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Australian sustainable phosphorus futures

Phase II: Adapting to future phosphorus scarcity: Investigating potential sustainable phosphorus measures and strategies

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Phase II: Adapting to future phosphorus scarcity: investigating potential sustainable phosphorus measures and strategies

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Foreword

Without adaptation to the way phosphorus is used and managed, global phosphorus scarcity could constrain Australian food production and global food security. As an essential nutrient in fertilisers for food production, phosphorus has no substitute. Australia and the world are currently dependent on phosphorus from finite phosphate rock reserves, which are becoming more expensive, scarce, difficult to access and geopolitically concentrated in only a few countries. Limited research exists to help understand and explore the regional implications of phosphorus scarcity and inform adaptation in Australia and other countries.

This analysis builds on earlier research that helps to understand the significant input and losses of phosphorus to the Australian food system. This research seeks to deepen our understanding of the phosphorus system and how it relates to Australian agriculture. The report identifies a range of factors influencing phosphorus supply and demand, and develops a framework for conceptualising and facilitating stakeholder dialogue on pathways on adapting to constrained phosphorus conditions and examining the economic, ecological, food security and rural livelihoods implications.

This analysis is important in identifying intervention points in the system that would increase the resilience, efficiency and 'closed-loop' nature of the food system, in addition to facilitating a dialogue on sustainable phosphorus pathways between disparate stakeholders with different goals and perspectives. It also enables individual sectors and associated stakeholders to assess the potential sustainable phosphorus measures available to them, the likely efficiency gains (in kt P saved/yielded), and current barriers/opportunities to implementation within their sector for sector-specific responses.

Phosphorus scarcity is one of a number of examples of 'wicked problems' facing modern agriculture, made difficult because of the complex interdependencies and incomplete information available to us. This research helps to inform our understanding of the issues and the gaps in our knowledge, and provides a framework for exploring the issues and facilitating debate and discussion on the implications and options for Australian agriculture. The report highlights the role of stakeholders and institutions outside of agriculture in helping to inform and develop measures to address this complex issue.

This report is primarily targeted at research and development organisations, policy-makers and industry groups concerned with sustainable agriculture and food production. Relevant industries include: phosphate mining and fertiliser industries, agriculture industry, food production, processing and distribution industries, wastewater and waste management industries.

This project was funded by RIRDC core funds in addition to in-kind support via a UTS Chancellor's Postdoctoral Research Fellowship.

This report is an addition to RIRDC's diverse range of over 2000 research publications and it forms part of our National Rural Issues R&D program, which aims to inform and improve policy debate on issues relevant to rural Australia.

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Craig Burns
Managing Director
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About the Author

The Institute for Sustainable Futures (ISF) was established by the University of Technology, Sydney in 1996 to work with industry, government and the community to develop sustainable futures through research and consultancy. Our mission is to create change toward sustainable futures that protect and enhance the environment, human well-being and social equity. We seek to adopt an inter-disciplinary approach to our work and engage our partner organisations in a collaborative process that emphasises strategic decision-making.

Acknowledgments

The authors would like to thank the members of the National Strategic Phosphorus Advisory Group and the Sustainable Phosphorus Futures workshop for generously offering their time, expertise, discussion and review. This includes: Phil Graham (Agriculture NSW), Tim Wright (AG*n*VET Services), Dr Richard Simpson (CSIRO Sustainable Agriculture Flagship), Gerry Gillespie (Zero Waste Australia), Dr Graham Turner (Melbourne University), Dr Rosemary Stanton (public health nutritionist), David Gough (Sydney Water), Dr Michele Barson and Adrienne Ryan (Department of Agriculture, Fisheries & Forestry), Nick Drew (Fertiliser Industry Federation of Australia), Prof Ronnie Harding (Wentworth Group of Concerned Scientists and UNSW), Leesa Carson and Allison Britt (Geoscience Australia), Anwen Lovett (Rural Industries Research & Development Corporation), Dr Glen Corder (Sustainable Minerals Institute, UQ) and David Eyre (NSW Farmers Association). The authors take full responsibility for the contents of the report.

Abbreviations

For the purpose of this report, the following abbreviations and terms have been used.

Model	The Sustainable Phosphorus Measures Model developed in Phase 2 of this project
Measure	a technical or behavioural practice that can potentially result in yielding phosphorus (e.g. recycling manure) or avoiding phosphorus being used (e.g. precision agriculture), in units of kt/a of P.
Phosphogypsum stockpile	The major waste by product generated during phosphorus fertiliser production (when phosphate rock is reacted with sulphuric acid)
GPRI	Global Phosphorus Research Initiative
ISF	Institute for Sustainable Futures
NSPAG	National Strategic Phosphorus Advisory Group
kt P/a	kilotonnes of phosphorus per year

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Executive Summary

What the report is about

This project investigates how Australia can manage phosphorus to ensure long-term food security, soil fertility, agricultural productivity, farmer livelihoods and environmental protection. The intended outcome overall is to deliver sustainable phosphorus adaptation strategies across a range of scenarios to increase the resilience of the Australian food system. An Australian phosphorus flows model, quantified and costed sustainable phosphorus measures and interactive future phosphorus scenarios, will enable stakeholders to identify policy implications and make informed policy decisions.

This report presents the findings from Phase 2 of this project, *Adapting to future phosphorus scarcity: investigating potential sustainable phosphorus measures and strategies*. That is:

1. a Toolbox of sustainable phosphorus measures
2. a future scenarios model of sustainable phosphorus measures
3. a high-level influence diagram on which phosphorus vulnerability can be mapped
4. a conceptual framework for deliberating on, and synthesising adaptive pathways.

Who is the report targeted at?

This report is primarily targeted at research and development organisations, policy-makers and industry groups concerned with sustainable agriculture and food production.

Where are the relevant industries located in Australia?

This research was conducted at the national scale, and hence is relevant to all geographical areas. It is relevant to all industries related to the direct or indirect use of phosphorus in the food production and consumption system in Australia. This includes, but is not limited to: phosphate mining and fertiliser industries, agriculture and livestock industry, food production, processing and distribution industries, wastewater and organic waste management industries.

Background

Impending global phosphorus scarcity is likely to compromise the resilience of Australian food production and global food security if no changes to the way we currently use and manage phosphorus are made. As an essential nutrient in fertilisers for food production, phosphorus has no substitute. Australia and the world are currently dependent on phosphorus from finite phosphate rock reserves, which are becoming more expensive, scarce, difficult to access and geopolitically concentrated in only a few countries. Yet research addressing the serious regional implications of phosphorus scarcity is lacking.

Aims/objectives

The overall objectives of the three-year project are to:

1. Analyse the phosphorus stocks and flows through the Australian food system (from mine to field to fork and losses to the environment)
2. Identify sustainable pathways for Australia to secure phosphorus for agriculture and food production in the long-term
3. Inform policy, through collaborative development of probable, possible and preferred future scenarios.

The specific objectives of *Phase 2* include:

- Identify and assess which key stressors/factors are likely to impact, increase or decrease Australian agriculture's vulnerability to phosphorus scarcity (e.g. increasing price of phosphate; geopolitical tensions, changing global diets)
- Develop a 'Toolbox' of demand-side and supply-side measures for meeting future phosphorus fertiliser demand
- Develop excel-based model of sustainable supply- and demand-side measures (based on the Toolbox) and analyse phosphorus supplied or saved (kt/a of P) to meet Australia's long-term future P demand
- Stakeholder workshop to validate priority stressors, map vulnerability and run through possible scenarios
- Synthesise and prioritise sustainable strategies to increase resilience of food system.

Methods used

The main methods employed in this project are: systems thinking to frame and integrate the development of the toolbox and model; future scenarios and dynamic modelling of substance flows to develop the interactive model, systems dynamics and adaptive capacity thinking to guide the exploration of vulnerability, adaptive pathways and synthesis.

Results/key findings

A sustainable phosphorus system was defined as "a system that allows Australian farmers to access and use phosphorus sustainably in the short and long-term to: support farmer livelihoods, optimise agricultural productivity, ensure ecosystem integrity, feed the Australian population, and contribute to food security in the region and globally". Phase 2 of this project both identified high-level paths of phosphorus vulnerability in the Australia food system, and, potential sustainable measures and strategies by which Australia could adapt in win-win scenarios for productivity, the environment and rural livelihoods.

The study found that the future trajectory of phosphorus use in this country is highly uncertain, in terms of business-as-usual, possible scenarios, and a shared preferred future scenario. This uncertainty is due to lack of existing research and policy debate, lack of baseline data, and a lack of consensus on what a shared trajectory would look like taking into account multiple and potentially competing goals.

Despite the importance of phosphorus to Australia's economy, rural livelihoods, environmental integrity and food security both in Australia and abroad, there is a serious lack of knowledge and data on key attributes of the current system. For example, there is a lack of complete and transparent data sets on Australia's phosphate reserves and production; and the breakdown of phosphorus use in this country for pastures vs cropping vs supplements.

A toolbox of ninety-six supply- and demand-side measures was developed and classified according to each sector – mining, fertiliser, agriculture, livestock, food production, wastewater sector. From this toolbox, a user-interactive model of sustainable phosphorus measures was developed to assess the likely contribution of implementing any combination of these measures at different rates, in terms of phosphorus saved or yielded (kt/a of P).

Multiple pathways were identified that could lead to vulnerability of the Australian food system with respect to phosphorus. Sixty-six variables were identified and mapped, indicating their key inter-linkages with other variables, ranging from exposure-related global megatrends such as price of energy, to sensitivity-related variables such as soil fertility status and variables related to adaptive-capacity such as level of R&D investment. This map was validated at a national stakeholder workshop through exploration of 'What If' scenarios.

Finally, a conceptual framework for exploring future national adaptive pathways was developed and road-tested during the national stakeholder workshop. The framework proved a useful cognitive tool for grappling with trade-offs between efficiency gains and current adaptive capacity, in the face of multiple competing goals related to agricultural productivity, ecological integrity, farmer/rural livelihoods and food security.

Implications for relevant stakeholders

The lack of consensus and existing policy/research debate on preferred phosphorus future scenarios was addressed through the development and collaborative exploration of 'What If' scenarios with stakeholders in the national phosphorus workshop. The process used in the workshop to elicit implications of potential future perturbations and prioritise sustainable strategies and pathways was novel and has great potential as a pilot for future workshops. It enabled collective deliberation on promising sustainable strategies, whilst acknowledging the presence of competing and co-existing goals.

The uncertainty was further managed by designing the sustainable future measures model with a high-level of user-interactivity. The interactive model is an excellent platform from which a more comprehensive and user-friendly interface scenario model can be developed (as a new project), including costing of sustainable measures. Such an interactive model can be used to: a) directly engage key stakeholders real-time with implications of different scenarios (such as investment in soil testing versus renewable phosphate fertilisers, b) improve the quality of the quantitative analysis of long-term sustainable options (to more accurately reflect the phosphorus savings/yields and costs; c) support decision-making for the agricultural/farming industry, government and non-government groups.

The research findings and stakeholder workshop highlighted the need to consider phosphorus in the broader context of the food system and other resources. Firstly, that non-phosphorus related incentives and avoided costs might be more strategic levers to trigger many of the sustainable phosphorus initiatives (such as avoided landfill levies or pollution costs as highlighted in the WS1.6 struvite and PS1.1 food/organic waste examples). Secondly, much can be learnt from effective strategies in water, carbon and climate change in relation to navigating a sustainable future trajectory. Thirdly, there are numerous potential synergies in terms of mitigation/adaptation strategies for phosphorus with other resources such as carbon that need to be identified to ensure win-wins and avoid mal-adaption. For example, ensuring soil carbon strategies leave phosphorus in a plant-available form, or that the development of bioenergy doesn't increase phosphate fertiliser demand for biofuel crops or permanently remove phosphorus from the field in agricultural wastes.

The research and stakeholder workshop also highlighted how the concept of adaptive capacity can guide adaptation pathways at the national level, in addition to its more typical application at the local level. The national adaptive pathways concept introduced in this research demonstrated a need to navigate future phosphorus pathways without exceeding important and co-existing thresholds/boundaries (related to food security, livelihoods, ecosystem integrity and the economy).

Finally, the research found that while there are sustainable initiatives already underway within specific sectors (that have a direct or indirect positive influence on phosphorus management), there is a strong need to integrate across sectors to assess trade-offs, identify synergies, prioritise strategies and ensure that co-existing boundaries are not exceeded. In turn, there is a strong need for participation from all sectors and perspectives to co-define and co-navigate this future space. Ongoing and expanded stakeholder/sector inclusion in the research will be crucial (e.g. representing key sub-sectors with agriculture and livestock, such as dairy industry, grains, horticulture).

Recommendations

If adopted, this research will guide prioritisation and investment in both R&D and implementation of appropriate sustainable phosphorus measures and strategies for Australia to increase the resilience of the food system in the long-term.

