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A strategic framework to improve phosphorus management in the Australian grains industry

Mike TF Wong, Mike Grundy, Michele Barson and Jim Walcott
June 2012

Report to the Department of Agriculture, Fisheries and Forestry

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Contents

Executive summary i
Key terms and concepts v
1 Introduction 1
1.1 Context 1
2 Assessment of P efficiency in agriculture 3
2.1 Issues and desired outcomes 4
P status in the Australia cropping industry 4
2.2 P balance in Australia 5
3 A Roadmap to Profitability and Efficiency 13
3.1 Scope and boundaries 13
3.2 The immediate response: tactical technology solutions to improve P fertiliser management 13
R1 Right amount of fertiliser 14
R2 Right type of fertiliser 17
R3 Right place for the fertiliser 18
R4 Right time of fertiliser 19
The Right Agronomy-the 5th R 20
Applying the 5 Rs to manage P in different soil scenarios 20
Communication and training to implement the 5 Rs of P management 21
4 Medium and long term strategic interventions to improve phosphorus use efficiency – beyond the 5 Rs 23
Accessing "sparingly available" P pools 24
Decoupling soil organic matter and organic P accumulation 25
Productive low P farming systems 26
Improving root-foraging 26
Accessing sparingly available pools of P 26
Improving internal P utilisation efficiency 27
5 Summary of R&D needs 29
6 Conclusions 31
7 References 33

Figures

Figure 1 Phosphorus balance efficiency (% P applied recovered in harvested products) and phosphorus balance (P applied in excess of amounts recovered in harvested products) in Australian cropping compared with sheep, beef, and dairy industries. The box and whisker plots represent median values, 10 and 90th (box), 25 and 75th percentiles (whiskers) and outliers (dots). Reproduced from Weaver and Wong (2011) 6

Figure 2 Temporal changes in Colwell P for soils grouped according to ranges of P buffering index (PBI) values. These values are indices of P sorption by soil (adapted from Weaver and Reed 1998). Overlain points show critical Colwell P values to achieve 90% of maximum production for wheat (○) compared with pasture (●). Upper x-axis shows estimated cumulative P applied assuming annual P input of 14 kg P ha-1. Reproduced from Weaver and Wong, (2011)....7

Figure 3 Changes in phosphorus used as fertiliser and exported in commodities for Australia from 1966 to 2010. Phosphorus calculated as elemental P from fertiliser data from Fertiliser Industry Federation of Australia, and from nominal concentrations in major commodities exported as reported by the ABARES Agricultural Commodity Statistics. Some key influences noted along the bottom of graph. 8

Figure 4 Maps of P application by Natural Resource Management (NRM) regions for 2007-08 and 2009-10 9

Figure 5 Spatial distribution of P status (expressed as Colwell P/ critical value90) for wheat (Castrignano et al., 2012) and achievable yields estimated from satellite imagery (Wong et al., 2001) for a paddock located at Corrigin, Western Australia 18

Tables

Table 1 Phosphorus Buffering Index (PBI) profiles for soil samples in south west WA and associated percentages of soils within each PBI group that exceed the ANZECC and ARMCANZ (2000) dissolved reactive phosphorus (DRP) guidelines for ecosystem health. 5

Table 2 Typical P inputs (kg ha-1 from feed, animals, seed, fertiliser and irrigation), P outputs (kg ha-1 from milk, animals, wool, crops, hay, silage and grain), P balance (kg ha-1), and P balance efficiency (PBE, %) for major enterprises. Within rows, values with different letters are significantly different and increase alphabetically (P<0.05). Adapted from Weaver and Wong, 2011. 6

Table 3 Total number of broadacre cropping businesses sampled and number and percentage of these businesses soil testing for nutrients each year in 2007-2010. Source: Barson et al. (2012). 10

Table 4 PBI-dependent critical Colwell P values for 90% (critical value90) of maximum wheat production. .15

Table 5 Percentage of Western Australian soils exceeding critical values of P for 90% of maximum wheat production and subject to other soil constraints.....20

Table 6 Estimated dissolved reactive P concentrations at critical Colwell P values for wheat (shown in Table 4). The environmental threshold DRP concentration for ANZECC is 0.07 mg P l-1 (Weaver and Wong, 2011) is exceeded by soils with PBI<52.5. 24

Executive summary

Purpose

To review key phosphorus management issues on-farm in the Australian grains industry and develop a strategic framework to respond to these issues and improve efficiency, profits and sustainability

Use of phosphorus (P) fertilisers is critical for agricultural productivity, profitability and food security. However, concerns are increasing in Australia about the security of global supplies of P, rising fertiliser prices and the potential for adverse environmental impact associated with P use. These concerns prompted this assessment of P management in Australian agriculture. We focused on the grains industry because it is one of the largest users of P in Australia. Together with sugar, rice and cotton, they account for ~65% of the 453 kt of P fertilisers currently used annually in Australian agriculture.

This analysis of P use is based on recently published research plus data from the Australian Bureau of Statistics. It identifies the potential to improve P management in the short, medium and long term through tactical and strategic interventions to improve profits and sustainability.

The analysis found contrasting P management issues across southern and northern Australian grain cropping regions. These differences have accumulated over decades of land management, soil type and climate interactions. The data for southern Australia include Western Australia and south-eastern Australia. Those for northern grains region include northern New South Wales and south east Queensland.

In the southern Australian region, we found that:

1. Current fertiliser practice is often causing build-up of soil available P beyond the levels required for near maximum crop production (the critical value). In Western Australia, 87% of 109, 000 soils sampled by farmers and analysed by CSBP in 2008-09 and 2009-10 exceed critical values. In south eastern Australia, the majority of commercial analytical results of soil sampled by farmers exceed the critical value by 1.5 times.
    - These figures should however be interpreted cautiously, since the statistics on the exceedance of critical values only represent growers who test their soils to determine P requirement. Currently about a third of growers surveyed each year undertake soil testing. The rest may be soil testing in the years immediately before or after being surveyed or may not soil test at all.

2. About half of applied P is recovered in grain crops. The other half accumulates in soil, causing build-up that often exceeds critical values and the point at which there is no longer a yield response to P fertilisers. Continued fertiliser P application at these rates may result in environmental damage, unnecessary expenditure by farmers and waste of P.

3. The use of soil testing is, however, not clearly linked with better fertiliser decisions since P continues to build up in soils despite many soil P tests commonly exceeding critical values. The current practice of applying twice as much P as is recovered in harvested crops has remained virtually unchanged compared with figures published twenty years ago. Several soil testing and interpretation issues needed to be addressed.

4. The commonly used Colwell P test did not predict crop response to P well in calcareous soils. The DGT-P soil test was developed in South Australia to address this issue. It works well on calcareous

as well as acid soils by taking account of both the amount of available soil P and its mobility to roots in a single measurement. The DGT-P test is becoming available in commercial laboratories. Predictability of the Colwell P test used on acid soils was improved by integrating it with a separate measure of the mobility of P to roots: the P Buffering Index. Quality accredited laboratories routinely provide Colwell P and P Buffering index tests. Because this approach using these two tests and the DGT P test are relatively new, their benefits in predicting P response better need to be communicated more widely to growers and their consultants to improve adoption. The GRDC "Better Fertiliser Decision" and "More Profits from Crop Nutrition" programs provide information on which soil test to use, how the data are interpreted to determine how much P to apply. These developments would improve grower-confidence to use soil testing to improve P management and profits.

5. A barrier to better fertiliser decisions is the lack of an appropriate tool to maintain the soils' P status once they reach their critical values. For soils that have adequate P, it is not possible with current fertiliser recommendation tools, such as the Soil Management Calculator, to calculate the amount of P required to maintain these soils at their critical values (maintenance rate) (Anderson et al., 2012). These tools are designed to manage P-deficient soils and return an erroneous maintenance rate of zero at and above critical values. Faced with lack of guidance on the correct maintenance practice, growers have continued to use their usual rate of P for last twenty years.

6. For soils with abundant supply of P, we have inadequate data on the rate of decline of soil available P if fertiliser is withheld. The length of time during which P fertiliser can be withheld without risking yield loss is not well documented. A soil monitoring strategy consisting of regular soil testing matched with data on yield and P removal in grains at the same georeferenced sites can help information on this process and make effective recommendations to growers.

In the northern grains region, we found that:

1. Many soils were initially well endowed with P because of their natural fertility. These soils allowed grains to be grown with limited amounts of P fertilisers. More P was often taken off in harvested grains than was applied as fertilisers. Continued use of this practice caused depletion of the natural soil P reserves and frequent occurrence of P deficiency. This deficiency can be corrected using current fertiliser recommendation tools such as the Soil Management Calculator (Anderson et al., 2012). The recommendation is based on measurements of crop response to P and prices of fertiliser and grain to estimate the most profitable amount of P fertiliser required to treat the problem.

2. The idea of using Colwell P and P Buffering Index together for fertiliser recommendation was developed in the Northern region but it applies elsewhere. The region updated information for growers by participating in The GRDC "Better Fertiliser Decision" and "More Profits from Crop Nutrition" programs. It shares a lack of maintenance practice with southern Australia. Here, lack of maintenance has allowed many soils with initially adequate natural supply of P to fall below their critical values and become deficient. An added complexity here is depletion of subsoil P and the need to supply P to the subsoil and to monitor its P status by subsoil testing.

A strategic framework or roadmap to improve soil phosphorus management is proposed to meet the needs of a more profitable and P-efficient grains industry. Additional outcomes are that the grains industry is more resilient against uncertain global P supply and increasing cost of P, and that it can minimise the offsite impact of P on the environment. These off site impacts include water eutrophication, loss of biodiversity, increased water treatment cost and loss of amenity value of water bodies and natural landscapes.

The strategic framework developed to achieve this vision contains immediate, medium and long term actions to improve the efficiency of P use in the Australian grains industry.

Immediate actions:

The immediate issue to be resolved in the grains industry across Australia is the mismatch between fertiliser use and requirement. This can be addressed with current soil test and fertiliser management practices that are captured by the International Plant Nutrition Institute's widely advocated "4 R" of fertiliser management - applying the right amount (R1) of the right type of fertiliser (R2), at the right place (R3) and time of application (R4) to support the farming system objectives for productivity, profitability, sustainability and the environment. We propose an additional 5th R - Right Agronomy (R5) since non-P constraints to crop yield are common in Australia, and adversely impact the efficiency of any fertiliser. The major components of this action consist of communication and training to better inform fertiliser management. The FIFA FertCare accreditation of advisors, federal and state government agencies, IPNI and RDCs as well as agribusinesses and Universities have a role in this action.

The use of soil testing to guide P fertiliser management is currently inadequate to implement an improved P fertilisation system. Several issues have been reported including low grower confidence in soil test data and interpretation; and use of a confusing set of soil testing methods that are sometimes not calibrated locally. Many of these issues have been resolved. Confidence in soil testing itself can be assured by the Australian Soil and Plant Analysis Council (ASPAC) accreditation of the soil testing laboratories. The GRDC's Better Fertiliser Decision and More Profits from Crop Nutrition programs are publishing their findings on soil testing and soil test interpretation to improve P management. The immediate action is to promote these findings through communication and training and underpin the 5 Rs for P management.

The medium term actions:

The medium term (4-6 years) action of this strategic framework aims to promote and complete the development of maintenance P practice and to start its implementation to allow the soil P status to be maintained reliably. A maintenance recommendation is needed because the availability of soil P declines with time due to a number of on-going sorption and/or precipitation reactions with soil, leaching and run-off losses and removal of P in harvested materials. Loss of P availability due to these processes needs to be estimated and off-set by a maintenance rate of P to ensure that the critical value is maintained and future yields and profits sustained. The development of the maintenance rate needs to account for the effect of local soil, climate and land use on P reactions and losses. This development is required for all the grains regions of Australia and needs to involve growers at all stages of development and implementation to promote adoption and better fertiliser use.

An important component of the maintenance rate is replenishment of these ongoing losses of P availability. In addition to applying the five Rs, development of enhanced efficiency P fertilisers has the potential to minimise these losses. Current development of tailor-made polymer treated fertilisers that control their rate of P release to synchronise with crop requirement would minimise losses through adsorption, precipitation, leaching and runoff. These types of fertilisers would decrease the amount rate of P required to maintain soil P. Development and evaluation of these enhanced efficiency fertilisers are needed as part of an integrated approach to improve P management.

Longer term actions:

The long-term action consists of developing cropping systems that need less available soil P and hence have lower critical values to achieve near maximum yields. This will improve the efficiency of use of fertiliser P and decrease fertiliser requirement. Plants take up P from the soil solution and the soil solution concentration required for near-maximum production is reflected in current critical values. At current critical values for sandy soils predominantly found in Western Australia, the concentration of P in soil solution exceeds water quality guidelines adopted in Australia and New Zealand for ecosystem health

(ANZECC and ARMCANZ 2000). This is the potential conflict between fertiliser requirement for productivity and environmental stewardship. While this may be regarded as the environmental cost of production, water quality degradation due to contamination with P is a problem in some regions of Australia.

