). **NOTE:** Presently there is only limited information available for crop systems on alkaline soils. Lack of knowledge of the fate of P after release from fertiliser or decaying plant materials constrains attempts to improve fertiliser effectiveness.	UR	3~6	Investigate the physical and chemical mechanisms by which Pi and Po from microbial and plant sources becomes stabilized in soil and design / develop management practices / fertilisers to maximize its availability.	UR/AR	3~6	Implement new management systems	D/E	

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	P reactions in soils	Understand the processes leading to accumulation of Po in soil and the bioavailability of Po substrates.	S-M	high	Clarify the relationship between soil Po & SOC. Determine whether substrate speciation and C:P ratio of soil Po pools varies with soil fertility and soil and fertiliser management. Determine the rates of turnover of soil Po pools. **NOTE:** An understanding of whether or not the C:P ratios of Po pools are constant underpins the ability to model soil P transactions and strategies to mobilise more P for plants from soil Po sources and has important implication for the management and sequestration of soil carbon.	UR	3~6	Use this information to inform studies aiming to improve microbial and (novel) plant access to Po in soils.	AR				
	P reactions in soils	Understand the processes leading to accumulation of Po in soil and the bioavailability of Po substrates.	S-M	high	Further characterise the chemical and physical nature of Po accumulated in fertilised soils BUT advance this field of knowledge by linking these studies to (a) studies examining the relationship between SOC and soil Po and (b) studies of the bioavailability of accumulated Po in soils (ie their susceptability to hydrolysis by plants/microorganisms, to phosphatases / phytases, and the influence of abiotic and biotic factors: (soil pH, organic anions, etc) on bioavailability.	UR	3						
	Northern cropping systems	Understand and quantify rundown in Nthn cropping systems	S-M	moderate-high	Northern grain systems (partic on Vertisols) are notably P-deficient; develop economic and sustainable P-management practices.	AR	(GRDC has a current research interest in this)						
	Northern grazing systems	Understand and prevent rundown in the more productive Nthn grazing systems	S-M	moderate-high	Assess both N and P constraints in established buffel grass systems (extent to which nutrient mining has lead to decline): if (new) legumes are part of the solution; how to introduce enough P economically for their growth and to avoid a repeat of issue.				AR	3 ~ 6	Will P mining also constrain other native pasture and Stylosanthes-based systems? How to introduce enough P economically to avoid an issue?	AR	3
		Understand and prevent rundown in the more productive Nthn grazing systems	M	moderate-high	Assess role of P mining in Leucaena-based systems which are in "decline": how to introduce enough P economically and thereafter maintain P -balance to avoid repeat of issue. UQ have started work on this issue but more required				AR	3 ~ 6			

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	Northern grazing systems	Quantify P-balance of Nthn grazing systems and assess (i) perceived risks to the contrasting grazing systems and (ii) options for correcting P-imbalances where necessary.	S	high	All Nthn grazing systems appear to be net P exporters; a benchmark audit of P (and other nutrients: S, N)-balances to extend the "calculations" undertaken for for the P-review is needed to confirm predictions and plan for the longer term sustainability of these systems. This could also prove useful in countering future threats (see Global P-supply issues) and might usefully be combined with a "footprint" analysis of other environmental issues. **Initial assessment:** P-supplements predicted to play a large role extensive breeder systems; Fertiliser application: not financial except in the more intensive farming systems; New cropping developmnts - can grazing piggy-back on P inputs to crops in mixed crop/grazing systems; Soil reserves - can they sustain extensive systems? Are they being depleted by intensification? If could mobilise more soil reserves where will sustainable P-supply come from?	AR	1 ~ 2						
	Northern grazing systems	Improve the efficacy & predictability of P-supplementation in extensive breeding systems	S-M	high	P-supplements increase productivity in P-limited systems when administered correctly and are predicted to play a large role in closing the P-imbalance of extensive breeder systems. **Issues**: accurately identify when supplements will give a livestock growth response (during wet season); develop prediction capacity such as feacal test that combines predicted intake of energy, N & P (a start in this area has been made by R Dixon [DEEDI, Qld] and D Coates [CSE,Townsville]); research in P-sources to avoid contaminants is also needed.				AR	3			
	P-efficient temperate farming systems	* Quantify the size and dynamics of P pools in soil as a consequence of fertiliser use. * Provide data to ratify models of soil P management * Educate practitioners to the dynamics of P in soil and the changes they are managing with fertiliser inputs. * Counter claims made for ineffective fertilisers and soil additives.	S-M	high	In conjunction with research/demonstration of the targeted management of soil P, quantify the cycling and contribution of P via inorganic and organic cycles to crop/ pasture nutrition. Determine size and chemical nature of soil P pools in relation to fertilise management and their rates of turnover. **NOTE:** this initiaitive should be linked strongly to a number of the other research questions/objectives; common sites; collaborating teams; and extension opportunities.	UR/AR	3~6						