Recommended improvements to the current research study include:

- Coordinate research around improved data across all key sectors (prioritizing the 'red' list identified in this work as poor quality and availability corresponding to an important/significant parameter)

- Develop an interactive visualised interface for the Model and make this available as a user-friendly web-based application (similar to v2.0 http://phosphorusfutures.net/australian-sustainable-phosphorus-futures/35-interactive-future-phosphorus-scenarios)

- Apply/use the interactive visualised model in future stakeholder workshop settings to further test/validate the model, seek stakeholder assumptions and increase stakeholder engagement and learning in the area of integrated sustainable phosphorus measures.

Recommended future research and policy priorities as part of the 3 year Sustainable Phosphorus Futures project include:

1. **Costed policy options:** a framework for systematically assessing and comparing selected sustainable phosphorus measures as a means to determine the least-cost sustainable phosphorus options ($/kt P saved or yielded) for Australia;

2. **Adaptive phosphorus pathways**:

    - further explore national phosphorus vulnerability and adaptive pathways, to investigate how Australia can govern phosphorus to ensure long-term food security, farmer livelihoods, soil fertility and environmental protection (building on the process developed in Phase 2). That is, to identify vulnerable regions and sectors within the Australian food system to the threat of phosphorus scarcity, assess in what ways they are vulnerable and prioritise polices and approaches to build national adaptive capacity; and

    - explore on-farm (bottom-up) phosphorus vulnerability and adaptive pathways through participatory means focusing on identified priority areas, such as soil testing and fertiliser application rate/time/placement ("4Rs"); explore farmer preferences, needs, vulnerability to phosphorus scarcity in specific regions and implications for sustainable phosphorus options;

3. **Geospatial analysis of phosphorus hotspots:** Geospatial model indicating dynamic relationship between phosphorus 'hotspots' across Australia (phosphorus sources, demand and 'sinks'), and the energetic and economic feasibility of transporting fossil versus recycled phosphorus;

4. **Phosphorus-carbon inter-linkages:** Assess the inter-linkages between phosphorus and carbon, in terms of physical and institutional flows (that is, around the intersections of their physical flows through the food system (e.g. in food waste, algae, soil) and synergistic and adverse impacts of management responses (such as soil carbon sequestration, bioenergy, influencing diets);

5. **Implications of low phosphorus-intensive diets:** Examine the dietary trends of Australians and overseas consumers of Australian food and agricultural commodities and implications for Australian phosphorus and food system. Analysis of the 'P footprints' of key Australian animal and crop-based food products (i.e. phosphate rock mined to produce a kg of grazed beef, sheep, milk, eggs, wheat, vegetables etc);

6. **Expanded sub-sector stakeholder engagement:** Engage more stakeholders in sub-sectors (e.g. within the livestock sector include stakeholders from dairy, feedlot, grazed livestock; within agricultural sector include grains, horticulture, organic sectors; within food sector include food processors, retailers, organic/food waste stakeholders; and so on). Within sectors, address how barriers to efficiency gains could be overcome and opportunities for improved technology e.g. exploring more cost-effective soil-testing (through R&D) and improved technology to both reduce costs and increase uptake of soil testing;

7. **Participatory development of future scenarios:** Continue to engage stakeholder via participatory development of future scenarios (e.g. collaborative input to user assumptions in the model); and

8. **Policy forum:** Further, a policy forum is recommended to raise the profile and understanding of the issue among policy-makers and support the development of policies and initiatives to improve phosphorus use. Such a forum could be supported by costed policy options from Recommendation 1 above, and/or the use of the national and local adaptive phosphorus pathways with multiple-thresholds concept.

Introduction

Global phosphorus scarcity is likely to threaten Australia and the world's ability to produce food in the future if concerted efforts to use phosphorus more sustainably are not taken by policy makers, scientists, industry and the community today. While phosphorus is an essential element for crop growth in the form of fertilisers, the world's main source of phosphorus (mined phosphate rock) is becoming increasingly scarce and expensive. Yet there is no substitute for phosphorus in food production. Historically there has been very little awareness, research and policy debate on global phosphorus scarcity. However the 800% phosphate price spike in 2008 drew the world's attention to the long-term phosphorus security issue (Cordell et al, 2009a; Nature, 2009; Bekunda et al, 2011).

Australia has naturally phosphorus-deficient soils and substantial dependence on imported sources of phosphorus to maintain agricultural productivity. This means food production and its value as an export industry for Australia will inevitably be threatened by declining availability of phosphorus. Analysis from Phase 1 of this project (Cordell et al 2013) found that despite being a net food exporter (predominantly to Asia), Australia is a net phosphorus importer (80 kt/a of P) to replenish naturally phosphorus-deficient soils and support a phosphorus-intensive agricultural and livestock export sector. The livestock sector represents over 60% of Australia's phosphorus demand due to fertilised pastures and animal feed. The manure produced by the 211 million head of livestock in Australia alone contains 60 times more phosphorus than the food consumed by the entire Australian population.

Simultaneously, there is a net phosphorus deficiency from the Australian food system (106 kt/a of P) due to substantial losses and inefficiencies from mine to field to fork (Cordell et al, 2013). While the productivity of the Australian food system is heavily dependent on substantial phosphorus inputs (215 kt/a of P) in the form of phosphate rock and phosphate fertiliser imports, even larger phosphorus outputs (321 kt/a of P) leave the Australian food system in the form of fertilisers, agricultural exports (mainly wheat, beef and live animal exports) and losses to the environment (mainly non-agricultural soil, water and landfill).

This suggests that the Australian food system is far from sustainable with respect to phosphorus. Further, while small amounts of phosphorus are recirculated within the food system (such as organic waste from food processing and consumption and biosolids from the wastewater sector), overall, there are substantial losses and inefficiencies within the food system with respect to phosphorus. A significant nutrient resource is therefore being lost from the Australian food system unable to be replenished, increasing the dependency on fertilisers and imports. This dependency of Australia's multi-billion dollar agricultural export industries coupled with the system losses at all key stages in the food production and consumption system, such as in agricultural soils, leaves the sector highly vulnerable to geopolitical, natural or economic shocks.

Sustainable phosphorus use means using phosphorus more efficiently, reducing phosphorus demand, closing the loop on waste and developing renewable phosphorus fertilisers to diversify sources and supplement phosphate rock-based fertilisers. Achieving phosphorus security in Australia (and globally) will likely require an integrated approach that recycles phosphorus from multiple sources and sectors of the food system (ranging from manure and excreta to food waste and crop residues), and, finds innovative ways to substantially reduce the long-term demand for phosphorus. Through wide ranging measures such as phosphorus use efficiency in agriculture, changing diets and reducing food waste in supermarket and household bins. Developing and implementing such practical solutions to meeting the world's long-term future phosphorus demand will involve substantial technical, institutional and social changes (Cordell et al, 2009b; Schroder et al, 2011; Cordell et al, 2011).

Unlike other important resources for sustainable food systems and ecosystem functioning, such as carbon, water, land, there has been relatively little research and policy debate on phosphorus at the national or international scale (Bekunda et al 2011; Cordell, 2010).

Research on sustainable phosphorus futures also needs to be embedded in the broader context of sustainable food and agriculture in this country. Figure 1 presents a picture of some of the key drivers (mega trends), past inertia and aspirations related to the Australian food system.

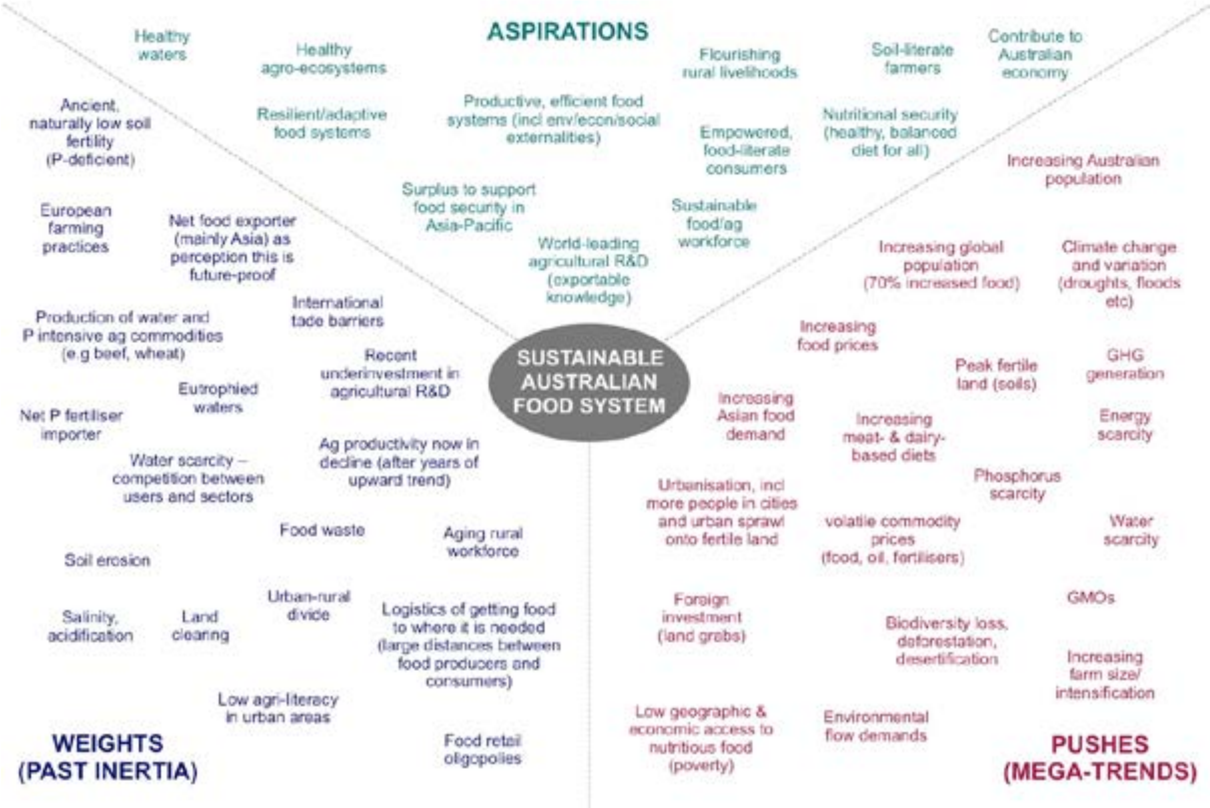

Figure 1: Key drivers (mega trends), weights of the past (inertia), and aspirations (future goals) related to the Australian food system.

Objectives

The ***Australian Sustainable Phosphorus Futures*** project aims to increase scientific knowledge on a range of issues relating to sustainable phosphorus use in Australia and will run over a period of 3 years, building on previous recent research (figure 1). This report documents outcomes from Phase 2: *Adapting to future phosphorus scarcity: investigating potential sustainable phosphorus measures and strategies*. Phase 2 has been undertaken with funding assistance from Rural Industries Research Development Corporation and the University of Technology, Sydney[1]. Figure 1 indicates previous research that this current project builds upon, in addition to locating Phase 2 in the project life cycle.

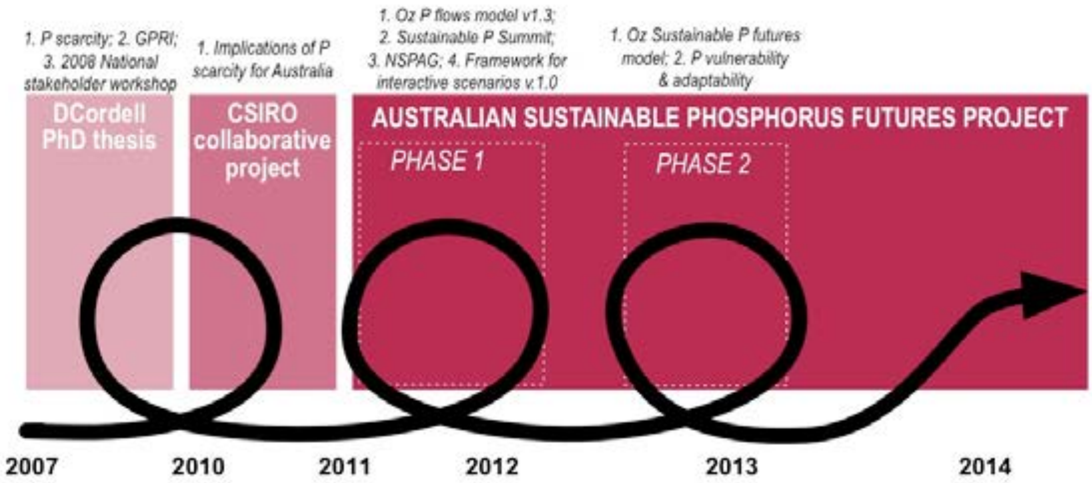

Figure 2: Timeline indicating connection between Phase 1 of the current sustainable phosphorus project and past related projects.[2]

The overall objectives of the three-year project are to:

- Analyse the phosphorus stocks and flows through the Australian food system (from mine to field to fork and losses to the environment)
- Identify sustainable pathways for Australia to secure phosphorus for agriculture and food production in the long-term
- Inform policy, through collaborative development of probable, possible and preferred future scenarios.