In the long-term, cropping systems that need lower critical values will pose a lower risk to the environment. Low soil solution concentration in low-P farming systems will also minimise loss of P availability due to on-going processes such sorption and precipitation. Decreased loss of P to the environment and decreased loss of P availability within the soil will result in a corresponding decrease in the amount of P required to maintain the soil at its lower critical value and will therefore decrease fertiliser requirement.

Ultimately, the maintenance rate can simply equate to the amount of P removed in harvested products when losses to the environment to sorption and precipitation processes are negligible. The P balance efficiency (PBE) of the farming system would then be 100% when the amount of P applied is accounted for in harvested grains. Several long established farming systems in Europe operate at close to 100% P balance efficiency. Strategies that can help the Australian grains industry achieve high P balance efficiency close to 100% at critical value are discussed in detail in the suggested road map developed to implement the strategic framework.

Key terms and concepts

Agronomic efficiency (AE) is the yield gained by using P compared with not applying P, and is usually expressed as kg ha^{-1} gained per kg ha^{-1} P applied. AE is high in P deficient soils and decreases to near 0 when critical value is reached.

BSES P is a measure of sparingly soluble P reserves in soil commonly used in the northern grains region.

Build-up phase of P management is used on deficient soils below their critical values. Profitable rates of P fertiliser and/or manures applied increase both available P in soil and grain yield. Poorly managed systems allow build-up to continue well beyond critical values, and this result in both low phosphorus balance efficiency and AE.

Colwell P is a measure of the amount of P in soil that is available to plants. It is the most commonly used measure in Australia, and is usually coupled with P Buffering Index (PBI) to determine soil P status and critical value.

Critical value (CV) for soil P is the soil test P value at which near maximum production can be achieved. Yield will not increase appreciably when the soil P status is increased beyond critical value, but losses due to leaching, runoff and erosion will increase and tie-up of P in sparingly soluble (poorly available to crops) forms will continue. There is therefore little justification for managing soils beyond critical value, but there may be farm business and environmental justifications for managing soil P below critical value (Simpson et al., 2011).

Diffusive Gradients in Thin-films P (DGT-P) is a recently developed test for available P that is particularly well suited for calcareous and alkaline soils where Colwell P does not work well. It also works well for acid soils.

Dissolve reactive phosphorus (DRP) is a soluble form of P that is readily available to plants and microorganisms. It affects the productivity of freshwater ecosystems and risk of algal blooms. Australia and New Zealand have in place, guidelines regarding maximum DRP concentrations to minimise this risk.

Maintenance phase of P management uses a smaller amount of P than the build-up phase to maintain the soil P status close to critical value (after this has been achieved by the build-up phase) and hence to safeguard against future yield loss. It is also required after drawdown of P abundant sites to their critical values. Adoption of the maintenance phase of P management allows maximum P balance efficiency to be achieved when AE is near 0.

Maintenance rate of P fertiliser is the amount of P required to maintain the soil P status close to its critical value. The minimum amount required needs to replace the amount of P exported in harvested materials giving a P balance efficiency of 100% and an AE of 0. The maintenance rate will usually exceed this amount because of loss of P to the environment and continued transformations of soil P to less available forms. Actual maintenance rates and the maximum P balance efficiency that can be achieved are largely unknown for Australian agriculture.

Olsen P is another measure of the amount of P in soil that is available to plants. It is commonly used in Victoria.

Phosphorus balance efficiency (PBE) is the amount of P removed in harvested materials expressed as a percentage of P applied as fertilisers and manures. It is low in deficient soils as applications of economically beneficial rates of P results in build-up of soil P. PBE should increase to its maximum value when critical value is reached and this should offset low AE that is near to 0.

Phosphorus buffering index (PBI) is an index of P sorption measured simply by allowing the soil sample to sorb P from a single solution of P. It can be corrected for P already sorbed onto the soil prior to measurement by adding the amount of Colwell or Olsen P contained in the soil sample. PBI affects soil-specific critical value which tends to increase in soils with high PBI values.

Phosphorus depletion or mining occurs when the amount of P applied is less than the amount removed in harvested materials. This results in decreased soil P status and in loss of yield if soil P is allowed to drop below critical value. Losses of P to the environment and sorption to less available forms increase the rate of P depletion.

1 Introduction

1.1 Context

Improved nutrient use efficiency is a key component of maintaining and increasing productivity, profits and environmental outcomes in the Australian grains industry and elsewhere. This is especially the case with the macronutrient phosphorus (P) – due to inherently low levels in most Australian soils, its increasing cost and its potential adverse impact on water quality. This document reviews the issues around P management within the farm and suggests a strategic framework or roadmap to enhance its efficiency and effectiveness in increasing profits, efficiency and sustainability.

Phosphorus is an essential plant nutrient and its supply from soil and fertilisers is fundamental to support agricultural production, food security and rural prosperity. Agricultural soils in most parts of Australia were largely unproductive until treated with P fertilizers (McLaughlin et al., 2011). Australian agriculture currently uses 453 kt a^{-1} of P fertilisers of which 290 kt a^{-1} is used in cropping systems and 163 kt a^{-1} in pastures and feedlots for livestock production (White et al., 2011). About 60% of P used in Australia is imported either as rock P or as fertilisers, the remainder is derived from domestic mines. The dependence of agricultural production on P fertilisers calls for sustainable management practices to ensure its economic viability and availability to farmers (Syers et al., 2011).

Estimates of the world reserves of rock P continue to evolve rapidly and are currently estimated to be around 65,000 Mt. This would last ~300-400 years at current production rates of 160 to 170 million tonnes per year (Syers et al., 2011). Morocco has the largest reserves (~77%) followed by China which has significantly smaller reserves (5.7%). Together with Algeria (~3.4%) and Syria (~2.9%), these four countries control about 90% of global rock P reserves (Jasinski, 2011). In contrast, the reserve in Australia is estimated at 82 MT or about 0.13% of global reserves. Australian reliance on P import and the concentration of global P reserves in only a few countries means that supply is insecure. The cost of P fertilisers is greatly influenced by large fluctuations in the global price of P which peaked in 2008 but continues on an increasing trend (White et al., 2011). This increasing trend in the price of P is unlikely to change due to demand for P to underpin food security for a growing world population, demand for biofuel production and from soil carbon sequestration which also results in an increase in the base level of P in soils.

It is imperative that P is used efficiently in agriculture. P deficiency restricts plant growth, leading to loss of revenue, low soil carbon accumulation and potentially to soil erosion due to limited root growth and ground cover. P overuse can result in losses to surface waters and environmental problems such as eutrophication of waterways (Environment Protection Authority, 2008). Recently, issues relating to food security, rising fertiliser costs, and debate over the quantity and longevity of global phosphate rock supplies have emerged in relation to sustainable use of P (Cordell et al. 2009; Kauwenbergh 2010; Schroder et al., 2010). While the solution to more efficient use of P is found both on-farm and off-farm (Schroder et al., 2010, White et al., 2011) through the management of P supply, processing and re-use, this work will focus on on-farm interventions to improve efficiency of P use, profits and environmental outcomes. In Australia, about 90% of the P in agricultural products is exported, and recycling will cover only 5-10% of the annual P requirements of agriculture (Simpson et al., 2010). While there will be an increasing role for P-fertilisers derived from waste streams, the major avenue for addressing increases in P-fertiliser costs in Australia will be through improved P-use efficiency on-farm.

2 Assessment of P efficiency in agriculture

Several methods are available to assess the efficiency of P use in agriculture (Syers et al. 2008, Chien et al., 2012). The choice of method depends primarily on purpose, but also on practicality and availability of data. The most commonly available data measures the agronomic efficiency of P in soils with varying P status (Peverill et al. 1999). Yield gained by using P is compared with not applying P, and allows economic assessment of fertiliser management. Agronomic efficiency is often complemented with nutrient budget approaches to assess whether the soil stock of P is being maintained, depleted or increased (Syers et al., 2008). Oenema et al. (2003) list three nutrient budget approaches of varying complexity (farm-gate, soil surface and soil system). Depending on the complexity of data gathered, nutrient budgets are used to increase understanding of nutrient cycling, to measure P efficiency, for inventory monitoring and as policy instruments (OECD 2008).

Farm-gate budgets are equivalent to the P Balance Efficiency (PBE) method described by Syers et al. (2008). Phosphorus balance efficiency is the percentage of P input from fertilisers, manures, animal feed etc that is recovered in harvested materials. It is widely used because it offers a simple approach with minimal data requirements to assess how soil P reserves are building up, depleting or maintained in relation to the soil P status. The P balance efficiency method is used as an indicator of environmental performance of agriculture in OECD countries (OECD, 1999; 2008).

Agronomic efficiency and P balance efficiency are ideal complements in assessing the management of P in relation to the soil P status. In deficient soils below their critical P values, yield response to the application of economically beneficial rates of P should result in good agronomic efficiency, increased soil P status and hence low P balance efficiency. This phase of P management is called the build-up phase. When soil test P values for near maximum production (critical values) are reached, response to P declines, yields are near their maximum and agronomic efficiency approaches 0. At that point a downshift to the maintenance phase of P management is required, where less P is applied to maintain soil P close to its critical values. Phosphorus balance efficiency should then be at its maximum to offset low agronomic efficiency close to 0 i.e. P balance efficiency and agronomic efficiency should offset each other in well managed farming systems.

In the northern grains region, soils with initially adequate natural supply of P above their critical values generally received less P than was removed in harvested product (Bell et al., 2010). This P depletion scenario gave P balance efficiency >100% (more P removed than applied) and agronomic efficiency close to zero. As P depletion lowered the availability of soil P to critical values, P input should then be increased to maintenance rates that at least match P outputs to give a P balance efficiency of 100% while agronomic efficiency remains close to zero.

The relationship between agronomic efficiency and P balance efficiency during the maintenance phase of P management is not well established. Simpson et al. (2010) suggest that when soil test P values for near maximum production have been reached in a soil, P additions will be required to maintain soil test P values at or close to critical values by replacing P losses (products, leaching and runoff), and transformation into less plant-available forms. This implies P balance efficiency <100% when agronomic efficiency is close to 0 (critical values being reached). In contrast, Syers et al. (2008) suggest that balancing P removal in products with an equivalent amount of fertiliser P is the maintenance requirement, and would lead to a P balance efficiency of 100% to offset an agronomic efficiency that is close to 0.

The implicit assumption by Syers et al. (2008) is that pools of non-bicarbonate extractable P are in dynamic equilibrium with the critical concentration, and would not increase further so long as the soil bicarbonate-extractable P is maintained at this critical concentration. They also assume explicitly that various pools of P can transfer P at rates matching those of plant uptake. Whilst P is transferred at varying rates between various pools of P, it is recognised that slow but continuing sorption reactions and precipitation of P will increase maintenance P requirements above that associated with removal in products and losses by leaching, runoff and erosion (Weaver and Wong, 2011).

2.1 Issues and desired outcomes

P status in the Australia cropping industry

The majority of soils sampled by growers across southern Australia have soil P values which exceed critical values for near-maximum wheat production (Table 1, Weaver and Wong, 2011, Figure 6, Simpson et al., 2011). In Western Australia, soil P levels in 87% of cropping soil sampled exceed their critical values, and most are acidic. This conclusion is based on analysis of 109,000 soil test (0-10 cm) data records for soils from south west WA for the soil sampling seasons of 2008/9 and 2009/10 (made available by CSBP Limited, http://www.csbp.com.au). Another study of 83 rural districts defined by postcodes in south-eastern Australia showed that the majority of commercial analytical results of soil samples taken by farmers under wheat (average 32 samples per postal district) exceeded their critical values by more than 1.5 times and were acidic (Simpson et al., 2011).

The situation is markedly different in the northern grains region (northern New South Wales, southern and central Queensland). Here inadequate use of P fertilisers to maintain the soil P status in crops has resulted in decline in soil P to deficient levels in an increasing number of soils across the region (Bell et al., 2010). The cropping system in the northern grains region is characterised by rotations and opportunistic sequences of winter and summer cereals. These are grown predominantly on Vertisols, Chromosols and Sodosols with high native fertility that have been subject to nutrient mining (especially P and potassium), with subsequent soil fertility decline. Erratic seasonal rainfall and a lack of reliable soil test calibration place a financial risk on growers, and this may partly explain the low investment in fertilisers in this region (Bell et al., 2010). There are some cropping soils with adequate levels of soil P due to naturally P enriched soils that have not been depleted to below their critical values. This is in contrast with southern areas, where soils with adequate and high P levels have resulted from fertiliser application to initially low P soils.