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	P-efficient temperate farming systems	Assess whether microbial (biomass) P can be used to slow loss of fertiliser residual value.	M	moderate	Investigate temporal and spatial dynamics of microbial P (in rhizosphere & food webs), its potential as a temporary store of P and its capacity to supply P to plants particularly in relation to the temporal P requirements of crops/pastures. Objective: greater synchrony between immobilization/release and plant demand	UR/AR	3	Establish the linkage between community structure and function in relation to P mobilisation and investigate whether organic inputs (especially legume residues) can be used to enhance the pool of microbial P, separately, or in conjunction with novel inoculants to improve the availability of P for crops.	UR/AR	3	Compare microbial access to 'recalcitrant' mineral & organic forms in laboratory studies with their efficacy under field conditions. **NOTE:** placement and persistence issues associated with use of inoculants dictate that this work should first be done in cropping systems and followed in pasture systems if success is achieved.	AR	3
	P-efficient temperate farming systems	Understand structure & function of microbial communities involved in P-cycling	M	moderate	Metagenomic studies of contrasting soils/systems (inorganic vs organic P pools) particularly examining interactions among microbes in the rhizosphere.	UR/AR	3						
	P-efficient temperate farming systems	Low P farm systems that utilise plants known to extract sparingly-available P from soil / improved farming system P-balance efficiency	S-M	high	Investigate **crop** systems that capture the P-efficiency benefits of plants (e.g. lupin(s), faba beans) with specialised root traits that can acquire sparingly-available P. **Aims**: Increased P acquisition from unavailable soil P, reduced P accumulations. **Issues**: (i) Interplanting releases P to companion species, but tranfer of P-release benefits between crop phases has not been demonstrated for field crops. (ii) Conduct row spacing and fertiliser placement experiments to ensure expression of P-extraction trait at levels of soil fertility needed to ensure optimum crop yields.	AR	3	If successful: develop agronomic guidelines for implemenation/adoption. Examine effects of changes in plant P economy on soil P dynamics, quality of plant residues, mineralisation and availability of P for subsequent crops.	AR	3~6			
	P-efficient temperate farming systems	Low P farm systems that utilise plants known to extract sparingly-available P from soil enabling improved farming system P-balance efficiency	M-L	moderate	Investigate **pasture** systems that capture the P-efficiency benefits of interplanting with 'P-mining species' (e.g. lupin(s), alternative (?) legumes, danthonia) **Issues:** Pastures are 'interplanted' crops and interplanting with P-mining species is known to release P to companion species, but suitable legumes species for pastures are not identified. Explore use of alternative legumes and perennial or decumbemt variants of P-mining plants for low-P pasture systems. Net benefits of P-release in pastures with P-efficient grasses (e.g. danthonia) is unknown, incompatability between pasture composition and P-acquisiton benefits are anticipated. Explore systems that permit synergistic gains in P-acquisition with high productivity.				AR	3~6	Examine effects of changes in plant P economy on soil P dynamics, quality of plant residues, mineralisation, fertiliser requirements and P-balance efficiency of new pasture system(s).	AR	3
	Crop inoculants	Capacity to improve nutrient availability by adding key microbes to the rhizosphere or farming system	**For crops** M-L **For pastures** not recommended ...until placement, efficacy and persistence issues are resolved in crops.	medium low	Studies of the autecology of P-solubilising rhizosphere inoculants in **crop systems** to clarify and assess impact of soil environment on mode of action, persistence, efficacy and relaibility are required. **Issues**: Crop rhizosphere inoculants for yield and P-efficiency are used with mixed success and often with relatively poor reliability. Method of operation can vary and may include: P-solubilization, plant (root) growth promotion, root disease protection. **NOTE:** Some work examining efficacy of inoculants in **pastures** may be required to test claims for microbial products that are on the market, but from a scientific point of view it would be more enlightening to seek to undestand the processes leading to accumulation of Po in soil and the bioavailability of Po substrates and to use this knowledge to inform studies aiming to improve microbial and (novel) plant access to Po in soils.				UR	3~6	Plant-inoculant interactions : genomic & functional genomic analyses./ Mechanistic understanding & markers for rapid isolation of novel strains P-solubilisation mechanisms : comparative genomics & gene expression plant-microbe : PGP (root growth), plant & microbial P transporters, organic acids. Plant-inoculant	AR	3~6

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	Mycorrhiza	Develop plants that utilise mycorrhizal associations more effectively and regardless of soil P status.	M-L	moderate	Critical basic research: understand the mechanism(s) by which mycorrhiza cause plant hosts to decrease the direct (plant) P uptake path; determine if there are associations with additive (plant and mycorrhizal) P uptake capacity.	UR	3~6	If symbioses with addative benefits identied, screen crop and pasture varieties for critical positive responses to both P and AMF	AR	??			
	Global P-supply issues	Address uncertainties in the exposure of Australia to global P shortages and price increases.	S	high	Global P supply - need estimates of the confidence interval around the predicted peak in P supply/demand ...(by using differing estimates of P resource sizes?)	UR	1	Improve the collection and management of P supply and use data for Australia (reliable, transparent, accessible, independent) to inform decision-making/research: **Issues include**: Christmas Island trade – production, reserves etc. Proportion of P lost to water and non-agricultural soils, vs temporary soil stock Optimal mix of agricultural enterprises for more output per unit fertilizer input Understand national organic P flows – manure, excreta, crop residues, food waste – inputs, outputs and accumulations.	UR	3			
	Global P-supply issues	Develop a sustainable P-futures strategy for agriculture	S-M	high	Improve estimates of the business-as-usual future trends for P-use in Australia – estimate the P-requirements for Australian agricultural soils to reach critical P levels, and saturated P status, etc.	UR	3	Use the understanding of soil P status to advise farmers about P-fertiliser mangement and strategies for profitable farming and a sustainable P-future.	AR/D/E	3			
	Global P-supply issues	Develop a sustainable P-futures strategy for agriculture	S	high	Investigate the feasibility and effectiveness of demand management and reuse/supply options (incl infrastructure, socio-technical changes, dietary change, altered farming practices) via thorough "paddock-to-plate" assessments (incl. recovery potential, logistics, energy, costs), to ensure solutions that are appropriate for the Australian context.	AR	2~3						

6 Bibliography

The bibliography is extensive and is currently being completed……………….

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7 Appendices

Appendices to this report are the draft (working) review documents (submitted separately) prepared for the workshop held in Canberra 8-9 June 2010. These documents were incomplete analyses of the situation prepared to stimulate discussion at the workshop. More complete papers are currently in preparation for publication in peer-reviewed journals.