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[1] Via a Chancellor's Postdoctoral Research Fellowship

[2] *2007-10*: Doctoral research by Dr Cordell on the implications of phosphorus scarcity for food security globally and in Australia;
2008: National Workshop on the Future of Phosphorus – high-level stakeholder workshop to share perspectives, key challenges and generate a shared vision;
2010: Preliminary research on Securing a sustainable phosphorus future for Australia (collaborative project with CSIRO) – refining the implications of and responses to phosphorus scarcity for Australia.
2012: Phosphorus Flows through the Australian food system: http://phosphorusfutures.net/australian-sustainable-phosphorus-futures/34-phosphorus-flows-through-the-australian-food-system
Interactive Future Phosphorus Scenarios - http://phosphorusfutures.net/australian-sustainable-phosphorus-futures/35-interactive-future-phosphorus-scenarios
National Strategic Phosphorus Advisory Group: http://phosphorusfutures.net/australian-sustainable-phosphorus-futures/36-national-strategic-phosphorus-advisory-group-nspag

The aim of *Phase 2* is to identify the specific ways Australian agriculture is likely to experience phosphorus scarcity and, assess which efficient phosphorus practices and sustainable strategies are likely to be the most appropriate for the Australian agricultural sector to invest in.

The specific objectives of *Phase 2* include:

- Identify and assess which key stressors/factors are likely to impact, increase or decrease Australian agriculture's vulnerability to phosphorus scarcity (e.g. increasing price of phosphate; geopolitical tensions, changing global diets)
- Develop 'Toolbox' of demand-side and supply-side measures for meeting future phosphorus fertiliser demand
- Develop excel-based model of sustainable supply- and demand-side measures (based on Toolbox) and analyse phosphorus supplied or saved (kt/a of P) to meet Australia's long-term future P demand
- Stakeholder workshop to validate priority stressors, vulnerability map and run through possible scenarios
- Synthesise and prioritise sustainable strategies to increase resilience of food system.

Toolbox of sustainable phosphorus measures

Methodology & assumptions

The Toolbox presents a comprehensive classification of all potential phosphorus supply- and demand-side measures to meet long-term phosphorus needs for food production. Examples range from increasing efficiency in the agricultural and mining sector, to technologies for recovering phosphorus from urine and food waste. Such measures are often undertaken in isolation from one another rather than linked in an integrated strategy. This integrated approach will enable scientists and policy-makers to take a systematic approach when identifying potential sustainable phosphorus measures. If a systematic approach is not taken, there is a risk of inappropriate investment in research and implementation of technologies and that will not ultimately ensure sufficient access to phosphorus to produce food in the future.

The sustainable phosphorus measures can also be considered as intervention points within the food system. This enables the Australian phosphorus substance flow analysis (developed in Phase 1 of this project) to be directly linked to sustainable measures (Cordell et al. 2011; Cordell et al, 2013). Figure 3 indicates the two types of supply measures – increasing recycling (S1) and new renewable sources (S2); and two types of demand measures – reducing avoidable losses and increasing efficiency (D1) and reducing phosphorus demand through changing diets (D2).

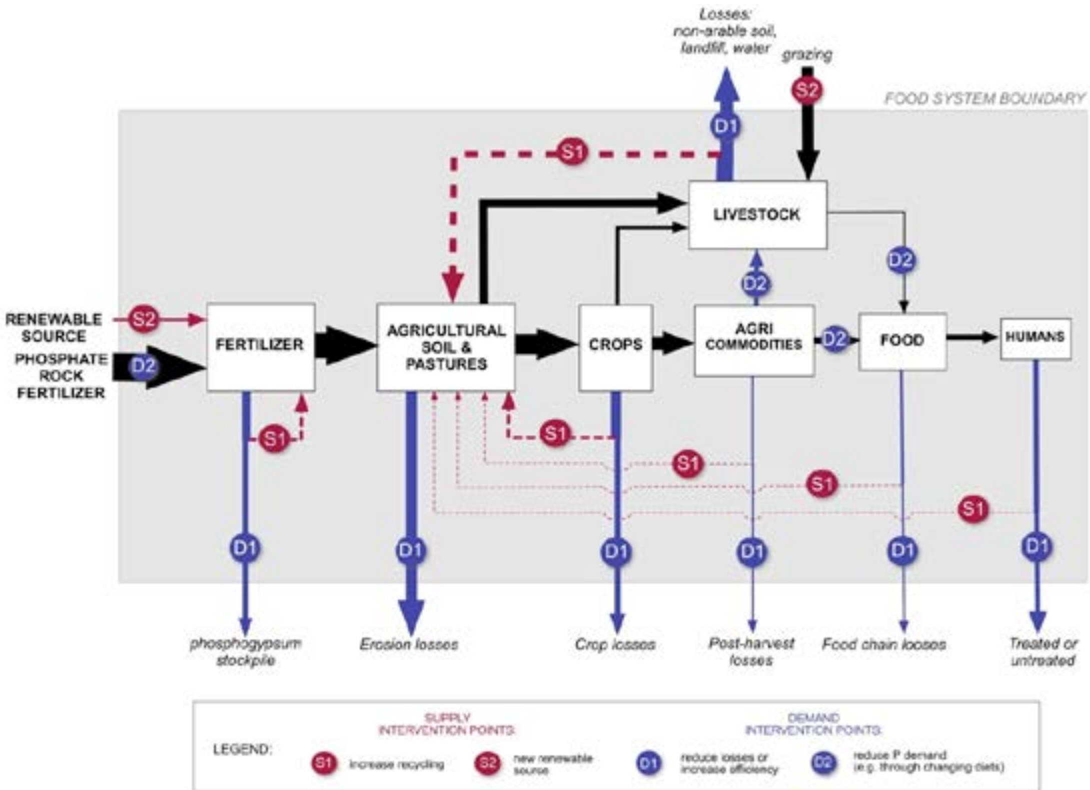

Figure 3. Sustainable phosphorus measures indicated as intervention points in the food system. These are classified as either supply measures – increasing recycling (S1) and new renewable sources (S2); or demand measures - reducing avoidable losses or increasing efficiency (D1) and reducing phosphorus demand through changing diets (D2). Adapted from Cordell et al (2011).

Supply measures

Supply measures deliver a phosphorus source for use as a fertiliser. These can include recycled phosphorus within the food system (such as composted food waste) which means it is recovered from one sector and reused in agriculture as a fertiliser, or new sources (such as phosphate rock or algae) which means it is sourced from outside of the food system and enters the agricultural sector. 'Renewable' phosphate fertiliser refers to a renewable resource (as opposed to a non-renewable resource like phosphate rock) and could include either a used/recycled source such as manure, or a new source such as algae that has grown from nutrients external to the food system such as brines and saltwater [Edwards, 2008].

Phosphorus sources vary widely in terms of phosphorus concentration, chemical form and state (solid, liquid or sludge). From a sustainability perspective, important considerations include: life cycle energy associated with sourcing, transporting and using phosphorus; level of contaminants; phosphorus concentration; other material/chemical inputs; bioavailability to plant roots, usability for farmers; long-term availability and accessibility to farmers; and reliability of quality and quantity (Cordell et al, 2011).

Demand measures

Demand measures seek to reduce total phosphorus demand while maintaining outputs, or increase productivity by increasing outputs per unit of input. Such measures vary widely and can include:

- reducing avoidable losses and wastage, such as food spoilage during food processing and distribution). Schroder et al (2010; table 3) present a typology of phosphorus losses, differentiating between permanent and temporary losses and hence sustainable management responses

- increasing efficiency, such as phosphorus uptake by crop roots; or

- reducing the total phosphorus demand through changing diets towards food that require less phosphorus input per nutritional output (i.e. reversing current trends towards meat and dairy as emerging economies like China and India increase in affluence (WHO/FAO, 2002) and reduce the already high rate of meat and dairy consumption in developed countries).

Phosphorus is essential for crop growth hence there will always be a demand for phosphorus. Indeed, 90% of the current phosphorus use is for food production, predominantly fertilisers (82%), animal feed supplements (7%) and food additives (2-3%) (Prud'Homme, 2010). For these reasons, this paper focuses on the food system.

Results

Table 1 provides a toolbox of sustainable phosphorus measures classified as supply or demand measures and by sector. There is no single solution to meeting Australia and the world's future phosphorus needs for food and agricultural demand. Rather, an integrated approach that involves the right combination of supply and demand measures in key sectors of the food system will be required. The Toolbox allows assessment of phosphorus measures classified either by type (columns) and by sector (rows). The explanation of each measure in each sector is described in Cordell & White (2013).

The intervention points within the agricultural and livestock sectors respectively are systematically identified in figures 4 and 5 and described in Cordell & White (2013, p96-102).

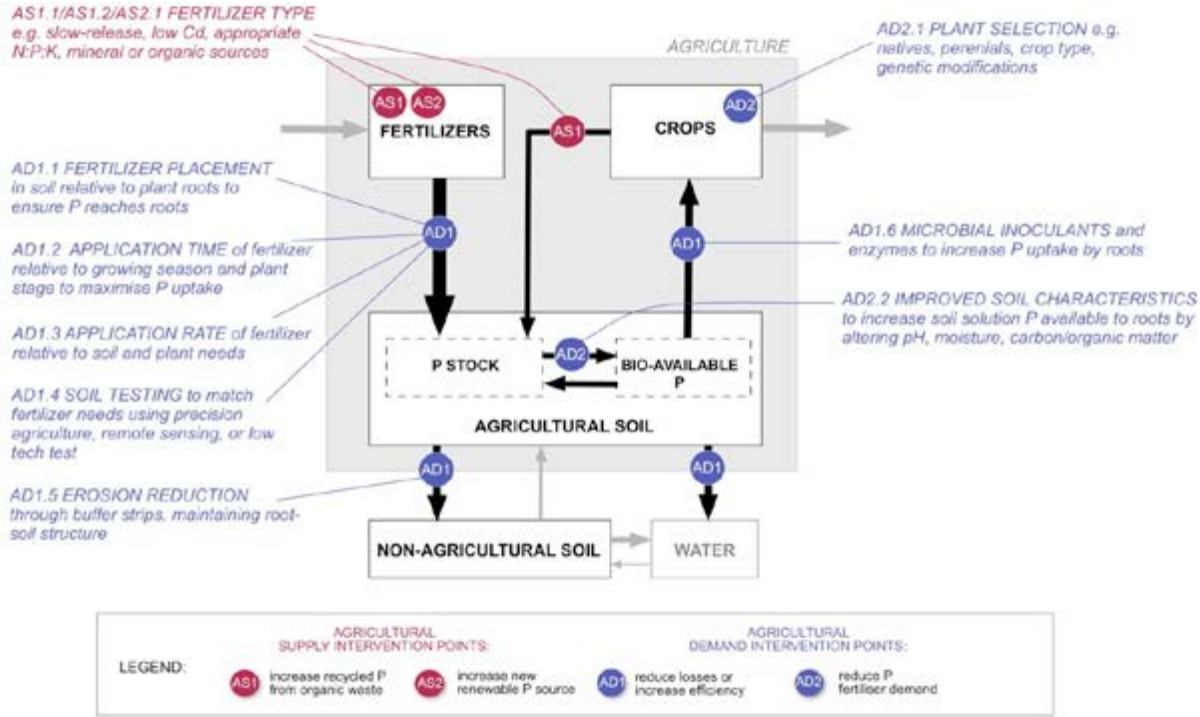

Figure 4: Sustainable phosphorus measures in agriculture – interventions in fertiliser selection and use, crop selection and soil management.