Common exceedance of critical values across southern Australian grains industry (Table 1) may have adverse environmental consequences. The ratio of Colwell P to P buffering index expresses the amount of available P in soil and how strongly it is held or adsorbed by soil. This ratio can be used to estimate calcium chloride-extractable P concentration in soil solution, and hence the source risk of dissolved reactive P (DRP) loss from soils (Moody, 2011). Samples with Colwell P/PBI ratio > 0.07 exceed the Australian (ANZECC and ARMCANZ 2000) water quality guidelines for ecosystem health. This ratio was calculated for data available for WA only (109,000 soil samples) and compared with these water quality guidelines (Table 1). There are insufficient data to compare WA with other cropping regions of Australia, but a similar problem of exceedance of critical values and DRP concentrations above water quality guidelines occurs across the Australian dairy industry (Weaver and Wong, 2011). Whilst high DRP concentrations in the catchment may not translate to contamination of streams, rivers and lakes, it provides a comparative measure of the source risk to water quality from soils of varied P status. Virtually all WA grain cropping soil samples do not meet DRP standards (Table 1).

Table 1 Phosphorus Buffering Index (PBI) profiles for soil samples in south west WA and associated percentages of soils within each PBI group that exceed the ANZECC and ARMCANZ (2000) dissolved reactive phosphorus (DRP) guidelines for ecosystem health.

PBI Range	PBI Profile (% sample in PBI range)	% exceedance of DRP guidelines	% exceedance of critical value to achieve 90% of maximum wheat production
<5	2	99.6	88
5-10	8.4	99.9	91
10-15	10.8	99.9	93
15-35	42.7	99.9	92
35-70	22.4	99.8	82
70-140	8.7	99.1	54
140-280	3.8	95.9	39
280-840	1.2	75.6	
>840			

2.2 P balance in Australia

With 87-89% of soil sampled by growers and analysed commercially from WA cropping farms exceeding their critical values for near-maximum production, current P management practices seem to be at the expense of profitability and environmental quality. Such exceedance of critical values is also reported in cropping soils of south east Australia (Simpson et al., 2011). The OECD (1999, 2008) uses a farm gate balance as an agro-ecological indicator to capture how well nutrients are used. A farm gate balance measures the differences between nutrient contents of farm inputs (from fertilisers, feed, manure etc) and the nutrient content of the outputs from the farm. The approach can also be applied at the paddock scale to separate farm gate P balance associated with different activities such as cropping and sheep production on the same farm.

Using this indicator and a comprehensive assessment of available data, Weaver and Wong (2011), found that the percentage of P inputs found in harvested grains (P balance efficiency, PBE) is less than 50%. This on its own does not indicate likely environmental impact. It has to be interpreted with other information especially soil test data and P cycling processes in soil. P balance efficiency averages 48% in southern grain areas (Figure 1), which is substantially better than for dairy cattle (29%), beef cattle (19%) and sheep (11%). These landscapes have a positive P balance and are accumulating P.

These P balance efficiency values have not changed appreciably since they were last studied by McLaughlin et al. (1992). These authors reported a P balance efficiency of 45-54% for grain crops and 20% in wool, meat, milk, live export. The amounts of P applied in excess of removals in harvested products are lower in cropping farms (6.1 kg P ha^{-1} a^{-1}) than in dairy farms (18.1 kg P ha^{-1} a^{-1}), beef (9.1) and in sheep (8.7) (Table 2).

The fate of on-going application of excess P and its effect on plant available P measured as Colwell P depends on P buffering index (Weaver and Wong, 2011). In soils with low P buffering index, there are small increases in Colwell P after critical values are reached (Figure 2), and losses from the 0-10 cm layer occur. In these typically sandy soils, Colwell P reaches its maximum value within a few decades after first application of fertiliser, and continued application of P is partitioned between removal in harvested materials and losses. Leaching is less important in high PBI soils (finer textured loamy and clayey soils that adsorp P more strongly) but growth in Colwell P values is dampened by sorption or precipitation into forms

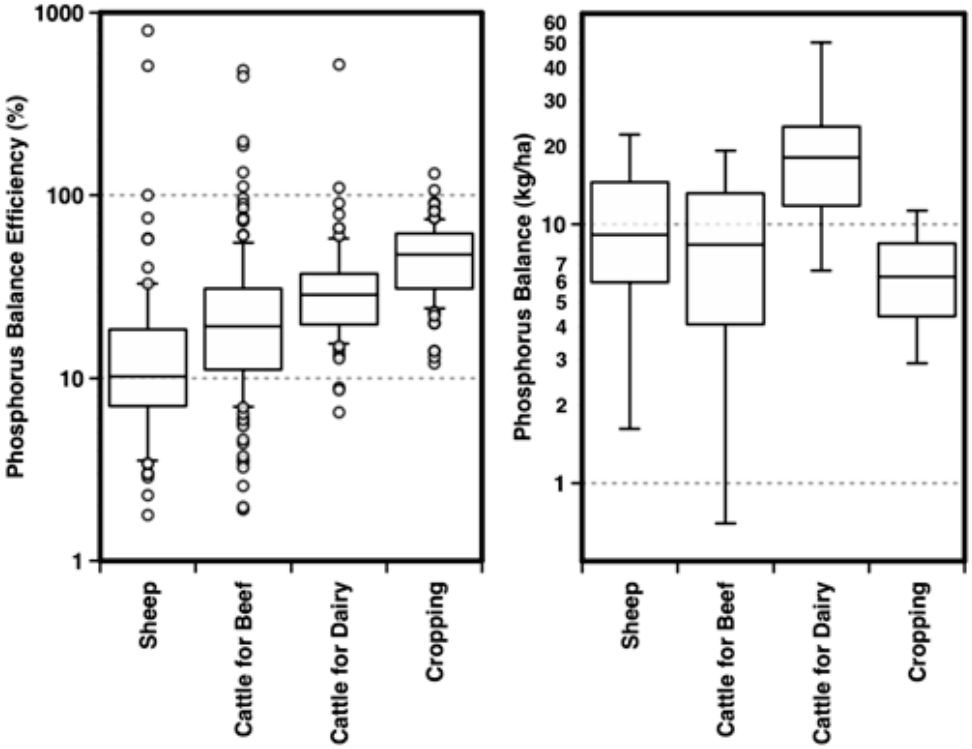


Figure 1 Phosphorus balance efficiency (% P applied recovered in harvested products) and phosphorus balance (P applied in excess of amounts recovered in harvested products) in Australian cropping compared with sheep, beef, and dairy industries. The box and whisker plots represent median values, 10 and 90th (box), 25 and 75th percentiles (whiskers) and outliers (dots). Reproduced from Weaver and Wong (2011)

that are not measurable by the Colwell method. There is also a trend towards a maximum, but this happens much later and at greater Colwell P values. This analysis of the trends in Colwell P with time in soils with varying PBI led Weaver and Wong, (2011) to conclude that Colwell P build up is continuing at different rates under current P management practice despite many soil samples examined already exceeding their critical values.

In the northern grains region, the P balance becomes negative once the yield of wheat, sorghum, chickpea and barley exceeds 2.0-2.3 t ha^{-1} thus causing nutrient mining, soil fertility decline and more frequent occurrence of P deficiency. This region uses dilute acid extraction (BSES P) to estimate the reserve of soil P below the surface 10cm. On average, cropped soils across this region contained 68% of the inorganic P reserves of the uncropped reference sites, suggesting that P mining has taken place (Bell et al., 2010).

Table 2 Typical P inputs (kg ha^{-1} from feed, animals, seed, fertiliser and irrigation), P outputs (kg ha^{-1} from milk, animals, wool, crops, hay, silage and grain), P balance (kg ha^{-1}), and P balance efficiency (PBE, %) for major enterprises. Within rows, values with different letters are significantly different and increase alphabetically (P<0.05). Adapted from Weaver and Wong, 2011.

	Dairy	Beef	Cropping	Sheep
P inputs (*kg ha^{-1}*)	20.7 – 27.3b	9.9 – 12.3a	11.2 – 12.3a	9.0 – 12.1a
P outputs *(kg ha^{-1})*	5.3 – 8.5d	1.6 – 2.2b	5.1 – 6.4c	0.9 – 1.4a
P Balance (kg ha^{-1})	13.7 – 20.4c	7.5 - 9.9ab	5.4 – 7.3a	8.0 – 10.9b
PBE (%)	23 – 32c	16 – 23b	42 – 53d	9 – 12a

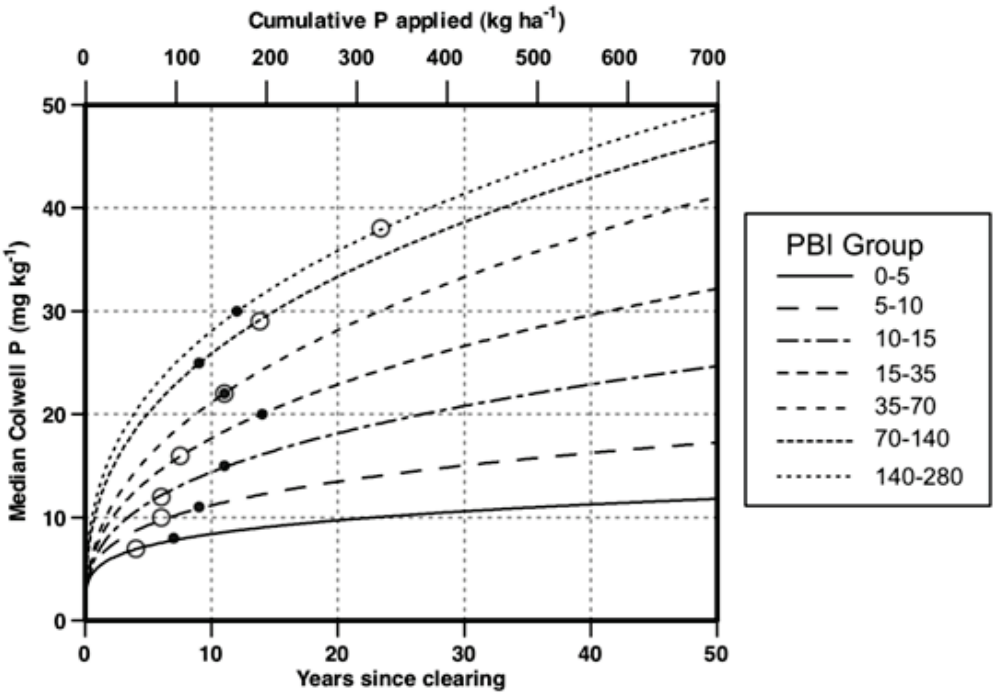


Figure 2 Temporal changes in Colwell P for soils grouped according to ranges of P buffering index (PBI) values. These values are indices of P sorption by soil (adapted from Weaver and Reed 1998). Overlain points show critical Colwell P values to achieve 90% of maximum production for wheat (○) compared with pasture (●). Upper x-axis shows estimated cumulative P applied assuming annual P input of 14 kg P ha^{-1}. Reproduced from Weaver and Wong, (2011).

P management and application

Only limited information is available on trends in the on-farm management of P. Figure 3 indicates that there is likely to be a high level of volatility in P applications in Australian agriculture. There is an overall mismatch between fluctuations in P use and export of P in agricultural commodities. Fertiliser use appears strongly linked to price signals. For example, P use increased rapidly in the years before the foreshadowed end of subsidies for P fertilisers in 1975 and declined rapidly thereafter. A similar decline occurred with the price spike in 2008. The P export in agricultural commodities responds more slowly to price signals but rapidly to climate effects such as drought. Amalgamated across Australian agriculture, these survey data show continued application of P in excess of export of P in commodities throughout the survey period 1966 to 2010. The narrower gaps between P application and export in 1975, 1989 and 2008 still indicate substantially more P applied than exported at the continental scale.

More detailed and comprehensive data on land management in Australia is now collected biennially by the Australian Bureau of Statistics in the biennial Agricultural Resource Management Survey (Australian Bureau of Statistics 2009). Figure 4 maps the data for P applications by Natural Resource Management (NRM) regions for 2007-08 and 2009-10. The rates for 2007-08 were similar to those in 2009-10. However, these periods coincided with the high price index and corresponding drop in fertiliser use. Later surveys will reveal whether trends are developing.