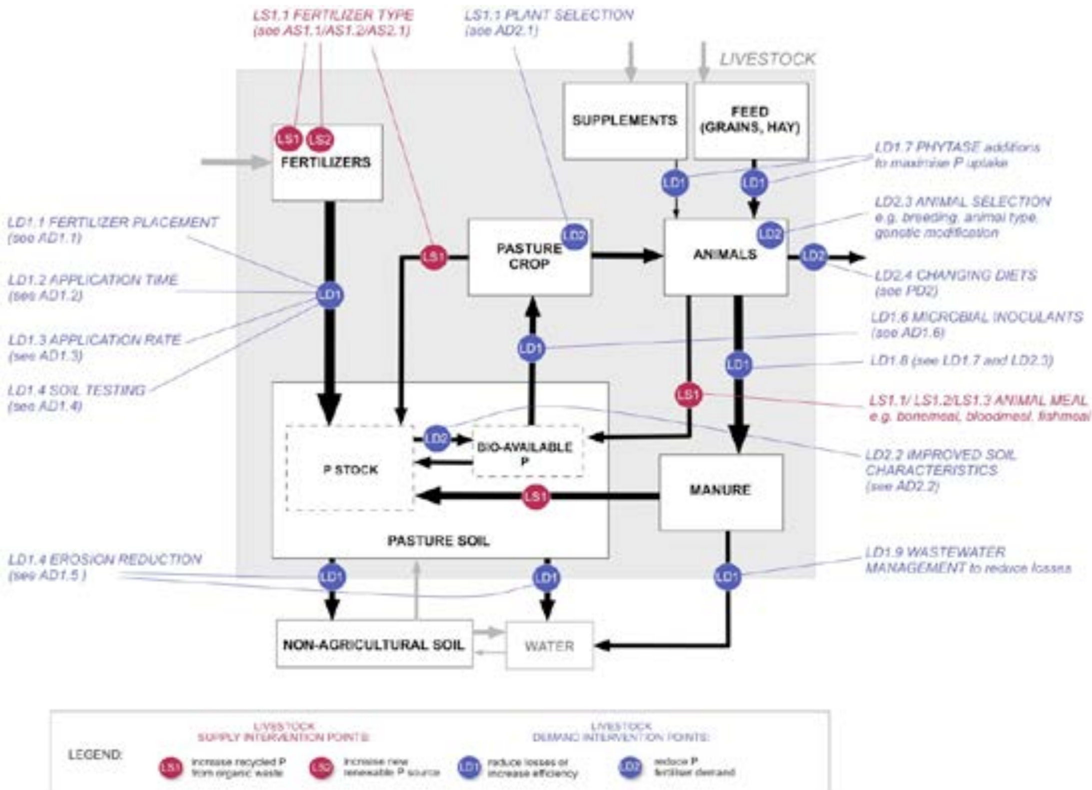

Figure 5: Sustainable phosphorus measures in the livestock sector – interventions in animal selection, fertiliser selection and application, soil management and plant management.

Table 1. Toolbox of sustainable phosphorus measures classified as supply and demand measures and by sector.

Sector	SUPPLY MEASURE (S)		DEMAND MEASURE (D)	
	Recycling (S1)	New source (S2)	Efficiency (D1)	Reduce demand (D2)
Mining (M)	MS1.1 – mine tailings [h]	MS2.1 – phosphate rock [h]	MD1.1 – reduce avoidable losses	MD2.1 – *(all other measures)*
Fertilizer (F)	FS1.1 – phosphogypsum [h]	FS2.1 – algae, seaweed	FD1.1 – reduce avoidable losses	FD2.1 - *(AD2, LD2, PD2)*
Agriculture (A)	AS1.1 – crop waste [b,d,e] AS1.2 - *(LS1, PS1, WS1)*	AS2.1 – *(FS2)* AS2.2 – green manure	AD1.1 – fertilizer placement AD1.2 – application time AD1.3 – application rate AD1.4 – soil testing AD1.5 – erosion reduction AD1.6 – microbial inoculants	AD2.1 – plant selection AD2.2 – improved soil characteristics
Livestock & Fisheries (L)	LS1.1 – manure [a,b,f] LS1.2 – bone [a,d] LS1.3 – blood [a] LS1.4 – fish [a]	LS2.1 – phosphate rock (supplements) [h]	LD1.1 – fertilizer placement LD1.2 – application time LD1.3 – application rate LD1.4 – soil testing LD1.5 – erosion reduction LD1.6 – microbial inoculants LD1.7 - phytase enrichment LD1.8 – manure P reduction LD1.9 – wastewater management	LD2.1 – plant selection LD2.2 – improved soil characteristics LD2.3 – animal selection LD2.4 – changing diets
Food production (P)	PS1.1 – food production waste PS1.2 – cooked food waste	PS2.1 – phosphate rock (additives) [h]	PD1.1 – reduce avoidable losses PD1.2 – producing food closer to demand PD1.3 – consumer food planning/preparation	PD2.1 – reduce P-intensive diets PD2.2 – reduce per capita overconsumption PD2.3 – healthy bodies PD2.4 – minimize use of P additives
Wastewater & human excreta (W)	WS1.1 – urine [a,c] WS1.2 – faeces [b,c,d,h] WS1.3 – greywater [c,h] WS1.4 – untreated wastewater [a] WS1.5 – treated effluent [a] WS1.6 – struvite [c] WS1.7 – biosolids [a,b,f,h] WS1.8 – sludge ash [d]	N/A	WD1.1 – repairing cracked pipes WD1.2 – minimizing sewer overflows WD1.3 – soil management WD1.4 – avoid dumping biosolids in water WD1.5 – reduce spreading biosolids on non-ag land	N/A

Recycled via: [a] direct reuse, [b] compost, [c] precipitation, [d] incineration, [e] fermentation, [f] dewatering, [h] other chemical treatment.

Australian sustainable phosphorus measures model

Methodology & Assumptions

Model overview

The excel-based model analyses a range of sustainable supply- and demand-side measures (based on Toolbox) and determines the flows of phosphorus in Australia (kt/a of P) needed to meet Australia's long-term future phosphorus demand. The model's key features/assumptions include:

- Projection of the flows of phosphorus in Australia into the future: 2040, 2070 (kt/a of P)
- Ninety-six measures or levers that can be pulled to create a more sustainable phosphorus system (64 related to the agriculture sector), based on those in the toolbox
- Additional assumptions not directly related to phosphorus, but influencing its usage such as land area, future population
- Capacity for user-input assumptions for each measure, that is, whether the measure is likely to: rapidly increase, slowly increase, remain steady, slowly decrease, rapidly decrease
- Capacity for these 96 phosphorus measures to be examined quantitatively to determine the amount (kt/a of P) saved or yielded and sectors that the measure affects
- Incorporation of overall characteristics for different types of farming methods such as: land area used, soil characteristics (density, depth).

The structure of the model is indicated in Figure 6 and in detail in Figure 7. See excel model in Appendix A1 for details.

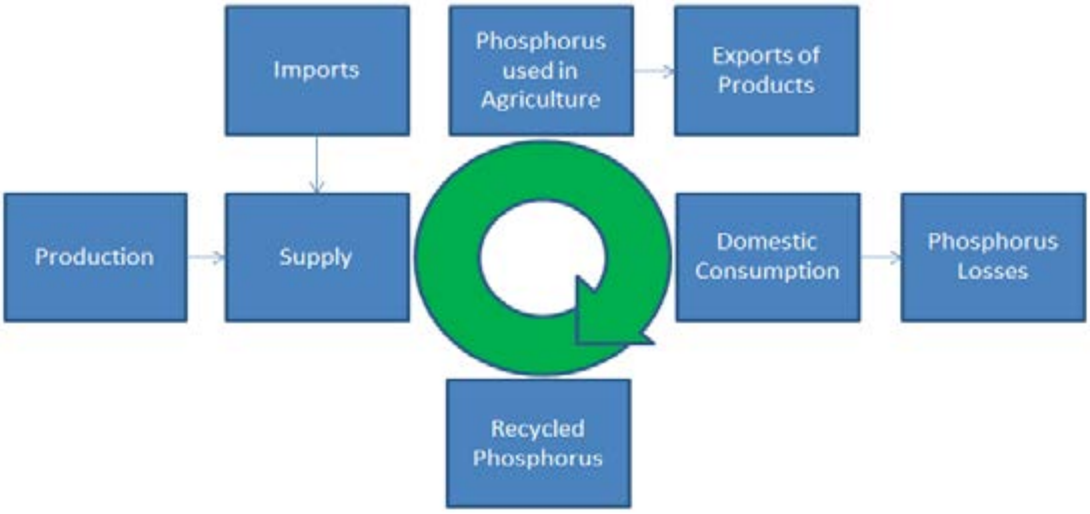

Figure 6: **Conceptual logic of model based on the Australian phosphorus flows model (Cordell et al, 2013) of production, consumption, imports, exports, accumulation, losses and recycling.**

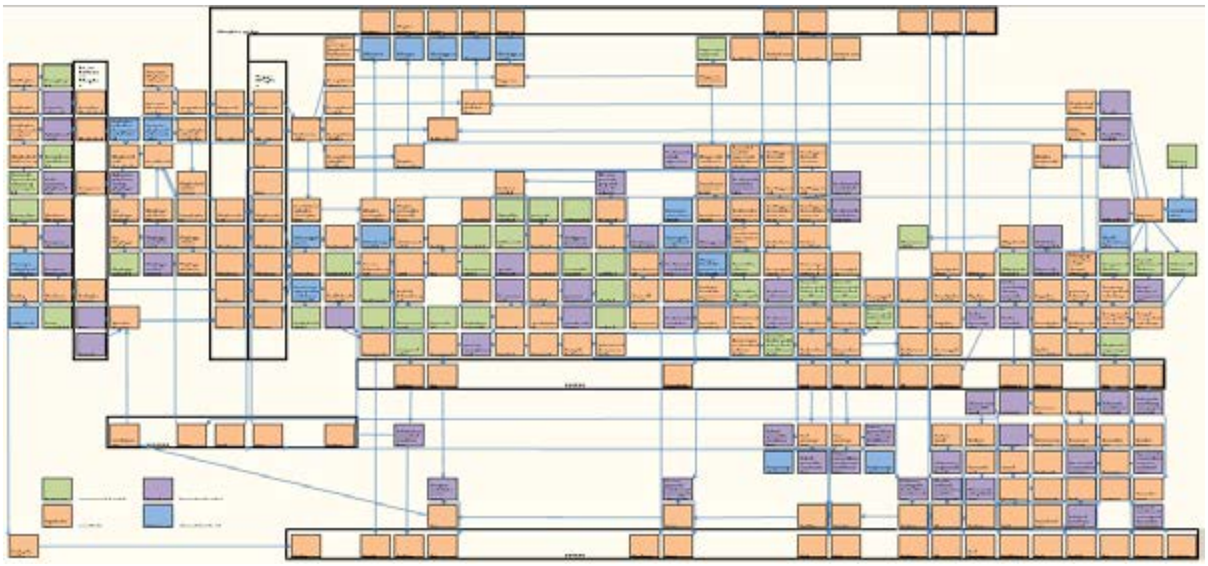

Figure 7: **Model variables and linkages. Green variables refer to complex assumptions (typically actual usage in 2010), blue variables refer to moderate assumption (things that affect phosphorus flows indirectly), orange variables are calculated by the model, purple variables refer to measures or levers that can directly affect phosphorus flows and black boundaries refer to the broad sectors. See Appendix A2 for explanation of variables.**

The steps required by the user to engage with the model include:

- **Step 1**: **Select the demand scenario desired**. This refers to total phosphorous demand for Australia. The high scenario was based broadly on the ABARES 2050 projection for food/agricultural demand growth in Australia (Linehan et al, 2012). The low scenario was based on steady-state (i.e. constant future demand), and the medium scenario was in between the high and low scenario. (figure 8);

- **Step 2: Select from the following phosphorus measures that should be considered in the model**. This allows users to tick the measures they wish to make a future trajectory assumption about (in Step 3). Those measures unselected will default to business-as-usual (figure 9);

- **Step 3: Assumptions for the selected measures.** For each measure selected in Step 2, the user can now choose the future trajectory in terms of increasing/decreasing and rate (figure 10)

- **Step 4: (optional) Select future trajectories.** The user can change assumptions that indirectly affect the phosphorus flows, such as changing the amount of land area for farming etc.

- **Step 5: View results.** Users can view the implications of their assumptions graphically (Figure 11). In particular specific graphs showing the amount of phosphorus:

    - Produced in Australia (mining, renewable harvesting of seaweed etc)
    - Imported into Australia (embodied in commodities)
    - Exported out of Australia (embodied in commodities)
    - Utilised domestically (on farms, pastures or manufacturing)
    - Waste generated
    - Recycled
    - Lost, portion of wastes streams that were not recycled, and uses of phosphorus that result in unrecoverable phosphorus (e.g. burning matches, erosion losses to waterways).

- **Step 6: run analysis of Top10 measures.** This step allows the user to run a sensitivity macro that orders all 96 measures in terms of kt of P saved, yielded, recycled etc. This enables the user to observe which measures have the greatest impact on the flows of phosphorus and the sector that it affects the most.

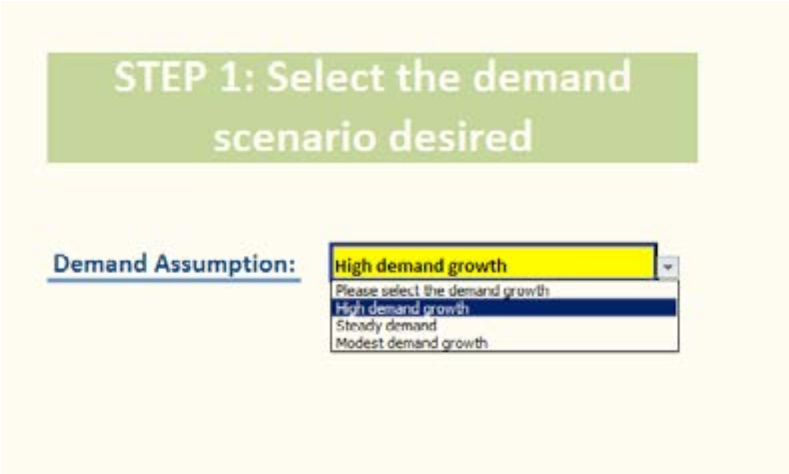

Figure 8: Step 1 – selecting business-as-usual demand.

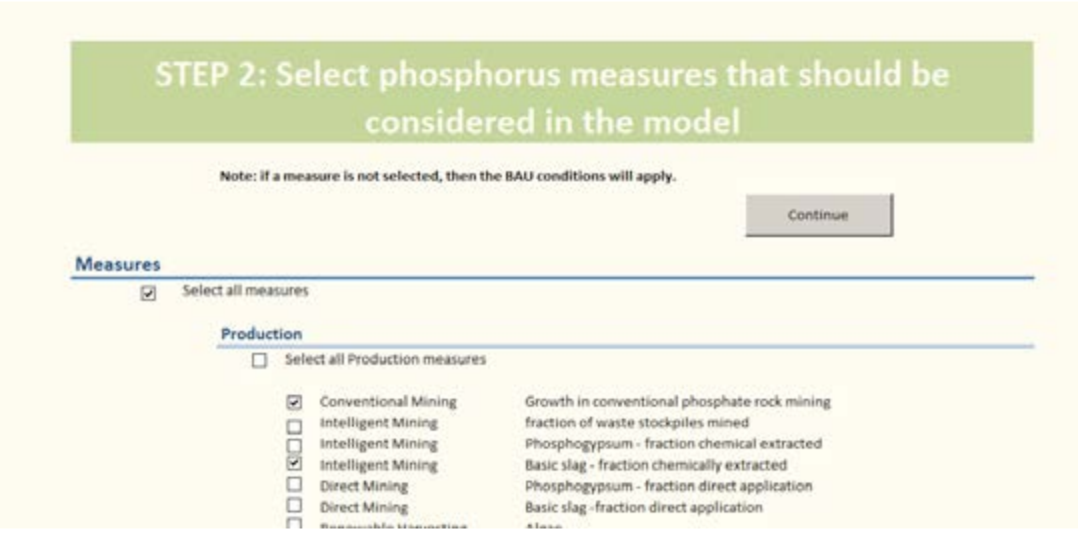

Figure 9: Step 2 – selecting measures to input assumptions for in Step 3.

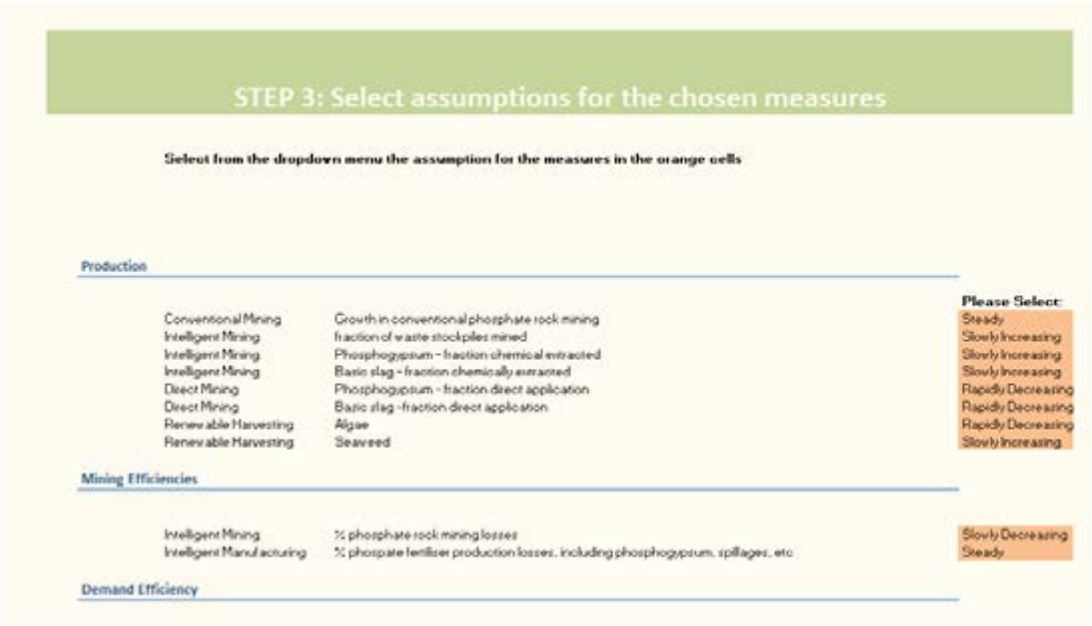

Figure 10: Step 3 – Assumptions for the selected measures.

Data assumptions

Data assumptions and calculations are in hidden sheets within the model. These provide assumptions for moderate and complex variables in the model. Data was sourced from a variety of sources, including: official government statistics (e.g. ABS, ABARES); reports and data sets (e.g. CSIRO studies); industry data and scientific studies (e.g. peer-reviewed literature); International data as a proxy for Australian situation (e.g. UNs Food & Agricultural Organisation or the International Fertiliser Industry Association); or data or outputs from *Phase I's Australian Phosphorus Flow Model* (Cordell et al 2013). Where sufficient data was unavailable, values were determined by mass balance, personal communication from NSPAG members and other experts or assumptions generated by the research team.

Actual data and associated assumptions, description, units and reference are provided in Appendix A2 and A3.

Results

The actual model is provided in Appendix A1.

The built-in user interactivity in the model allows the targeted stakeholder groups to engage with possible futures despite the high uncertainty (in part due to lack of high-quality data) and lack of consensus regarding preferences/priorities and future trajectories. For example, rather than stakeholders dismissing the model due to poor data or disagreement with its' assumptions, the stakeholders can themselves select the assumptions. For example, whether soil testing and subsequent improved application of fertilisers will rapidly increase, slowly increase, remain steady, slowly decrease or rapidly decrease in the long-term future (2040 and 2070). This interactivity with respect to assumptions not only allows stakeholders to test their preferred assumptions and scenarios about the future, it also facilitates a dialogue between the disparate group of stakeholders (e.g. fertiliser industry, wastewater sector, public health sector) whom may hold different views and assumptions about the future.

The graphical results from the model therefore depend on the user input assumptions for Steps 1-3. By way of example, the graphs in figures 11 (a)-(f) below indicate the results for a specific scenario tested, that assumed high phosphorus demand in future (Step 1), high mining of stockpiles, high recycling/efficiency rates (Steps 2 and 3).

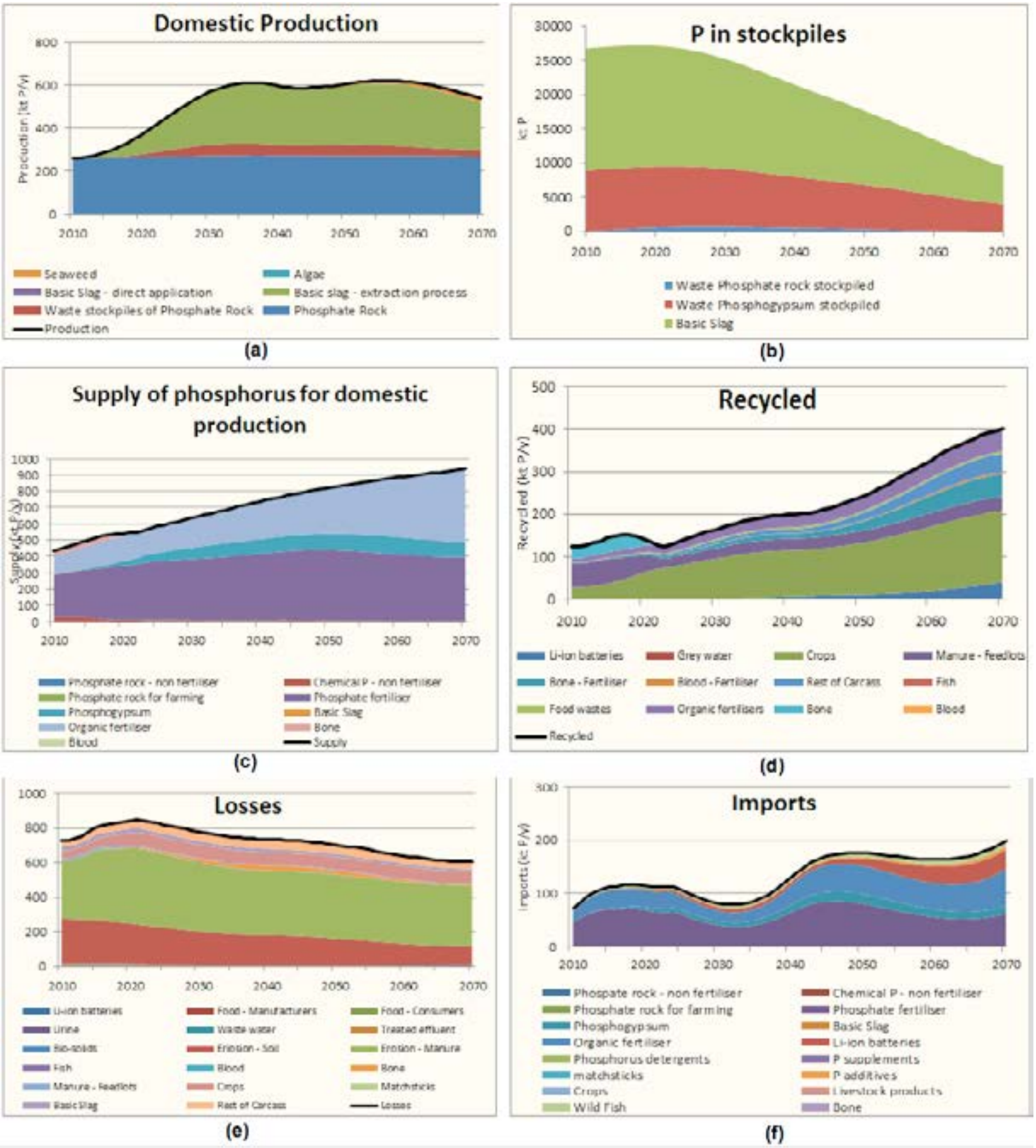

Figure 11: Model outputs from selected scenario, indicating: (a) Domestic production of phosphorus from new sources; (b) P in waste stockpiles; (c) supply of phosphorus from fossil or recycled sources for domestic use in agriculture; (d) recycling of phosphorus from both within and outside the food system; (e) phosphorus losses from the entire food system; and (f) imports of phosphorus in fertiliser, feed or chemical form to supplement domestic supply.

The scenarios in figure 11 indicate that domestic production of new sources of phosphorus would come largely from phosphate rock, recovered phosphorus from mine waste stockpiles, and phosphorus extracted from slag stockpiles, supplemented by a very small amount from algae and seaweed (figure 11a). Figure 11b indicates the draw-down of slag stockpiles due to moderate phosphate recovery, while Figure 11c indicates that phosphorus consumption in this country would largely be from phosphate fertilisers derived from phosphate rock and slag, with an increasing amount supplemented from renewable phosphate sources such as manure, food waste and human excreta. Figure 11d shows an increasing amount of phosphorus recycling over time, predominantly for productive reuse in agriculture, but also for non-food uses (such as batteries) and non-fertiliser uses such as blood/bone/animal meal. Crop waste represents the largest flow of recovered phosphorus for use in agriculture, and to a lesser extent manure, blood and bone, animal meal, food waste and human excreta. The reuse of phosphorus from Lithium-ion phosphate electric vehicle batteries is also indicated on this graph. Each battery contains some 60kg of phosphate, which is presumed to be recovered and recycled in new batteries at the end of their life. Figure 11e shows a steady decrease in phosphorus losses from the entire food system, predominantly associated with permanent losses due to soil erosion from cropping and livestock based systems, followed by smaller amounts of crop waste and bones. Finally, figure 11f shows imports of phosphorus to supplement domestic supply. Imports are largely in the form of phosphate rock, phosphate fertilisers, and to a lesser extent phosphogypsum.

Framework for developing costed phosphorus policy measures

The outputs of the model are indicated in kilotonnes of phosphorus associated with different measures. In practice, implementation of these measures usually requires the action of a range of stakeholders and policy instruments, particularly to overcome institutional barriers and market failures that inhibit their uptake. Policy instruments in this context refer to the spectrum of implementation measures, ranging from regulation to market mechanisms, as indicated in Figure 12.