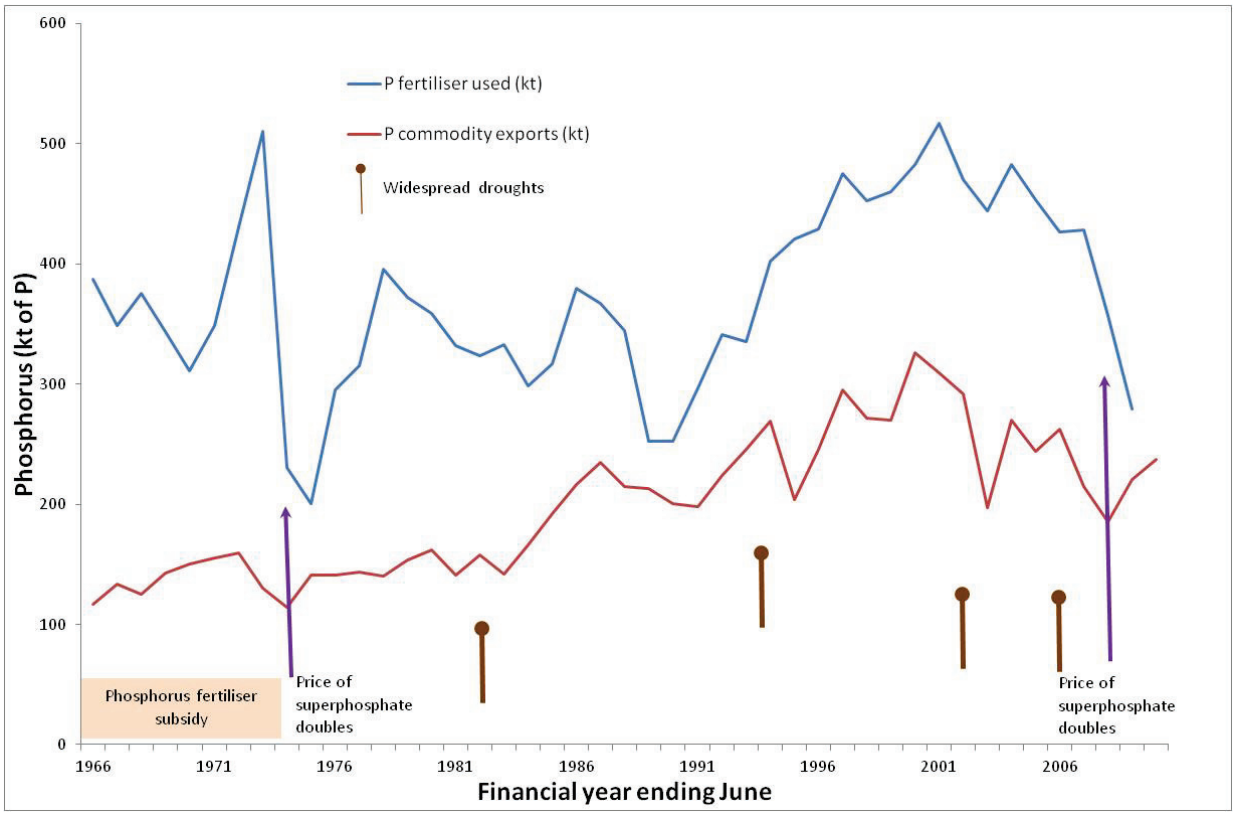
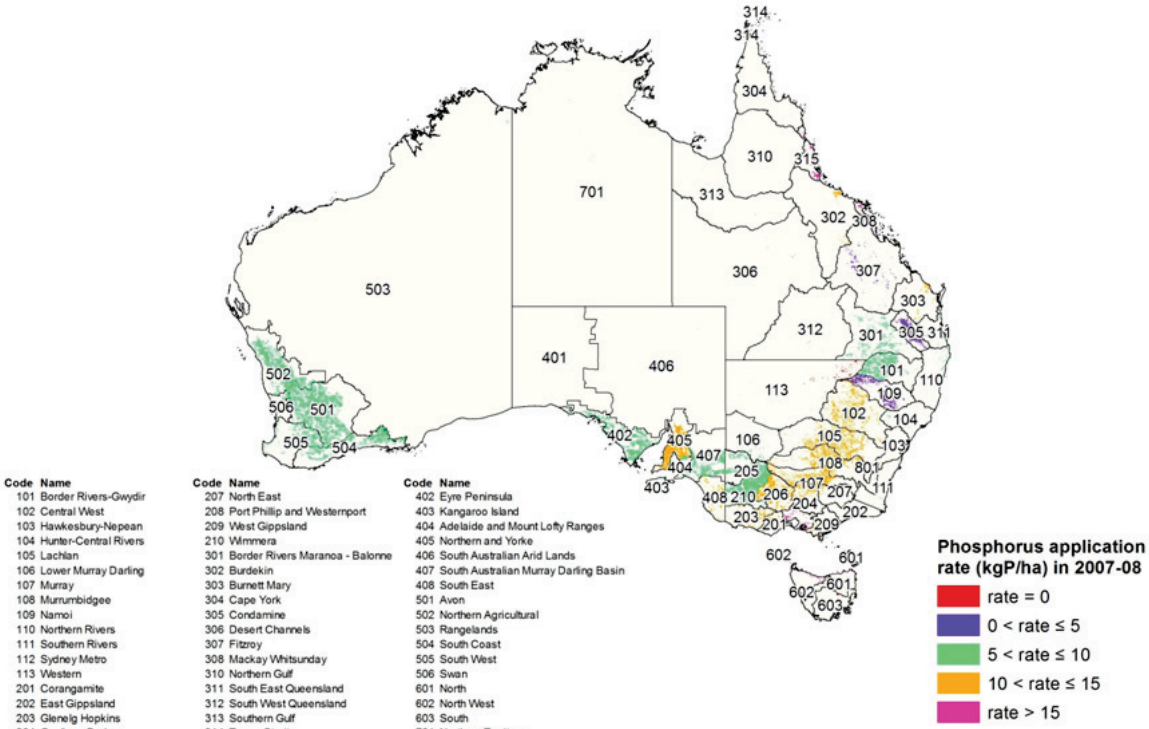


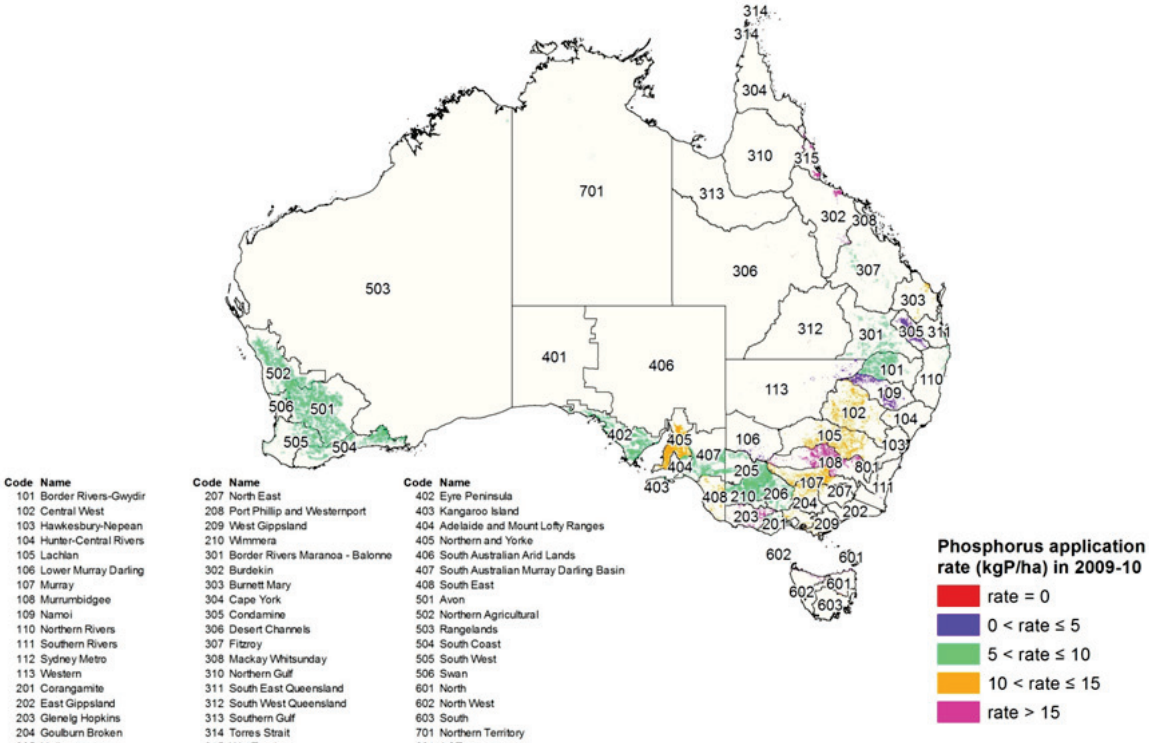
Figure 3 Changes in phosphorus used as fertiliser and exported in commodities for Australia from 1966 to 2010. Phosphorus calculated as elemental P from fertiliser data from Fertiliser Industry Federation of Australia, and from nominal concentrations in major commodities exported as reported by the ABARES Agricultural Commodity Statistics. Some key influences noted along the bottom of graph.



Code	Name	Code	Name	Code	Name
101	Border Rivers-Gwydir	207	North East	402	Eyre Peninsula
102	Central West	208	Port Phillip and Westernport	403	Kangaroo Island
103	Hawkesbury-Nepean	209	West Gippsland	404	Adelaide and Mount Lofty Ranges
104	Hunter-Central Rivers	210	Wimmera	405	Northern and Yorke
105	Lachlan	301	Border Rivers Maranoa - Balonne	406	South Australian Arid Lands
106	Lower Murray Darling	302	Burdekin	407	South Australian Murray Darling Basin
107	Murray	303	Burnett Mary	408	South East
108	Murrumbidgee	304	Cape York	501	Avon
109	Namoi	305	Condamine	502	Northern Agricultural
110	Northern Rivers	306	Desert Channels	503	Rangelands
111	Southern Rivers	307	Fitzroy	504	South Coast
112	Sydney Metro	308	Mackay Whitsunday	505	South West
113	Western	310	Northern Gulf	506	Swan
201	Corangamite	311	South East Queensland	601	North
202	East Gippsland	312	South West Queensland	602	North West
203	Glenelg Hopkins	313	Southern Gulf	603	South
204	Goulburn Broken	314	Torres Strait	701	Northern Territory
205	Mallee	315	Wet Tropics	801	ACT
206	North Central	401	Alinytjara Wilurara		

The map shows the kilograms of phosphorus applied per hectare of total area fertilised by broadacre crop farmers within each NRM region.

Kilograms of phosphorus were calculated by multiplying the kg of phosphorus-containing fertilisers applied, by the approximate proportions of phosphorus they contain (as advised by the Fertilizer Industry Federation of Australia). Results are rates calculated as kilograms of phosphorus applied to the hectares of total area fertilised (which could also include pastures and horticulture) by broadacre crop farmers in each NRM region, and are shown masked to cropping areas.
Data come from the ABS' 2007-08 Agricultural Resource Management Survey.



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Data come from the ABS' 2009-10 Agricultural Resource Management Survey.

Figure 4 Maps of P application by Natural Resource Management (NRM) regions for 2007-08 and 2009-10

Soil Testing Issues

The percentage of broadacre crop businesses soil testing for nutrients varies between Australian states and territories. Across Australia, about a third of the broadacre cropping businesses sampled each year in 2007-08 and 2009-2010 soil tested for nutrients (Table 3). These periods again coincided with the high price index and corresponding drop in fertiliser use. It is possible that those who did not soil test in the year when they were surveyed may have soil tested in the years immediately before or after they were surveyed. It is also possible that they do not soil test at all. A frequency of soil testing of once every 2-4 years is likely to be adequate to inform fertiliser decisions since a soil test is only required every 2-4 years depending on soil, farming system and the stability of the soil test value. Soil test P values are expected to fluctuate more rapidly in sandy soils with low PBI such as those commonly found in the Western Australian cropping zone. This may explain the high frequency of soil testing in Western Australia compared with other states where finer textured soils with higher PBI dominate.

Table 3 Total number of broadacre cropping businesses sampled and number and percentage of these businesses soil testing for nutrients each year in 2007-2010. Source: Barson et al. (2012).

	Year	Estimated number of broadacre crop businesses using soil testing	% broadacre businesses soil testing	Estimated total number of broadacre crop businesses sampled
Australia	07-08	20 245	29	70 008
	09-10	17 565	27	64 571
NSW/ ACT	07-08	5 626	30	18 642
	09-10	4 356	25	17 203
Vic	07-08	5 383	27	20 090
	09-10	4 759	24	19 772
Qld	07-08	2 792	26	10 883
	09-10	3 376	34	9 791
SA	07-08	1 876	22	8 649
	09-10	1 432	19	7 685
WA	07-08	3 476	39	8 877
	09-10	2 847	37	7 593
Tas	07-08	1 034	38	2 741
	09-10	787	32	2 463

In most states except Queensland, the percentage of businesses soil testing appears to have dropped slightly in 2009-10. The increase from 26 to 34% of broadacre businesses soil testing in Queensland may be influenced by the implementation of the Reef Plan that requires farmers in NRM regions within the catchment for the Great Barrier Reef lagoon to do soil testing and use the results of these tests to determine the optimum amount of fertiliser for the crop (Great Barrier Reef Protection Amendment Act, 2009). Although Western Australian broadacre cropping businesses had the highest percentage of businesses testing soils for nutrients; they also had a high proportion of these soil tests exceeding their critical values.