The analysis of barriers to the uptake of resource efficiency measures, and the policy tools, or instruments that are needed to overcome those barriers can be generalised across a range of resource issues. Previous research in this aspect has been undertaken by researchers in the water (White et al 2008) and energy (Dunstan et al 2009) sectors. A useful categorisation of the barriers and associated policy tools includes:

- *Regulatory* instruments, such as targets (e.g. recovery of phosphorus from excreta or manure etc); limits (e.g. discharge limits on phosphorus to sensitive waterways) or bans

- *Economic* instruments such as taxes (e.g. phosphorus tax) or trading schemes (e.g. phosphorus trading scheme in a catchment)

- *Communicative* or educational instruments such as stakeholder engagement processes and outreach (e.g. workshops, seminars); developing stakeholder-specific resource material.

Figure 12 depicts these policy tools on a policy palette as either primary instruments (in the primary colours red, blue and yellow) or secondary instruments (orange, purple and green) (Dunstan et al 2009). Examples of phosphorus options, comprising the measures plus the associated instrument, are shown as annotations on the graphic. The role of co-ordination is important as it combines the full range of instruments, and in the case of phosphorus is conspicuously absent in terms of the lack of institutional oversight of the issue of phosphorus scarcity (Cordell, 2010).

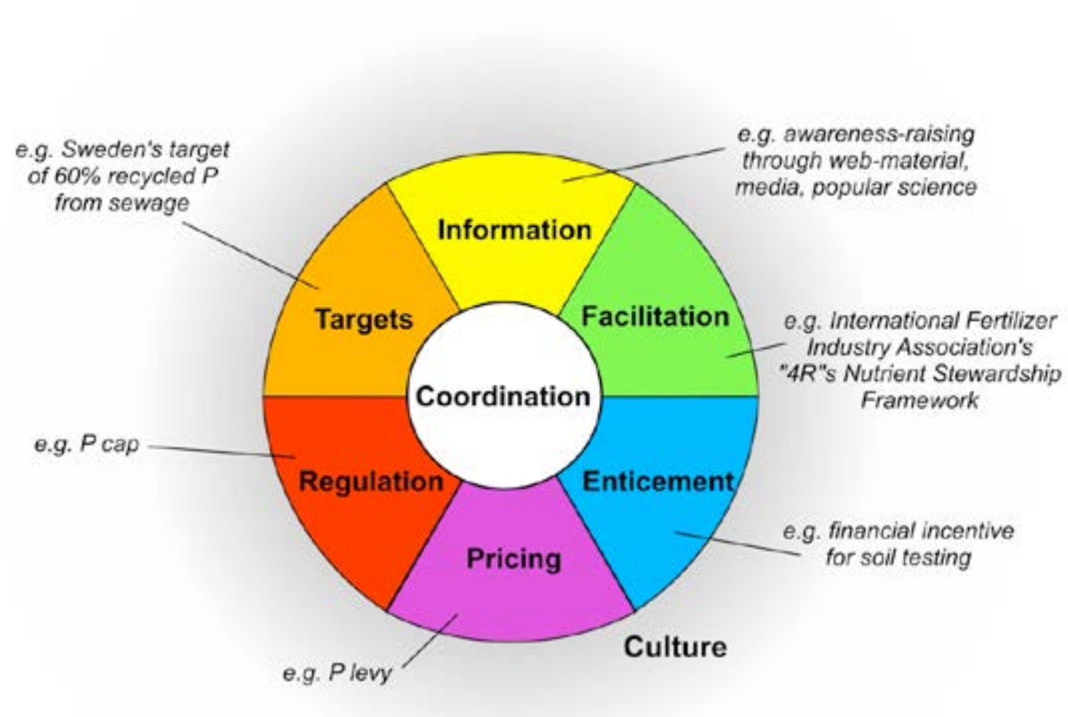

Figure 12: The policy palette, indicating seven policy instruments embedded within society/culture and requiring co-ordination across instruments. Phosphorus-related examples are also indicated (adapted for P from Dunstan et al, 2009).

Combining the measures outlined in the toolbox, with a selection of appropriate policy tools or instruments, in figure 12 yields options that can be not only assessed in terms of their phosphorus impact (kt P yielded or saved), but can also be assessed for their cost of implementation. A useful metric for comparison of the relative cost-effectiveness of these options is the unit cost, or levelised cost expressed, for example as $ per tonne of P per annum ($/kt/a of P). Figure 13 provides an indicative graphical representation of this in terms of a 'supply curve of saved or supplied P', showing a sample of the measures from, the Toolbox, combined with policy instruments to create options.

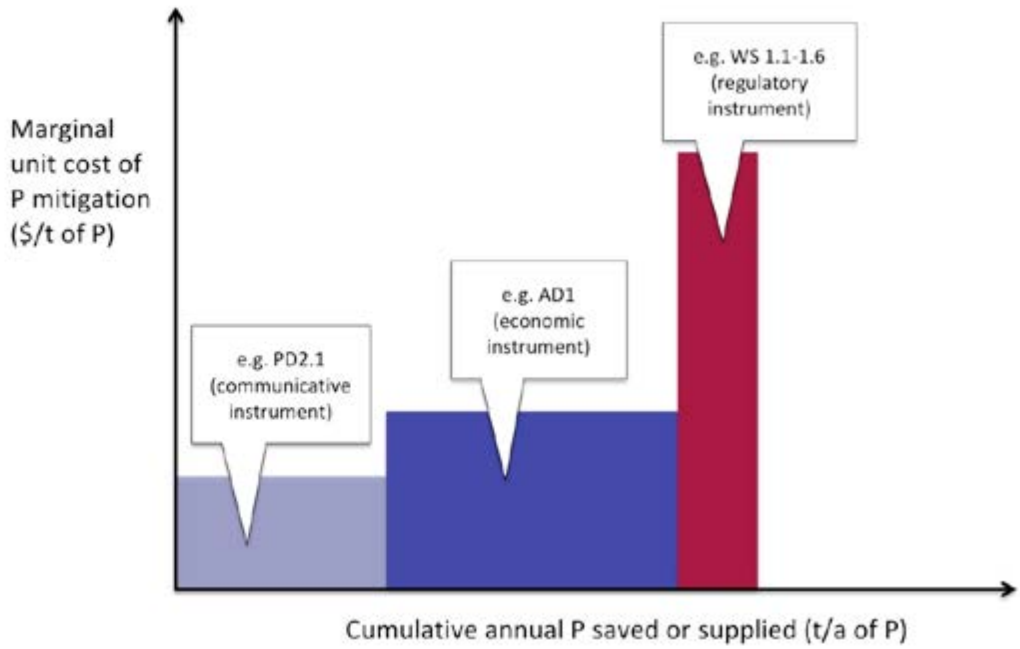

Figure 13: An indicative 'supply curve of saved or supplied P' using some of the measures in the Toolbox. The ranking is illustrative only.

The process of identifying the unit cost of options, is part of a decision-making framework determining the best portfolio of options for implementation. The water and energy sectors provide such a framework in terms of integrated resource planning, as described by Turner et al (2010) and White et al. (2008).

The overall framework, adapted to the case of phosphorus would include:

1. Identify objectives and drivers, by seeking agreement amongst the key stakeholder regarding the key drivers and objectives, as these will influence the most suitable measures (e.g. pollution prevention, desire for renewable phosphorus fertilisers, farmer productivity) (Cordell et al 2011)

2. Identify a baseline, or Business-as-Usual demand trajectory, sometimes called a reference case, which can explicitly show targets, and from which the impact of options can be compared (Cordell et al 2009b)

3. Identify and categorise the most comprehensive range of measures that could meet the objectives, and assess the P savings or yield associated with the measures

4. Match the measures with appropriate policy instruments, using the policy palette described in Figure 8, and with reference to stakeholder roles and responsibilities (Cordell, 2010; Childers et al 2013; GPRI, 2013)

5. Estimate the annual amount of phosphorus saved (e.g in 'megatonnes per annum' in the case of efficiency options) or supplied (in the case of recycling options) for the selected options and represent these graphically in a 'supply curve' (such as figure 13)

6. Based on the cost-effectiveness of options, construct a realistic and achievable portfolio of options for implementation, based on the complementarity of different options, and taking into account other parameters beyond unit cost, such as risk, environmental impact or benefit, or even spread across sectors.

Mapping vulnerability in the Australian phosphorus system

Methodology & assumptions

Defining a sustainable phosphorus system

For the purpose of facilitating a dialogue on potential vulnerabilities and adaptive strategies for long-term phosphorus security, a definition of sustainability was developed for the Australian phosphorus system, which takes into account multiple goals and is defined as:

> *A system that allows Australian farmers to access and use phosphorus sustainably in the short and long-term to: support farmer livelihoods; optimise agricultural productivity; ensure ecosystem integrity; feed the Australian population; and contribute to food security in the region and globally.*

This definition explicitly incorporates 4 different worldviews/perspectives, based on previous sustainable phosphorus research and stakeholder engagement (e.g. ISF 2008, 2010, 2012, 2013; Cordell & White 2013):

- *Economic worldview*: Agricultural contributes to the Australian economy
- *Livelihood security worldview*: Agriculture supports rural/farmer livelihoods
- *Ecological worldview*: Agriculture protects/enhances soil fertility, natural resources and the environment
- *Food security worldview*: Agriculture ensures domestic food needs are met and contributes to regional and global food security.

Influence diagram of the Australian phosphorus system

An influence diagram (Newell et al 2011) was constructed to explore relationships and establish causal pathways between the many interconnected variables that may influence the sustainability of the Australian phosphorous system. Key variables were selected based on the generic national Phosphorus Vulnerability Assessment framework (Cordell & Neset, 2013) and the pre-workshop NSPAG survey. The influence diagram was used as a visual tool to:

- Facilitate group discussions and integrate multiple-perspectives
- Establish an interconnected view of the system as a whole
- Explore *'What If"* scenarios for their potential effects on the system by mapping out potential vulnerable pathways through the system
- Identify key variables that could make the system vulnerable if they changed state
- Identify variables that could make the system more sustainable if they changed state
- Map out potential adaptive pathways through the system.

Vulnerability and 'What If' Scenarios

Vulnerability can be defined as the degree to which a system is susceptible to or unable to cope with, adverse effects of a hazard, shock or perturbation that disturbs the system's operation in some way. Vulnerability is viewed as the state of susceptibility to harm from exposure and sensitivity to stresses associated with environmental and social change and from the absence of capacity to adapt (figure 22). Many hazards, such as those associated with global phosphorus vulnerability, are associated with system complexity, long time horizons and high levels of uncertainty about the severity and timing of impacts. In such cases the best strategy is often to increase the flexibility of systems to function under a wider range of stresses by enhancing system capacity to adapt.

To address phosphorus vulnerability in the national phosphorus workshop, 'What If' scenarios were used to bring the static influence diagram to life by collaboratively exploring the vulnerability implications of potential perturbations in the system. For example, how might each of the following perturbations affect the four defined sustainability goals if one or more of the variables changed state:

a. What if the price of phosphate rock rose to $500/t? (short-term impacts?);

b. What if the price stayed above $500/t? (long-term impacts?);

c. What if the price stayed above $500/t *and* global food prices increase;

d. What if Australia had invested in sustainable phosphorus measures and c occurs?; or

e. What if Australia had invested in sustainable phosphorus measures (due to groundswell of interest in global resource management of finite resources and pollution management to mitigate algal blooms) and no hazards occur?

The following matrix in table 2 was developed to provide a framework for assessing the implications of perturbations for different stakeholders or goals. This was used to guide the discussion in the workshop, the results of which are shown in the next section.

Table 2: Framework matrix for assessing who/what might be affected adversely/positively by changes/scenarios in the system and in what way.

"What if?" scenario	Implications for…			
	Rural/farmer livelihoods	Australian economy	Biodiversity & aquatic ecosystems	Food security
A. Price of P rose to $500/t? (short-term impacts?)				
B. P price stayed above $500/t? (long-term impacts?)				
C. Price stayed above $500/t + food prices rose?				
D. Invested in sustainable P measures + C?				
E. Invested in sustainable P measures only?				

Results

Validated influence diagram

The following influence diagram (figures 14 and 15) was validated by NSPAG members during the workshop. Participants were first presented with a diagram indicating sub-groupings of system variables (figure 14), such as *farm practices* or *global trends/drivers*, to reduce the initial confusion that can occur from viewing a complex system diagram. The red variables denote exogenous *global trends/drivers*, while blue variables denote the remaining endogenous variables. The circles also locate the four key sustainability variables within the system.