Several issues may hamper the use of soil testing to inform better fertiliser decisions. Confidence in the soil test values themselves would be improved by analytical quality assurance/quality control and accreditation process provided by the Australian Soil and Plant Analysis Council (ASPAC). Several commercial and government laboratories are ASPAC accredited. In addition to accurate soil analysis, it is important that the soil sample represents the area of land being managed accurately. Sampling strategies to achieve this are discussed later.

Confusion may arise due to different soil tests for P being used in different regions. The Colwell P test commonly used in Australia does not perform well on calcareous and alkaline soils commonly found in South Australia. It gives poor calibration with yield response on these soils. Development of the DGT-P method has addressed this issue by integrating the amount of available P in soil with its ease of transport to plant roots in one measurement (Mason et al., 2010). The DGT-P test also works well in acid soils because the same principle applies. Although promising, this soil test is not yet widely available commercially. Meanwhile, a recent improvement in the interpretation of the Colwell P test also integrates data on the amount of available P in soil (Colwell P) with the ease of its transport to plant roots (assessed as PBI). This approach works well in acid soils (Moody, 2007). The Colwell P and P buffering index tests are widely available and complement the DGT-P method for calcareous and alkaline soils. These developments are relatively recent and their benefits for predicting yield responses should be communicated more widely to growers and their consultants. Some other methods are being used (e.g. Mehlich P) but there is little data on their calibration with field response and this may be a source to grower confusion with soil tests.

The GRDC's Better Fertiliser Decision and More Profits from Crop Nutrition programs focused on soil testing, its interpretation to improve fertiliser management and in improving profits. The findings of these programs are being published. This should improve grower confidence about which soil test to use and how the data can be interpreted to inform better fertiliser decisions. Training and communication through the FIFA FertCare accreditation of advisors, federal and state government agencies, IPNI and RDCs as well as agribusinesses and Universities have a role in promoting the adoption of these findings.

3 A Roadmap to Profitability and Efficiency

VISION: A MORE PROFITABLE AND P-EFFICIENT GRAINS INDUSTRY THAT IS MORE RESILIENT TO UNCERTAIN GLOBAL SUPPLY AND INCREASING COST OF P AND THAT MINIMISES OFFSITE IMPACT ON THE ENVIRONMENT

IMPLEMENTING THE 5 R APPROACH TO P FERTILISATION

3.1 Scope and boundaries

The scope of the roadmap is on-farm P management to close the gap in P use efficiencies (P balance efficiency and AE) and in so doing improve profits and environmental outcomes from better P management. It focuses on the grains industry in southern Australia (which includes Western Australia and south east Australia) and the northern grains region of northern New South Wales and south east Queensland – although the principles apply across cropping regions throughout Australia. The purpose is to define a set of actions and immediate tactical interventions to improve the efficiency of P use as well as strategic interventions that could be implemented in the 5-10 year time frame. The road map is intended to be used by policy makers as well to guide investment and policy to encourage better P management in Australia. The roadmap excludes farm to fork to farm recycling of P, recovery from waste streams and fertiliser manufacture, although these remain important for the management of P across the whole economy.

3.2 The immediate response: tactical technology solutions to improve P fertiliser management

In 2008 the International Plant Nutrition Institute (IPNI) released a global framework to facilitate development and adoption of practices to improve management of fertilisers for better economic, social and ecological outcomes (IPNI, 2008). The framework formulates the key tactical issues to be addressed as the 4 R of fertiliser management - applying the right amount (R1) of the right type of fertiliser (R2), at the right place (R3) and time of application (R4) to support farming system objectives for productivity, profitability, sustainability and the environment. Each of the four issues of fertiliser management interacts with each other for example, the type of fertiliser influences its time of application and the place where the fertiliser is applied influences the amount needed.

The relative importance of each issue varies according to country, regions and various dimensions of farming systems. Across Australia, applying the right amount (R1) is a dominant problem for P fertilisers due to science and technology lagging behind changes in soil P status reported across its agricultural industries (Weaver and Wong, 2011). Soil testing and more importantly inadequate use of soil data to guide fertiliser management is an issue to be addressed through research, development and extension through education and training. A fifth R (R5), the right agronomy, is essential to derive the most benefits from fertilisers. Constraints such as acidity and soil compaction that limit water uptake, common in Australia, lower the agronomic benefits of fertilisers and need to be addressed to optimise fertiliser management.

R1 Right amount of fertiliser

Soil testing

Soil tests coupled with the results of field calibration based on yield response to P are used to inform the decision on how much P to apply (Gourley et al., 2007, Moody, 2007, Windsor et al., 2010). Soil test P values used to assess P status and hence likely response to P application are commonly measured using sodium bicarbonate extraction in Australia. The Olsen method (Olsen 1954) is used in Victoria and Tasmania, the rest of Australia uses a modified version of the Olsen procedure called the Colwell method (Colwell 1965). Both methods are a measure of the amount of P in soil that can be extracted by sodium bicarbonate, and this correlates with the amount taken up by crops and pastures. They differ in the ratio of soil to extracting solution and duration of extraction.

Soil P needs to be transported to root surfaces to allow uptake, and the major transport process is by diffusion. The partitioning of P between the solution and solid phase, or P buffering, affects the rate of P diffusion to root surfaces (Olsen and Watanabe, 1970). This should be taken into account when interpreting the results of bicarbonate extractable P in relation to soil P status. The agreed Australian measure of P buffering is the single point P sorption index (Burkitt et al., 2002, Bolland and Windsor 2007) known as the P buffer index (PBI) of the soil. In addition to its effect on diffusive transport of P to roots, PBI also affects the concentration of dissolved reactive P in solution. This is correlated with the Colwell P/PBI ratio (Moody, 2011). PBI is calculated from measured sorption of P upon a single addition of P plus pre-existing Olsen or Colwell P and the equilibrium solution P after sorption (Burkitt et al., 2002).

A PBI test should be carried out along with the soil Colwell P test to give a measure of how much is in the soil and how easily this can be transported to root surfaces. This approach using Colwell P and PBI is a recent development that improves the predictability of Colwell P (Moody, 2007). PBI values range from <15 for extremely low P sorbing soils to >280 for high sorbing soils. Either the Colwell or Olsen soil P test is routinely available in quality accredited commercial and state laboratories – with differences in emphasis on methods between state laboratories. These laboratories also perform PBI tests. Both tests are needed for each sample.

The approach using Colwell P and PBI only works well in soils where sorption (measured as PBI) is the dominant process tying up P. It is not useful in calcareous and alkaline soils where precipitation is the dominant process. Calcareous alkaline soils are common in South Australia. In these soils, the Diffusive Gradients in Thin-films P (DGT-P) provides a good single measure of both the amount of soil available P and its transport to the thin-films that is well correlated with crop response (Mason et al., 2010). By combining availability and transport in one measure, the DGT-P method also works well in acid soils where sorption predominates. The DGT-P soil test is becoming available in commercial laboratories. Both the DGT P method and use of Colwell P with P buffering index are relatively recent and need to be communicated widely to growers and their consultants to improve prediction of response to P.

Soil sampling

The Olsen, Colwell, P Buffering Index and DGT-P tests used to assess P needs are usually carried out on soil sampled at 0-10 cm. P concentration is commonly highest in the top few mm of soil, especially in no or minimal-tilled cropping systems (McLaughlin et al., 2011). It is therefore important that a consistent soil depth is sampled to avoid bias, this can be achieved using a “pogo” sampler. The “pogo” sampler is a steel tube with a horizontal disk set at 10 cm to allow sampling at a fixed depth. The pogo sampler collects < 100 g soil each time, and between 30-40 pogo samples should be taken across a uniform area to represent it adequately (Russell, 2010). This uniform area can be small paddocks < 10 ha, or uniform soil types or topographic locations within larger paddocks. Sampling patterns across the uniform area include transects and zig-zags along the general direction of transects across the area. The statistical benefits of these patterns across the assumed uniform area have not yet been fully evaluated, but it is thought that cluster

or monitor plot sampling is more efficient than transects in terms of accuracy and cost (Blair and Lefroy 1993).

Use of 0-10 cm soil samples is not enough in the northern grains region. There subsoil P provides a significant proportion of the crop requirement due to access to stored water in the subsoil. Subsoil sampling and testing is required to predict response in soils and farming systems of this region (Bell et al., 2012).

With the advent of cheap and accurate GPS, cluster sampling within uniform areas of the paddock is becoming increasingly popular. Again 30-40 pogo samples near to the point are recommended. This strategy allows changes in P status to be monitored in a simpler manner by minimising the effect of spatial variability. In crop and pastures, sampling is commonly carried out before the start of the growing season normally in January to March. To allow ease of comparison, it is recommended that soils are sampled at approximately the same time each year. Russell (2010) provides more detailed advice on soil sampling. It is recommended that records are kept of soil analyses to track changes over time and space. Sharing the data with research organisations would further enhance their value by allowing overviews of the industry as a whole; this information could be used to help prioritise RD&E efforts.

Interpretation of soil test results

The outputs of recent work delivered in 2007 and 2010 have vastly improved the interpretation of soil test results for P (Moody (2007, Gourley et al., (2007)), Windsor et al., (2010)) across Australia. These studies determined soil test P values required to reach near-maximum production (critical values) from yield response - soil test relationships. A critical value for 90-95% of maximum production is commonly used as a reference point to assess whether soils are sufficient or deficient, and whether application of P is likely to increase yields. When Colwell P was used, the critical value varied significantly between soils due to differences in PBI. For this reason, soil specific Colwell critical values are required for both crops and grazed pasture (Gourley et al., 2007, Moody, 2007, Windsor et al., 2010). Table 4 shows critical values for 90% of maximum wheat production derived from data from Queensland, NSW, Victoria, South Australia and Western Australia (Moody, 2007). The critical values will be lower for lower production targets (Bolland at al., 2010).

When direct measurements are not available, PBI can be estimated from the ammonium oxalate extractable iron oxide (Amox Fe) content of the soil (Weaver and Wong, 2011) to determine applicable critical values:

$$log_{10}(PBI) = -0.662 + 0.773 \times log_{10}(Amox\ Fe)$$, $R^2 = 0.76$, n = 320

Table 4 PBI-dependent critical Colwell P values for 90% (critical value$_{90}$) of maximum wheat production

PBI range	*Mid PBI*	*Moody's estimates wheat (critical value$_{90}$)*[1] mg P l^{-1}
0-5	2.5	7
5-10	7.5	10
10-15	12.5	12
15-35	25.0	16
35-70	52.5	22
70-140	105	29
140-280	210	38
280-840	560	N/D

[1]Critical value$_{90}$ = 4.60 x PBI$^{0.393}$, r^2 = 0.64 (Moody, 2007)

How much to apply

The amount of fertiliser to apply is calculated for deficient soils based on the anticipated crop response to P fertilisers, fertiliser cost and commodity prices (Anderson et al., 2012). In these soils, application of economically beneficial rates of P causes a build-up of soil P and a subsequent yield response. The agronomic efficiency of the fertiliser quantifies this yield response in terms of yield gained due to fertiliser application (Syers et al., 2008). Because of build up of soil P, high agronomic efficiency in deficient soils should be accompanied by low P balance efficiency. This phase of P management is the build-up phase.

During the build-up phase, P deficiency will ensure that low P balance efficiency does not translate to high environmental risk. When critical values are reached, response to P becomes small and agronomic efficiency approaches 0. At that point a change to the maintenance phase of P management is required, and less P is applied to maintain soil P close to its critical values to sustain productivity. Phosphorus balance efficiency should then be at its maximum i.e. P balance efficiency and agronomic efficiency should offset each other in well managed farming systems.

However, P maintenance practices have not been developed in Australia. Nutrient calculators such as the Soil Management Calculator (Anderson et al., 2012) used to calculate the economic optimum amount of P required to correct P deficiency in crops cannot recommend a maintenance rate. Its P recommendation tends to zero as a soil's P status approaches its critical value (Summers, 2001). Faced with not having the science to provide information on maintenance rates needed to maintain the soil P status at non-limiting levels, the response in crop, milk and meat industries in southern Australia appears to be to follow traditional P application rates, causing build-up to critical values and beyond. The P balance efficiency of grain cropping has therefore not changed from the value of 50% reported twenty years ago (McLaughlin et al., 1992). Lack of maintenance practice in the northern grains region has allowed depletion of initially adequate levels soil P to often fall to below critical value (Bell et al., 2010). The added complication in this region is subsoil depletion resulting in the need to supply P to the subsoil and subsoil monitoring (Bell et al., 2012).

Determining the maintenance rate requires consideration of several P processes in soil. Syers et al. (2008) suggest that once critical values are reached, maintenance rates of P can be based on replacing the amounts of P removed in harvested products. Hence P balance efficiency managed at close to 100% would completely offset low agronomic efficiencies close to 0%. The data analysed by Weaver and Wong (2011) suggest however that perfect offset of agronomic and balance efficiencies would not be possible due to continued sorption of P into less plant-available forms and leaching and runoff losses. The maintenance rates of P should take these fluxes of P into account by adding it to the amount removed in harvested products in order to maintain the soil P status. The amounts of P adsorbed plus lost from topsoil can be as high as 7.3 kg P ha^{-1} a^{-1} in some pasture soils maintained close to their critical values (Simpson et al. 2010). Comparative values are not available for grain crops. The extent to which P balance efficiency can be made to approach 100% when agronomic efficiency is close to 0 is unknown, and should be investigated to develop maintenance P management.

While maintenance practices are being developed, growers are encouraged to experiment on a number of P rates ranging from replacing the amount of P removed in harvested materials to twice this amount (equivalent to current P balance efficiency of 50%). Carried over several years, these on-farm-experiments will inform what the maintenance rate is for the paddock, farming system and location in question.

R1: the Right amount of fertiliser:
Test the soil (Available P and the P buffer index; or DGT-P), sample the space and repeat at the same time after a few years;

If in 'Build up phase' – then add P as recommended for the soil P and buffer index value or for the DGT-P test

When critical values are reached or exceeded, use P to match export in crop and soil P sorption and inevitable losses

R2 Right type of fertiliser

Matching the type of P fertiliser with the soil type and environmental conditions improves P uptake. Reactions with soil such as precipitation with carbonates in alkaline soils, sorption on hydrous oxides of Fe and Al in high PBI neutral to acidic soils affects availability of added P. On highly calcareous soils where precipitation of P on carbonate surfaces is important, fluid fertilisers are more effective than granular P. In South Australia, fluid P fertilisers were up to 15 times more effective than granular sources at equivalent P application rates on calcareous soils. This is mainly attributed to increased diffusion from fluid P, which in turn reduced P precipitation. Benefits from fluid P on P uptake and agronomic efficiency occurs in both calcareous and alkaline non-calcareous soils (McLaughlin et al., 2011).

Slow release P fertilisers can decrease leaching loss in sandy soils with low PBI where leaching is an important problem. Sparingly soluble P sources such as magnesium ammonium phosphate and reactive phosphate rocks (RPRs) have slow P release characteristics. However, annual plants require P to be supplied quickly for their short growth period; slow release fertilisers may disadvantage rapidly growing crops. Formulations of rock P with elemental sulphur (S) have been used to increase P solubility by acidification due to sulphur oxidation. The success of this approach depends on the amount of S used and the soil (McLaughlin et al., 2011).

There is a growing interest worldwide in the development of Enhanced Efficiency Fertilisers to minimise losses to the environment and adsorption and precipitation of P as poorly plant-available forms in soil. Soluble P fertilisers that are thinly coated with polymers are currently available (e.g. P Avail). These fertilisers are claimed to decrease sorption and precipitation of fertiliser P by soil (Chien et al., 2009). There is little information on the mechanism of enhanced efficiency by polymer coating. An independent evaluation of effectiveness is required.

Developments in polymer science in Australia would allow supply of P from fertilisers to be synchronised with crop demand. The potential to minimise excess P in soil while fully meeting the crop requirement promises to lift P balance efficiency and profits and minimise losses to the environment. This potential and the scope for future development have been the subject of several recent reviews (Trenkel, 2010, Chien et al., 2009) and offer an opportunity for R&D investment in more efficient types of fertilisers.

R2 Right type of fertiliser:

Match fertiliser forms to the soil type e.g. fluid fertilisers on highly calcareous soils;

Choose P fertiliser formulations and compounds to match plant needs and soil types eg. avoid slow release fertilisers with quick-growing annual crops

R3 Right place for the fertiliser

Fertiliser rates across the paddock

Management of spatial variability both down the soil profile and across the paddock has the potential to improve P outcomes. Variation in soil type and soil depth, grazing and topography result in nutrient and yield gradients across the paddock (Simpson et al., 2011, Wong et al., 2001). This variability impacts on soil sampling strategy and site specific fertiliser requirements as well as management by precision agriculture. Maintenance P requirements will typically vary across a paddock where there are large contrasts in clay content and type (Wong et al. 2008) since this results in differences in PBI and soil P status. Work on a paddock in Corrigin by Wong et al., (2012) and Castrignano et al., (2012) show a clear spatial pattern of P status expressed as Colwell P/ critical value for 90% wheat production (Figure 5). Values of <1 are regarded P deficient. Only a small area of the paddock (dark blue area) is slightly deficient in P and current fertiliser recommendation tools such as the Soil Management Calculator (Anderson et al., 2012) developed to manage P deficiency and to build up soil P status to critical value can be used to ameliorate it. The remaining area has sufficient and excess P needing only maintenance rates. The maintenance rate will partly depend on yield.

Differences in soil texture across the paddock and farm will result in varying deep drainage and leaching risk (Wong et al. 2006), crop yields (Wong and Asseng 2006) and hence crop P removal across the paddock. Site and season specific recommendations similar to those described by Wong et al. (2001) may be needed to account for interaction between site and amount of fertiliser and improve P balance efficiency and profits. New geophysical sensing techniques including electromagnetic induction and gamma-ray spectrometric surveys now allow soil type and likely P sorption, accumulation and status to be mapped cost-effectively, and assist in site and season specific management (Wong et al. 2010, Castrignano et al., 2012).

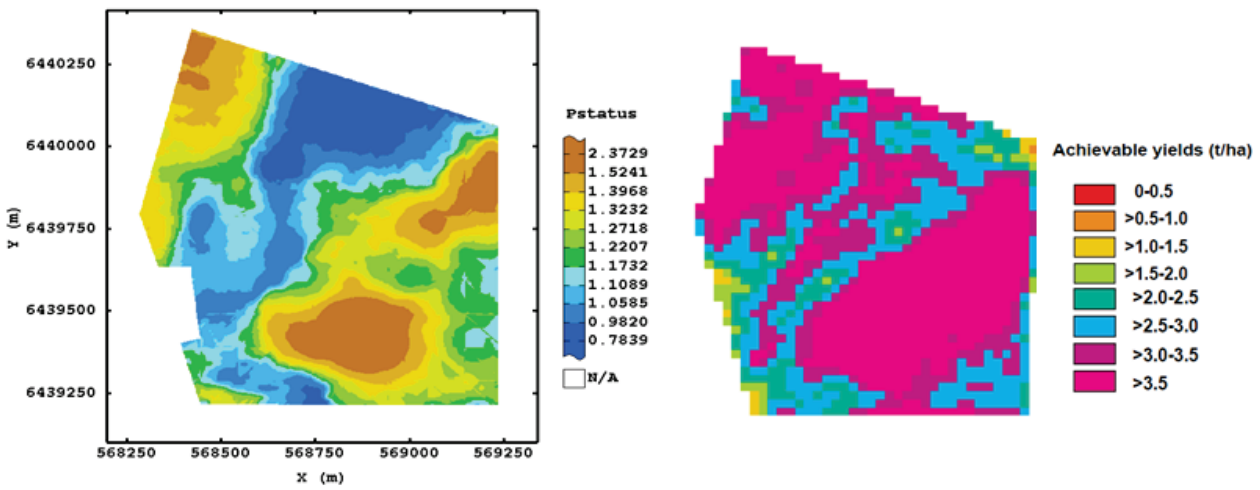

Figure 5 Spatial distribution of P status (expressed as Colwell P/ critical value$_{90}$) for wheat (Castrignano et al., 2012) and achievable yields estimated from satellite imagery (Wong et al., 2001) for a paddock located at Corrigin, Western Australia

Fertiliser placement near the plant

Because P is only slowly mobile in most soils, a supply of available P near the root zone will improve plant uptake, especially during the most active growth period. Banding of P fertiliser near the root zone improves P uptake where sorption reactions dominate such as in fine textured soils with medium to high PBI. However, high local P concentration produced by banding may induce precipitation in soils such as calcareous soils and decrease P uptake (McLaughlin et al., 2011). Development of controlled release P

fertiliser that matches the crop requirement would help minimise precipitation in these soils by lowering unnecessarily high local P concentration (Chien et al., 2009).

Reduced or no till methods and shallow banding of fertilisers at the time of seeding cause stratification of P down the soil profile under crop. The subsequent movement of P down the soil profile is related to soil texture and P buffering capacity, hence less P stratification occurs in coarser textured - sandy soil profiles due to leaching (McLaughlin et al., 2011). Accumulation of P near to the soil surface also increases risk of loss of soluble and particulate P by runoff and erosion. Placing fertilisers deeper in the soil profile could increase nutrient acquisition and utilisation by plants as the nutrients are in moist soil for a longer part of the growing season (Ma et al., 2009, Bell et al., 2012). Large yield increases are possible with deep placement of P in infertile subsoils, but the cost of subsoil placement may limit the use of this technology (McLaughlin et al., 2011). A long interval timing of such subsoil placement of the order of once every 5 to 10 years would be more economic and needs to be investigated. In the northern grains region, reliance on subsoil moisture for summer crops has resulted in P depletion occurring mostly in the 10-30 cm layer and in responses to subsoil application of P (Bell et al., 2012. The development of mobile enhanced efficiency P fertilisers may help provide a cost-effective solution to supplying P to the subsoil.

R3 Right Place for the fertiliser:

Be aware of variation within the paddock and adjust P management to fit;

Adjust fertiliser placement to match the soil and plant – eg. band in high clay soils with high buffering index but not in calcareous soils

R4 Right time of fertiliser

Young seedlings of annual crops require high phosphorus concentration around their small and relatively inefficient root systems to ensure early vigour for high yield potential. Starter P fertiliser applied as bands in, or near to, the seeding trench at planting will meet early crop demand. This starter P provides 1–2 kg P ha^{-1}, and can result in up to 20% yield increases in wheat and sorghum.

Timing of P fertiliser application when the intensity of off-site transport processes through runoff and erosion is at its minimum will minimise the risk of P loss. In WA, application of P in autumn avoids the risk of severe topsoil and nutrient loss due to summer storms.

While leaching of P is a well documented cause of P loss in sandy soils, the management response has focused mainly on using less soluble forms of P. This approach may not be ideal for rapidly growing annual crops which require a source of readily available P to match their growth rate and corresponding demand for a rapid supply of P. Split application rather than slow release fertiliser is used to control nitrate leaching. This approach may be transferable to manage P leaching in annual crops. Split application can occur as a foliar P spray to meet the crop's demand tactically depending on the season and avoid high levels of P in soil (Noack et al., 2010). Another option is to develop controlled release P tailored to the crop requirement rather than slow release P fertiliser.

R4 Right time of fertiliser:

Match P management to crop growth stage;

Time P fertilisation with an eye to environmental processes eg. avoid high rainfall and runoff events

Use split applications to avoid P leaching where slow release formulations are not suited eg. rapidly growing annual crops

The Right Agronomy-the 5th R

Ameliorating other constraints to yield

At a given rate of P input, P balance efficiency can be increased by increasing yields and P outputs in harvested materials. Given that many cropping soils sampled in southern Australia exceed their critical values, yields are more likely to be constrained by other factors such as lack of water, soil compaction, soil acidity, and other nutrient deficiencies. Soil constraints to root growth and soil exploration (e.g. soil acidity, root diseases, soil compaction) will impede P uptake, yield and P export and will directly lower P balance efficiency. Constraints due to nitrogen, potassium and sulphur deficiency and soil acidity are common, and accurate statistics are available for Western Australia cropping soils (Table 4). Published critical values are generally determined under controlled field conditions on soils that are practically free of constraints to yield. These critical values are likely to be too high for soils where yields are constrained, and would result in over-application of P to plants that are not able to reach their potential. It is essential to ameliorate these soils to allow P (any any other inputs) to be used efficiently. If this cannot be done, then critical values relevant for the specific field situations should be determined to avoid over-fertilising soils.

Table 5 Percentage of Western Australian soils exceeding critical values of P for 90% of maximum wheat production and subject to other soil constraints

Samples exceeding critical Colwell P to achieve maximum production	87
Samples with pH ($CaCl_2$) < 5.5	70
Samples with Colwell K deficiency	8
Samples exceeding critical value to achieve maximum production and pH ($CaCl_2$) <5.5	63
Samples exceeding critical value to achieve maximum production and likely to respond to K	7

R5 Right agronomy:

Manage and optimise non-P constraints to yield – and adjust P management in turn

Applying the 5 Rs to manage P in different soil scenarios

High P soils

These soils occur from south eastern Australia across to Western Australia. The first question to ask is whether funds invested in P fertilisers would not be better spent to alleviate other constraints to yield. Applying the right agronomy is important to ensure maximum benefits from the high P soils.

These soils must be tested regularly if they are being depleted because of the risk of inducing P deficiency (Bell, 2010). An added complexity in the northern grains region is depletion of subsoil P and the need to monitor deeper than the 0-10 cm layer (Bell et al., 2012).

The objectives in these high P soils are to maximise P balance efficiency by lowering P application since AE is close to zero and to maintain soil P at its critical value.