The diagram represents a static picture of the system, and efforts were made to word each variable in a fashion where it could shift one way or the other based on a system perturbation. For example, variables are framed so that they could potentially increase or decrease. The relationships or causal linkages are represented here as dashed lines.

In a functioning system diagram each variable should logically influence the variables that it directly connects to with an arrowhead. The best way to read an influence diagram is to pick a starting point and ask *'does this variable logically cause or contribute to the variable that it connects to'.* Causal paths can then be followed through the system as a whole.

Participants were initially asked to validate the diagram (figure 15) and identify any important missing variables. A key addition to the diagram by the group for example was the inclusion of the *government intervention* and *industry intervention* variables, as the key drivers for *R&D investment* (top left of the diagram). As most participants were experts in one particular area of the system, the sub-groupings allowed each participant to start by thinking about their particular area of familiarity. The group discussions that followed allowed each participant to explore how their area of expertise connected with other knowledge of the system, to collaboratively build a more detailed picture of the system.

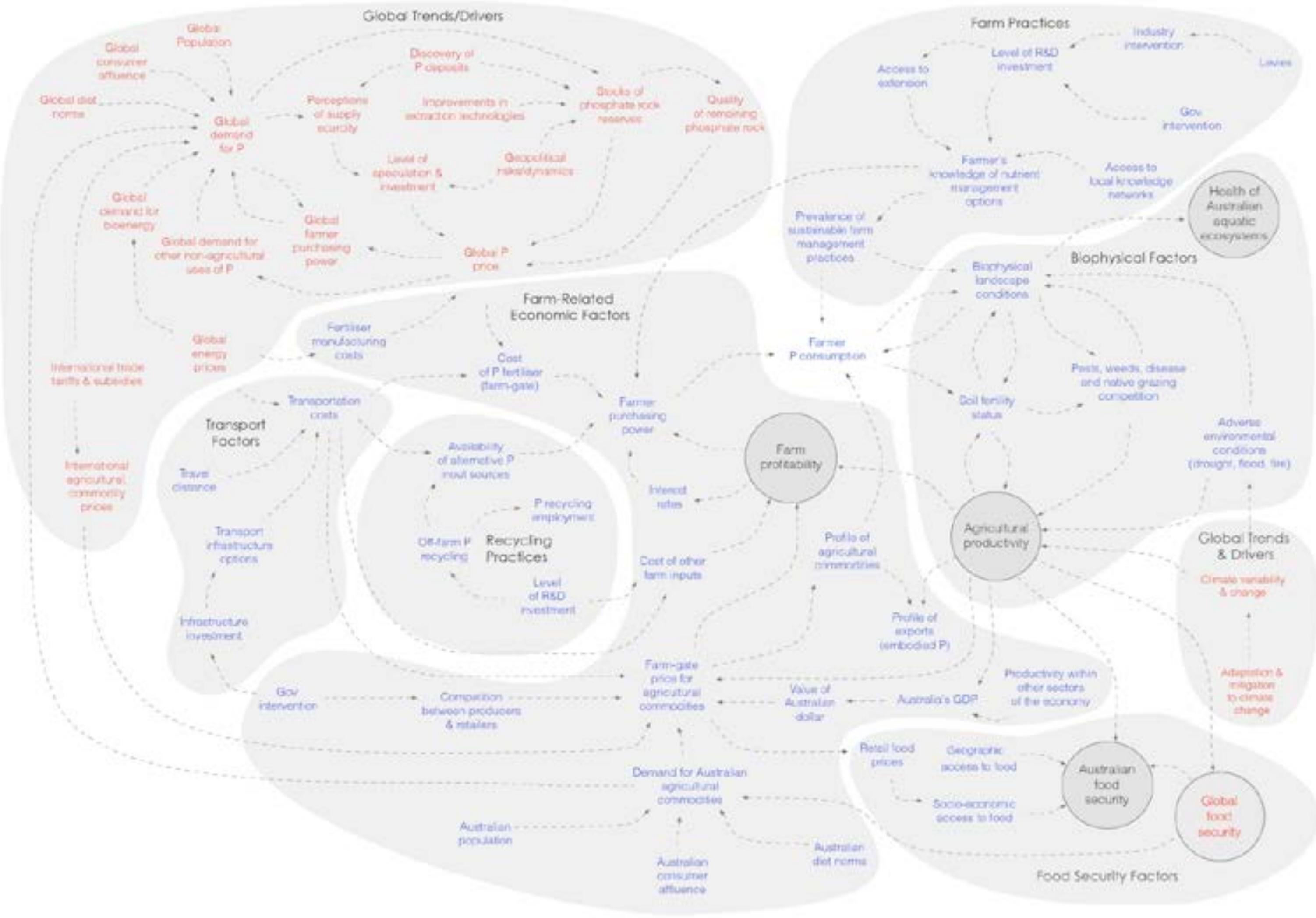

Figure 14: Influence diagram of the Australian phosphorus system indicating clustered variables: global trends and drivers, farm-related economic factors, farm practices, biophysical factors, transport factors, recycling practices and food security factors. Circled variables represent end goals of the system.

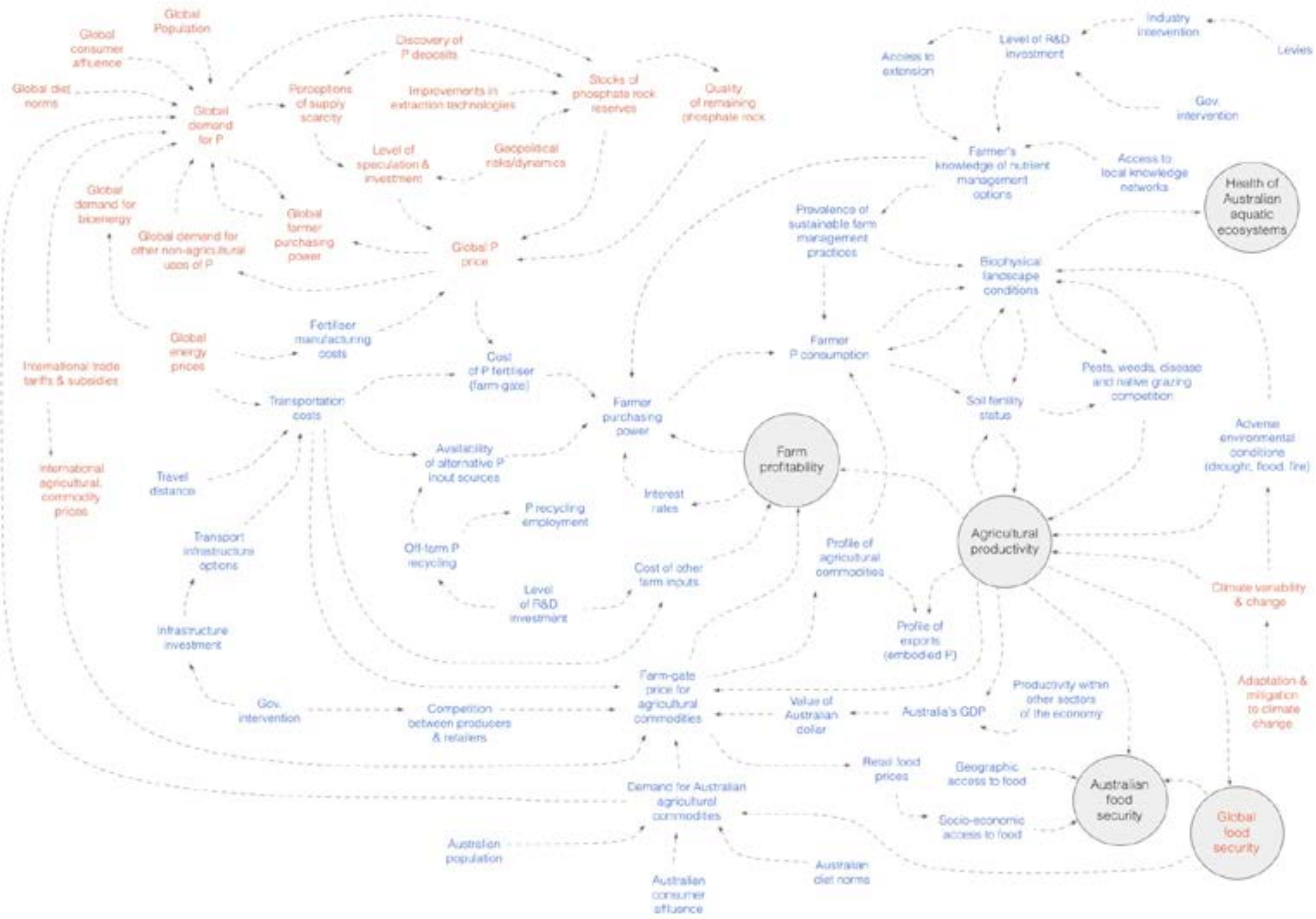

Figure 15: Stakeholder-validated influence diagram of the Australian phosphorus system. Global variables are indicated in red, Australian variables in blue, sustainability goals in grey circles, potential causal links between variables as dotted arrows.

Stakeholder “What If” scenarios

The scenarios explored during the workshop using the influence diagram predominantly focused on the pre-prepared *‘what if’* scenarios a) and b): What if the price of P rose to $500/t in both short-term or the long-term? However a number of participants chose to explore additional vulnerable paths and adaptive pathways.

Participants were asked to add a chosen perturbation to the influence diagram and then track likely consequences of the change through the system. By doing this exercise the participants could ascertain whether the system was vulnerable to a specific change by following the potential impacts through to the defined sustainability goals. Each participant was asked to use plus and minus symbols to indicate how each variable would change the next. Within this particular diagram the logic follows that a plus will lead to an increase and a minus will lead to a decrease.

Figure 16 is an example of a participant tracking a vulnerable pathway through the system: beginning with a long-term global phosphate price increase, leading to increased farm-gate fertiliser costs, reducing the farmers purchasing power, decreasing the amount of phosphorus applied, reducing soil fertility over time, in turn reducing agricultural productivity, increasing food prices and further reducing the farmers purchasing power.

After drawing individual vulnerability maps using the influence diagram template in small groups, the whole group discussed the specific events that could be trigged by the ‘what if’ perturbations. The following potential paths emerged during the group discussion which cover a range of additional consequences that may arise from phosphate price rises in the future:

- **Path A**: if phosphate fertiliser prices rise and graziers apply less phosphate fertilisers to pastures, this can reduce productivity of pastures, however:
    - (i) can have a positive impact on landscape ecological integrity by increasing biodiversity (since less pasture grasses and more native vegetation);
    - (ii) or, conversely, reduced phosphate consumption in livestock sector (for pastures) could also result in adverse environmental outcomes by increased growth in weeds/pests;
    - (iii) these less productive pastures can also result in increased erosion due to lower groundcover (thereby increased phosphorus-containing soil runoff into receiving water bodies, hence reducing aquatic ecosystem integrity);
- **Path B:** If phosphate fertiliser prices increase in the short-term and farmers purchasing power is reduced:
    - (i) farmers might be able to cope (can use soil P stock in short term); indeed, the 2008 price has influenced farmers application rates (more hard nosed than before rather than blanket applications);
    - (ii) however rural communities might be hurt by the lack of business/labour associated with farming;
- **Path C:** When phosphate fertiliser price goes up:

- (i) some alternative renewable phosphorus sources (e.g. ACTEW's Argi-Ash[3], a byproduct from wastewater) increase their prices in response, while remaining competitive;
- (ii) this increases the opportunities to invest in phosphorus recycling in the long-term.

- **Path D:** If the price of phosphate increases then previously unviable phosphate rock deposits might become economically feasible:
  - (i) this would initially trigger the collection of phosphate rock data and exploration in the short-term (this was evidenced after the 2008 price spike, which saw an increase in estimates of reserves);
  - (ii) in the longer-term, that is, a sustained price rise, extraction would increase. Importantly, the quality of new reserves which may be considered economically viable are typically of a lower grade, containing less phosphorus;
  - there are some self-managed loops – if the timing is right, the market might be able to correct the situation if prices rise. However thermodynamics might override economic management – lower grades require more energy, more labour, more processing, more waste. That is, the market might drive some improvements but alone not be sufficient; and

- **Path F**: if food prices increased at the appropriate timing (before fertiliser price rose) then farmers might be able to afford more fertilisers i.e. if timing was synchronised.

In addition to the pre-prepared *'what if'* scenarios, a number of the participants also chose to map out paths beginning from alternative vulnerable or adaptive perturbations. Figure 17 presents an example of an alternative vulnerable pathway emerging from a *long-term increase to global energy prices*. That is, increasing the cost of both manufacturing and distributing phosphate fertiliser, increasing the cost of transporting additional farm inputs, and increasing the cost of transporting the produced agricultural commodities. These changes were tracked through to decreasing farm profitability: as farmers' capacity to purchase phosphorus fertiliser and additional farm inputs may decline as a result of rising input costs, which could then impact their productivity over time (as stocks of phosphorus within the soil bank decline). The further consequences of this path may be rising retail food prices in the short term and greater impacts to Australia's food security in the longer-term if agricultural productivity continued to decline.