Low P soils

These soils occur with increasing frequency in the northern grains region. Applying the right type of fertiliser at the right amount, time and place are important to support the farming system objectives. We suggest that this should be extended to the applying the right agronomy. Tools based on response curves, commodity prices and fertiliser cost help to decide how much P to apply to maximise profits, and in so doing build-up the soil available P reserves in soil. In these soils high AE is offset by low P balance efficiency as a significant proportion of the fertiliser is held by the soil. An added challenge in these soils is the difficulty to supply P to the subsoil (Bell et al., 2012). This is currently done mechanically. In the future, development of enhanced efficiency P fertilisers that are able to be transported to the subsoil would help.

Soils with high P sorption

These are fine textured soils with iron and aluminium oxides that adsorb P. High P Buffering Index associated with these soils will result in high critical value and high amounts of fertiliser required by the plant grown. The tie-up of P in soils results in lowered P balance efficiency since loss of available P by sorption has to be replenished by fertiliser application. The effect of sorption or PBI on fertiliser requirement is partly catered for in current fertiliser recommendation tools. Placement of the fertiliser near to the root to minimise contact with soil and subsequent sorption will lower such a requirement. It will also minimise risk of runoff and erosion which is more important in these soils than in low P sorbing soils. Crops with low external P concentration requirement e.g. with roots that can extract strongly sorbed P, are well suited to such soils. Liquid P fertilisers are more easily taken-up by plants grown in alkaline and calcareous soils which tend to cause the precipitation of solid forms of P. Development of polymer coated fertilisers promises to decrease loss of P availability by sorption and precipitation (Chien et al., 2009).

Soils with low P sorption

These soils are common in Western Australia and are characterised by their sandy texture and low PBI <70. These soils can lose relatively large amounts of P by leaching in high rainfall cropping (>450-600 mm) regions. The need to replenish P loss with fertilisers lowers P balance efficiency. This can be minimized by not exceeding the critical value, and by ameliorating soil constraints to root growth. Use of slow release P is beneficial for minimising leaching in perennial crops. Slow release P fertilisers may not meet the demand of rapidly growing annual crops. A possibility is splitting the application of P across the growing season to minimise leaching in annual crops. Another is to develop controlled release P fertilisers to ensure that crop requirements are met while minimising leaching.

Communication and training to implement the 5 Rs of P management

Rapid gains in P balance efficiency, profits and sustainability can be found in the short term by communicating and implementing the 5 Rs of P management. The shrinking of state department extension programs has led to an expansion of industry and private consultant to advise growers on fertiliser use. Across Australia, 78% of grain growers currently use private consultants. These consultants provide the opportunity for effective delivery. It is important that they are provided with knowledge, skills and tools to provide growers with good advice. Information flow from researchers to these consultants starts during

their training at Universities, which need to have access to latest developments in fertiliser research. The most effective way is through publication of research and development outputs in readily available formats. The planned publication of the outputs of GRDC's Better Fertiliser Decision program in an Australian Journal in 2013 is an example of dissemination to those tasked at training the advisors. This publication should contain information on which soil test to use and how to interpret the results and improve the grower's and consultant's confidence in the better fertiliser advice. Journal publication together with GRDC's Ground Cover and updates and bulletins and publications from state government agencies will help close the gap between R&D outputs and use by consultants. The 5 Rs should be communicated through these channels.

Many grain growers can be reached and the 5 Rs implemented by encouraging their consultants to undergo training and accreditation by FIFA FertCare program. In turn, growers could then be advised to use accredited consultants. The FIFA FertCare program should ensure that the 5 Rs are a central part of their program. Many agribusinesses already employ FIFA FertCare accredited consultants to ensure that the fertiliser advice given is appropriate and this must be encouraged. The International Plant Nutrition Institute (IPNI) is represented in Australia. It developed and advocates the use of the 4 Rs (expanded to 5 Rs in Australia) of fertiliser management. We should engage with it with FIFA for widespread dissemination and adoption of the 5 Rs.

The GRDC developed its Regional Grower Services as a new channel of delivery. These Regional Grower Services can also act as regional links between FIFA and regional consultants and as a direct conduit of knowledge, skills and tool to growers and consultants. It can also coordinate on-farm demonstration trials to improve the grower's confidence in the 5Rs. This is especially important when the recommendation is to use little P as we sense an apprehension to use such a practice for fear of perceived yield loss even in high P soils.

4 Medium and long term strategic interventions to improve phosphorus use efficiency – beyond the 5 Rs

The 4 Rs framework advocated by IPNI (2008) and the 5th R advocated here are tactical interventions aimed at delivering immediate benefits when effective practices for P maintenance have been developed, communicated and adopted. Development of the maintenance practice is the medium term component of this plan to improve P management. The maintenance rate is the sum of P removed in harvested products, P adsorbed or precipitated in sparingly available forms in soil and unavoidable losses by run-off and leaching. Those processes and the maintenance rate of P can be minimised by applying the 5 Rs of P management. The choice of the right type of fertiliser (R2) designed to minimise these sorption and loss processes is currently limited and not thoroughly tested (Chien et al., 2009). Further efficiency gains can be achieved in the medium term by investment in assessing enhanced efficiency fertilisers tailored for different soils, regions and cropping systems of Australia.

In the long term, further benefits will be derived from agronomic interventions to improve the P balance efficiency of farming systems (Simpson et al., 2011). These interventions can be broadly grouped as (1) minimise losses by run-off and leaching, (2) minimise P sorption in poorly available forms in soils and (3) use crop and pastures that are better able to take up soil P and hence have lower critical value. The purpose of these interventions is to decrease loss of P to the environment, and its accumulation and subsequent transformation in sparingly available forms in soils. It is not to decrease P export in products since this is closely associated with yields and profits. In soils maintained close to the critical value, high yields close to the site's potential and high P exports in products can ultimately be balanced with fertiliser, manure and feed inputs to give P balance efficiency close to 100% (Syers et al., 2008).

Minimising run-off and leaching of P

Large leaching losses of P in the order of 40-90% of applied P can occur in sandy soils with low PBI<70 (Ozanne et al. 1961; Lewis et al. 1987). The accumulated soil store of P is also prone to leaching in these low PBI soils because of high P concentrations in the soil solution (Weaver and Wong, 2011). The 4R of P management already helps farmers to minimise P losses by using appropriate amount, forms, placement, and timing of fertiliser in relation to rain and plant requirement. These tactical management interventions are mostly targeted at controlling run-off and erosion pathways of P loss; the severity of leaching has often been underestimated and ignored until recently. A management response to minimise P leaching loss on sandy soils is to use less soluble P-fertilisers (water solubility <40%) and more deep rooted crop varieties (Weaver et al. 1988; Ozanne et al. 1961). As already mentioned, use of slow release P fertilisers is not ideal for meeting the P demand of rapidly growing annual crops. Development of polymer controlled release of P tailored to crop demand would be more effective. The most common practice to minimise leaching of N fertilisers is split fertiliser application. There is potential for developing this practice for P management on sandy soils.

P loss due to runoff and erosion is usually a small component of the P-balance, especially when best-practice 4R management is followed (Weaver and Wong, 2011). However, the small amounts of P lost may have a significant effect on water quality and need to be addressed (Simpson et al., 2011). In addition to best-practice management, strategies aimed at lowering the external P requirement of future farming systems developed with lower critical value will decrease P concentration of materials carried by run-off and erosion.

Conflict between critical value for productivity and the environment

The concentration of dissolved reactive P (DRP) in soil solution poses a risk of P leaching in sandy soils maintained at their critical values. These soils are characterised by low P sorption capacity, PBI< 70 and reduced ability to retain P against leaching. This results in the environmental threshold for DRP concentration being exceeded in soils maintained at their critical values, and there is a conflict between the amount of P required for production and the cost to the environment (Table 6). The risk is increased unnecessarily by widespread exceedance of critical values. Soil samples with PBI<70 and exceeding critical values are common in Western Australia. Many finer textured soils with higher PBI also exceed their critical values in south east Australia (Simpson et al., 2011). The immediate priority is to apply the 5 Rs especially in relation to applying the right amount of fertiliser and the right agronomy to alleviate constraints to yield. Soil acidification, including subsoil acidification is a significant constraint to production in the Western Australian wheatbelt (Herbert 2009). In the longer term, the option is to increase PBI by claying and/or additions of mining by-products rich in iron and aluminium oxides with high P sorption properties should be developed to control P leaching in these soils (Weaver and Wong, 2011). These iron and aluminium oxides are commonly found in healthy weathered soils. The form of aluminium found in these oxides is not toxic to crops. From the plant side, developing farming systems with lower external P requirement and lower critical value will result in lower DRP and leaching risk.

Table 6 Estimated dissolved reactive P concentrations at critical Colwell P values for wheat (shown in Table 4). The environmental threshold DRP concentration for ANZECC is 0.07 mg P l^{-1} (Weaver and Wong, 2011) is exceeded by soils with PBI<52.5.

PBI range	Mid PBI	DRP concentration (mg P l^{-1})
0-5	2.5	5.6
5-10	7.5	0.48
10-15	12.5	0.24
15-35	25.0	0.12
35-70	52.5	0.08
70-140	105	0.06
140-280	210	0.05
280-840	560	N/D

Accessing “sparingly available” P pools

Continuing reactions in many soils gradually transform available P to sparingly available inorganic and organic forms that are no longer measurable as Colwell or Olsen P. This loss of P availability limits plant uptake and lowers AE and P balance efficiency, especially in finer textured soils (PBI>50). One contributing reaction is slow diffusion into soil particles after initial sorption of fresh P is added to the soil (Barrow 1999). This reaction causes loss of residual value of P fertilisers with time in deficient soils. More recently, precipitation with Ca, Al and Fe was also found to be important in decreasing P availability (McLaughlin et al. 2011). Accumulation of P in poorly mineralisable organic forms has a similar effect in lowering availability. The limited number of measurements available in Australia suggest that these transformations are also important during the maintenance phase of P management, resulting in the maintenance P requirement exceeding the amount of P removed in harvested materials and hence P balance efficiency <100%. The amount accumulated in soils maintained close to their critical values was ~4.6 kg P ha^{-1} $year^{-1}$ (P balance efficiency ~60%) in a crop-pasture rotation compared with ~7.3 kg P ha^{-1} $year^{-1}$ (P balance efficiency ~20%) on a permanent pasture (Simpson et al., 2011).

One way to use fertilisers more efficiently and to decrease the maintenance rate is to decrease the rate of P accumulation in soils. In soils where sorption and slow diffusion into soil particles dominate availability, the rate of accumulation of P into sparingly available forms is dependent on concentration of DRP in the soil solution (Simpson et al., 2011). Concentration of DRP will also determine precipitation of Ca, Al and Fe P according to the solubility product of the precipitate formed. This indicates that strategies that allow a farming system to be operated at lower critical value and lower DRP concentration should reduce the rate of soil P accumulation and improve P balance efficiency. Field evidence appears to support this anticipated effect of lower critical value on lowering P accumulation (Simpson et al., 2010). In soils with low PBI, this strategy of lowering critical value will result in lower DRP concentration and P leaching. Farming systems that can operate at lower critical value can be developed by using plants with (i) better root architecture and foraging strategies that improve P acquisition at lower critical value, (ii) P-mining strategies such as those able to lower the pH of the rhizosphere or exude organic anions and phosphatases to enhance the desorption, solubilisation or mineralisation of P already accumulated in sparingly-available sources in soil (Richardson et al., 2011; Simpson et al., 2010; 2011).

A limited number of species have the ability to modify the chemistry of their rhizosphere to enhance the uptake of P. In white lupins (*Lupinus albus L.*), citrate exudation from proteoid roots and in chickpea (*Cicer arietinum L.*), malonate exudation confer ability to access P that is otherwise sparingly-available (Richardson et al., 2011). In buckwheat (*Fagopyrum esculentum*) root exudates that lower the rhizosphere pH in response to low P concentrations enhance P uptake in calcareous soils (Simpson et al., 2011). The potential for improving P uptake by modification of the rhizosphere is unclear in agricultural plants as exudate concentrations are responsive to soil P status, and are reduced at high levels of soil P fertility (Richardson et al., 2011) encountered in some Australian soils. In spite of these challenges and based on glasshouse evidence of benefits, the potential of using P-efficient plants to improve P-availability for other crops is being researched to evaluate benefits under field conditions (Simpson et al., 2011). Options for increasing P-availability to less P-efficient species include (1) mixing P-efficient with inefficient species in either crops or pastures (intercropping) or (2) using residues of P-efficient species for subsequent less efficient species grown in rotation. Rotation is routinely practiced in Australian farming systems and provides a potential way of increasing P availability in the less P-efficient phase of the rotation.

Decoupling soil organic matter and organic P accumulation

Farming systems that increase soil organic matter content, for example through changes in land-use, tend to increase organic P in soil. Accumulation of soil organic matter happens following the application of P fertilisers to pasture established on low-P soils. These soils then accumulate P in both inorganic and organic forms (McLaughlin et al., 2011). In contrast, P accumulates almost predominantly in inorganic forms in cropping soils (McLaughlin et al., 2011). Organic P accumulation of 1.7–4.0 kg P ha^{-1} $year^{-1}$ has been recorded in pastures when P is applied to build up soil P from low values (Simpson et al., 2011). A similar level of organic P accumulation of the order of 2.2–3.0 kg P ha^{-1} $year^{-1}$ has been reported during the maintenance phase of P management in a crop-pasture rotation on a red earth (Helyar et al., 1997) due to continuing accumulation of soil organic matter, especially during the pasture phase of the rotation. In crop-pasture rotations, the levels of organic P oscillate due to accumulation during the pasture phase and mineralisation and use of P released from organic matter during the cropping phase (Simpson et al., 2011).

Continued accumulation of organic P in some farming systems would diminish P balance efficiency due to sparing availability of various forms of organic P. Orthophosphate monoesters such as phytate are a major form of organic P in many soils. Phospholipids, nucleic acids, phosphonates and other compounds occur in lower amounts. It should be possible to enhance the release of P-esters by plant or microbial phosphatases independently of soil organic matter accumulation (Richardson et al., 2005). The ratio of C:P and C:organic P is variable in soils and farming systems. Understanding this variation in C:P ratio should allow decoupling

of soil organic matter and organic P accumulation and improve P availability. This is important since current interest in sequestering carbon in soil may also tie-up P in sparingly-available organic forms. Part of this variation is due to the fact that P contained in green and senesced plant materials and in manures is mostly inorganic. Another reason is microorganisms can accumulate P in their cells following mineralisation resulting in variable release of mineralised P (McLaughlin et al., 2011). The reason for different organic P accumulation under crops and pastures remains unclear.

Productive low P farming systems

The strategic option to improve P balance efficiency further is to develop profitable farming systems that can achieve their maximum yield potentials in soils with lower available P content. The plant and microbial strategies to improve uptake of P in soils with low available P and to improve yield per unit of P uptake were reviewed by Richardson et al. (2011). They outlined three potential strategies which could be developed to improve P efficiency: (1) root-foraging strategies that improve P acquisition by lowering critical value; (2) P-mining strategies to enhance desorption, solubilisation or mineralisation of sparingly available P using root exudates (organic anions, phosphatises) to minimise accumulation of P in sparingly available forms; and (3) improving internal P utilisation efficiency by using plants that yield more per unit of P uptake. The first two strategies improve P balance efficiency by lowering critical value and minimising accumulation of P in medium to high PBI soils. Low critical value will decrease leaching losses in low PBI soils. The third strategy decreases the amount of P needed to sustain yields by lowering the P concentration of harvested products. These potential strategies are summarised here. One salient feature of many of these strategies is interaction with the root environment. There is often a requirement of low P levels in soils for these strategies to work. Many of these strategies would therefore be ineffective in parts of current Australian intensive agricultural systems that are characterised with soils close to or above their critical values. They are therefore seen as potential strategies that could be used when soils have been drawn down to low P status for current crops such as those of the northern grains region or in countries and regions, for example in Africa, where low P soils are common.

Improving root-foraging

The amount of available P is normally greatest in the topsoil, and selection for architectural root traits that enhance topsoil foraging to improve P acquisition could be undertaken (Richardson et al., 2011). Large increases in P acquisition of 600% in beans and 100% in maize and in yields (300% in beans) due to shallower root growth angle (RGA) have been reported (Richardson et al., 2011). Selection of crops with shallow RGA is therefore used widely to enhance P acquisition and yields in low P soils. In maize, genotypes with more lateral rooting in low P soils had up to 100% more P accumulation and greater growth rates than closely related genotypes. Root hairs have substantial effect on P acquisition at a low metabolic cost due to minor allocation of carbon to their growth. Improvement of root architectural traits is regarded to be one of the most promising approaches to develop low P farming systems. There may be a trade-off however, as decreased drought resistance is likely without deep roots accessing subsoil water.

Hyphae of arbuscular mycorrhizal (AM) fungi fulfil some of the same roles as root hairs with respect to P acquisition, but extend further from the root into the soil. This advantage of AM fungi in P acquisition diminishes with increasing soil P availability and there is often little advantage in intensive agriculture with soils maintained close to their critical values (Richardson et al., 2011).

Accessing sparingly available pools of P

Roots of some plants can release organic anions, enzymes, and protons to mobilise and take up sparingly available P. Organic anions are thought to improve availability of inorganic forms of P by competing for

sorption sites. Release of organic anions can be from specialised root structures made up of clusters of rootlets and abundant root hairs. These cluster roots are found in white lupin (*Lupinus Albus L.*). Some species of Lupinus, pigeon pea (*Cajanus cajan L.*), chick pea (*Cicer arietinum L.*) and field pea (*Pisum sativum*) do not form cluster roots, but modify the rhizosphere by root exudation in P deficient soils. Investment in cluster roots or exudates release in non-cluster roots are both suppressed at high available P concentrations and this is a problem for many Australian soils. Direct evidence of the importance of organic anions in P mobilisation and uptake is scarce, and warrants further study to determine how this process can help develop low P farming systems.

Free living fungi and in particular *Penicillium* species can exude organic anions, and do not appear to exhibit specific plant or soil associations and inhabit the rhizosphere of diverse agricultural plants. Products based on *Penicillium bilaiae* have been commercialised. Under controlled conditions, these products improved growth of many plant species including wheat, canola, grain and pasture legumes. They can solubilise sparingly-available P and stimulate root growth and the production of root hairs. These benefits are less consistent under field conditions and further development is required to test the mechanistic claims for P solubilisation and ascertain the grower benefits of these products.

Substantial flows occur between the organic and inorganic pools of P through mineralisation and immobilisation processes. Mineralisation of organic P is important because (1) uptake by plants is in the form of inorganic orthophosphate anions and (2) poorly available forms of organic P accumulate in soil. Mineralisation occurs through the activity of phosphatase enzymes produced by plant roots and soil microorganisms. The extracellular phosphatase activities of plant roots are enhanced in P deficient soils. However enhanced activity may not be correlated with increased plant access to organic P since enzyme activity may not be the limiting factor and organic P exists in different forms that have not been fully characterised, but some of which may not be hydrolysed by root phosphatase enzymes.

Inositol phosphates are an important component making up between 4-20% of organic P. Plant access to inositol phosphates is mediated primarily by microorganisms with extracellular phytase activity. This extracellular phytase activity can be conferred to genetically modified plants, but benefits from mobilisation of inositol phosphates depend on substrate availability, reaction of the enzyme with soils and strength of inositol phosphate sorption and protection against enzyme activity. When enhanced phosphatase activity enhances plant access to organic P, it is difficult to separate the direct effect of phosphatase from other factors such as root foraging or exudation of organic anions (Richardson et al., 2011). Work is therefore needed to evaluate the potential of these enzymes in mobilising organic P in soil.

Improving internal P utilisation efficiency

Producing more yield per unit of P uptake and decreasing the concentration of P in harvested products would decrease fertiliser requirement (Richardson et al., 2011). Crops vary in their internal P utilisation efficiency (yield per unit of P uptake) resulting in significant differences in shoot mass per unit of P uptake and in biomass production under both low and high P conditions. Mechanisms of increased internal P use efficiency include translocation of P from metabolically inactive to active tissues, decreased leaf P concentrations with less P stored in vacuoles. Grain P concentration varies widely and independently of grain size, yields and harvest index and can be selected to minimise the amount of P leaving the farm and increase P balance efficiency. However, a low P content in grains may impact adversely on seedling vigour.

5 Summary of R&D needs

There are several knowledge gaps that hamper the transition to more P efficient and profitable grains cropping systems and require further research and development.

Many soils in western and southern Australia and the northern grains region have sufficient P due to either good natural soil supply or to on-going fertiliser applications. Lack of maintenance practice has resulted in an increasing frequency of initially well supplied soils in the northern grains region becoming P deficient. Over application of P fertiliser to initially deficient soils elsewhere has led to them exceeding their critical values through continued build-up of soil P. P management practices need to be developed to maintain soil P near to their critical values for near-maximum levels of production for different soils, cropping systems, regions and climate. In addition, this work needs to target the recruitment, participation and retention of farmers in research to promote adoption.

A particular challenge is to address depletion of subsoil P in the northern grains region. This requires development of economically sound strategies to supply P to the subsoil. These strategies would also benefit other grains growing regions due to topsoil drying and decreased root access to topsoil P while the subsoil may remain moist.

For many soils that have abundant P, draw down practices need to be developed to bring these soils closer to their critical values. The pattern of soil P decline will depend on soil type, climate and yield. A clear understanding of these patterns needs to be included in developing these practices.

Both crop yield and accumulation of soil P display clear spatial patterns across paddocks. Further benefits from better fertiliser management will accrue from development of novel methods to match P application to site-specific requirements. This would need the development of rapid soil P test and precision agriculture practices.

Leaching of P is an important issue on sandy soils and the use of slow release P fertiliser is unable to meet the P requirement of rapidly growing annual crops. Current interventions aimed at safeguarding water quality by controlling run-off and erosion have little effect on P leaching and stream water degradation. There is therefore a need to develop practices to minimise P leaching under crops grown on sandy soils.

Development of enhanced efficiency fertilisers such as use of polymer coating with appropriate P release patterns will decrease leaching of P.

In the long term, P balance efficiency can only approach 100% if losses by leaching and by accumulation of P in poorly crop-available forms approach zero. Accumulation of soil P is currently an important component of P balance in all soils. There is therefore a need to develop understanding to manage P accumulation in contrasting soils and farming systems to improve P balance efficiency. Development of polymer coated P fertilisers has shown promise in decreasing these reactions. Leaching, run-off, erosion of P and its accumulation in soil would decrease in low-P farming systems. Several options are available but there is a need to demonstrate the economic and P-efficiency benefits of low-P agricultural systems that can support high productivity.

Several mechanisms have been advanced to improve crop uptake of inorganic and organic P stored in soils. There is a paucity of field data to back up mechanistic claims of P solubilisation. The scientific evidence is lacking to allow growers to assess the benefits of these mechanism and products in P management.

Using the right type of fertilisers can decrease leaching, run-off, erosion of P and its accumulation in soil and increase P balance efficiency. Choice of types of fertilisers to address these issues is currently limited. This offers the opportunity to develop and evaluate modern enhanced efficiency P fertilisers for different soil, climate and cropping systems of Australia.

6 Conclusions

Several actions will improve P balance efficiency and profits from P fertiliser in the short, medium and long term. Rapid gains in P balance efficiency and in profits and sustainability can be found in the short term by communicating and promoting the implementation of the 5 Rs of P management. In Australia's grains cropping regions, we are currently depleting initially fertile soils that were made deficient in the northern grains region and building up soils that often exceed their critical values in soils across southern Australia.

Communication and training through the FIFA FertCare accreditation of advisors, federal and state government agencies, IPNI and RDCs as well as agribusinesses and Universities have a role in this implementation of the 5 Rs of P management.

Applying the 5 Rs of P management requires soil testing to inform fertiliser decisions in grains cropping. Currently about a third of growers surveyed each year undertake soil testing. Others may be soil testing in the years immediately before or after being surveyed or may not soil test at all. Several issues relating to soil testing and its interpretation have been resolved and need to be communicated widely.

A road block to applying the 5 Rs of P management occurs across the grains growing regions of Australia due to lack of information about the maintenance regimes to manage soils that have reached their critical values. This has resulted in (1) exceedance of critical values reported in south east across to Western Australia due to continued use of build-up practice that has not changed since this was last investigated 20 years ago and (2) increasing frequency of P deficiency in the northern grains region due to continued depletion of initially adequate soil P reserves. There is an urgent need to develop, communicate and promote the adoption of maintenance P practice for contrasting soils, climates and cropping systems will provide further efficiency gains in the medium term.

Developing, communicating and promoting the adoption of draw down P practice for contrasting soil, climate and cropping systems will also provide further efficiency gains in the medium term for soils that have abundant P. Soils with high natural levels of P occur in the northern grains regions. Development there should ensure that depletion does not eventually turn these soils P deficient by identifying when maintenance practice should start. Elsewhere, abundant P soils occur due to continued build-up of soil P beyond what is required for maximum crop yields.

The threshold for environmental risk to water quality is currently lower than for agronomic response. This environmental risk can be decreased in the medium term by modifying soils to increase PBI. In the long term, using crop varieties with lower critical value will minimise environmental risk and decrease fertiliser requirement by minimising both P accumulation in soils and losses by leaching, run off and erosion.

Selection of root traits to increase mobilisation and uptake of accumulated soil P appears promising. There are strong interactions between these traits and the environment and many strategies to improve uptake of both organic and inorganic forms of accumulated soil P seem ineffective in soil with adequate P content for current crop varieties.

The 5Rs of P management recommend using the right type of fertiliser. Inadequate choice of P fertilisers is an opportunity to develop and test enhanced efficiency P fertilisers to improve P balance efficiency and minimise its accumulation in soil and offsite environmental impact.

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