Figure 18 is another example of a causal path emerging from an alternative perturbation. In this instance an adaptive strategy of increased government intervention as a means to drive R&D and extension services specifically targeting sustainable nutrient management practices on farms. The causal path tracks the consequences of improving sustainable farm management practices through to decreasing fertiliser consumption and maintaining the longevity of soil fertility (via improving biophysical landscape conditions). For example, by reducing overall fertiliser consumption by increasing the prevalence soil testing practices (to guide applying the right amount of fertiliser at the right time) and maintaining soil fertility by reducing phosphorus losses to the environment (by improving natural resource management practices such as ground cover retention).

[3] See: http://www.actew.com.au/Water%20and%20Sewerage%20Systems/ACT%20Sewerage%20System/What%20is%20sewage/Agri-Ash.aspx

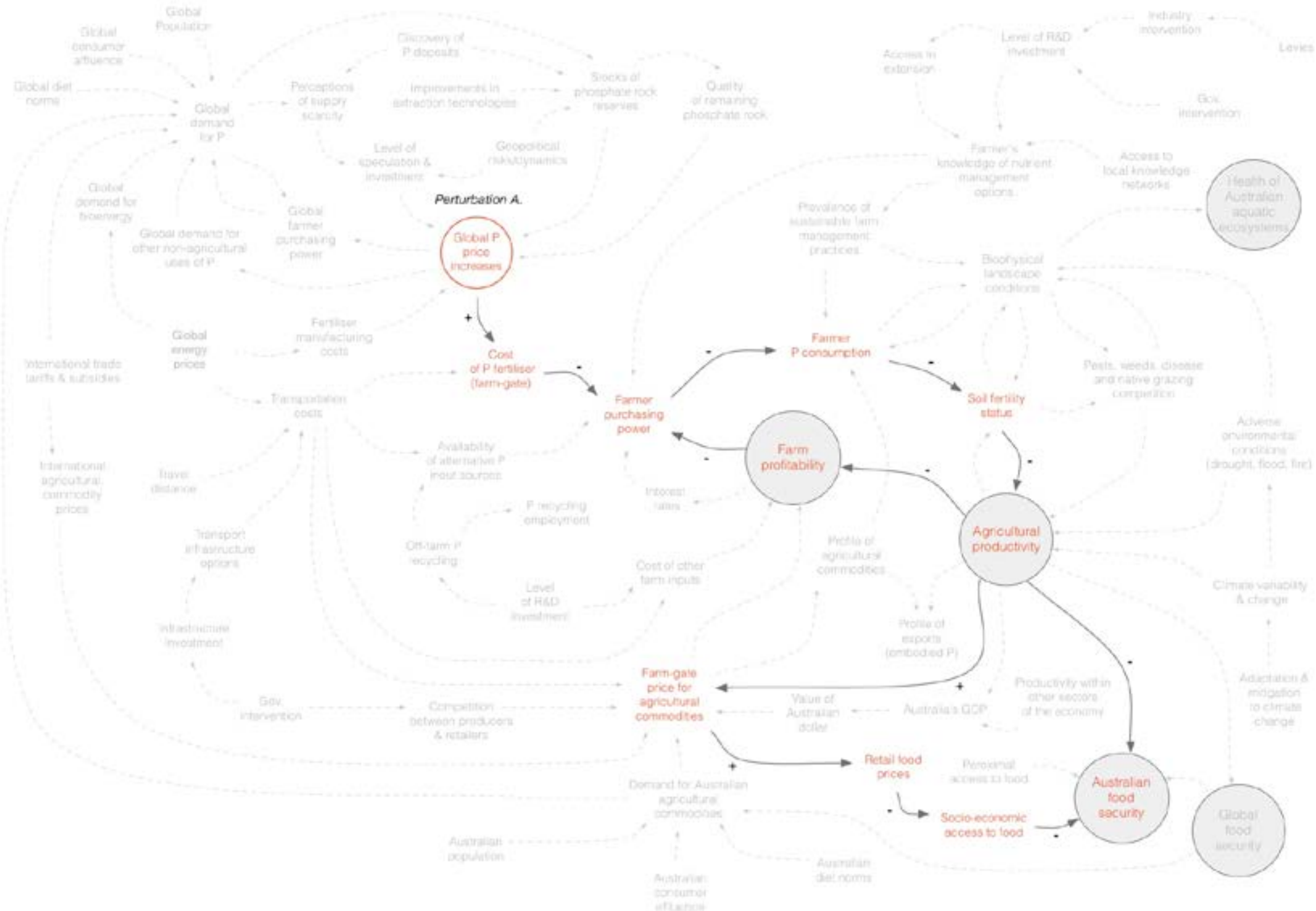

Figure 16: Example of a participant generated vulnerability path, beginning with a long-term global phosphorus price increase.

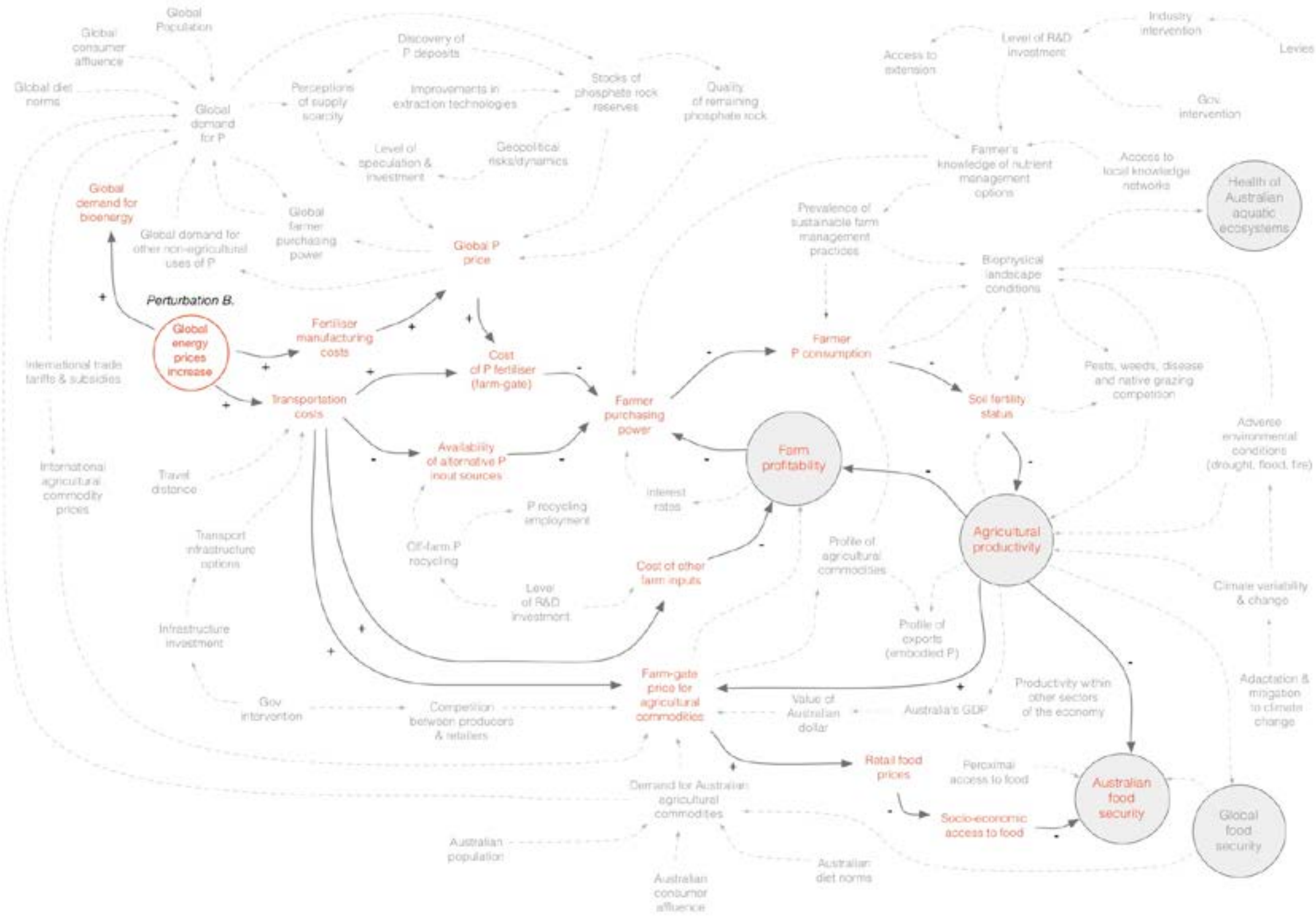

Figure 17: Example of a participant generated vulnerability path, beginning with a long-term increase to global energy prices

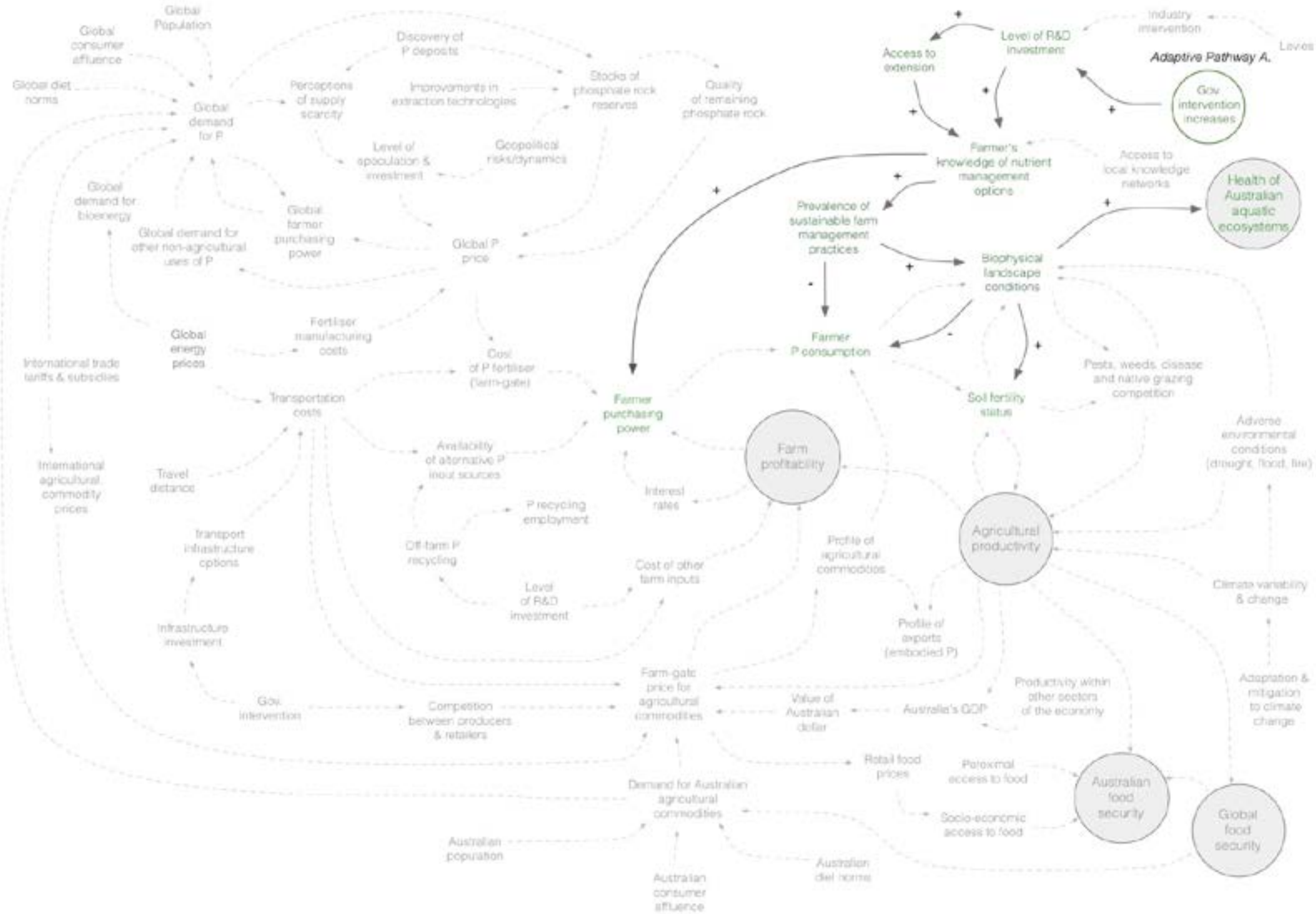

Figure 18: Example of a participant generated adaptive path, beginning with increased investment in agricultural R&D and extension targeting farm nutrient management.

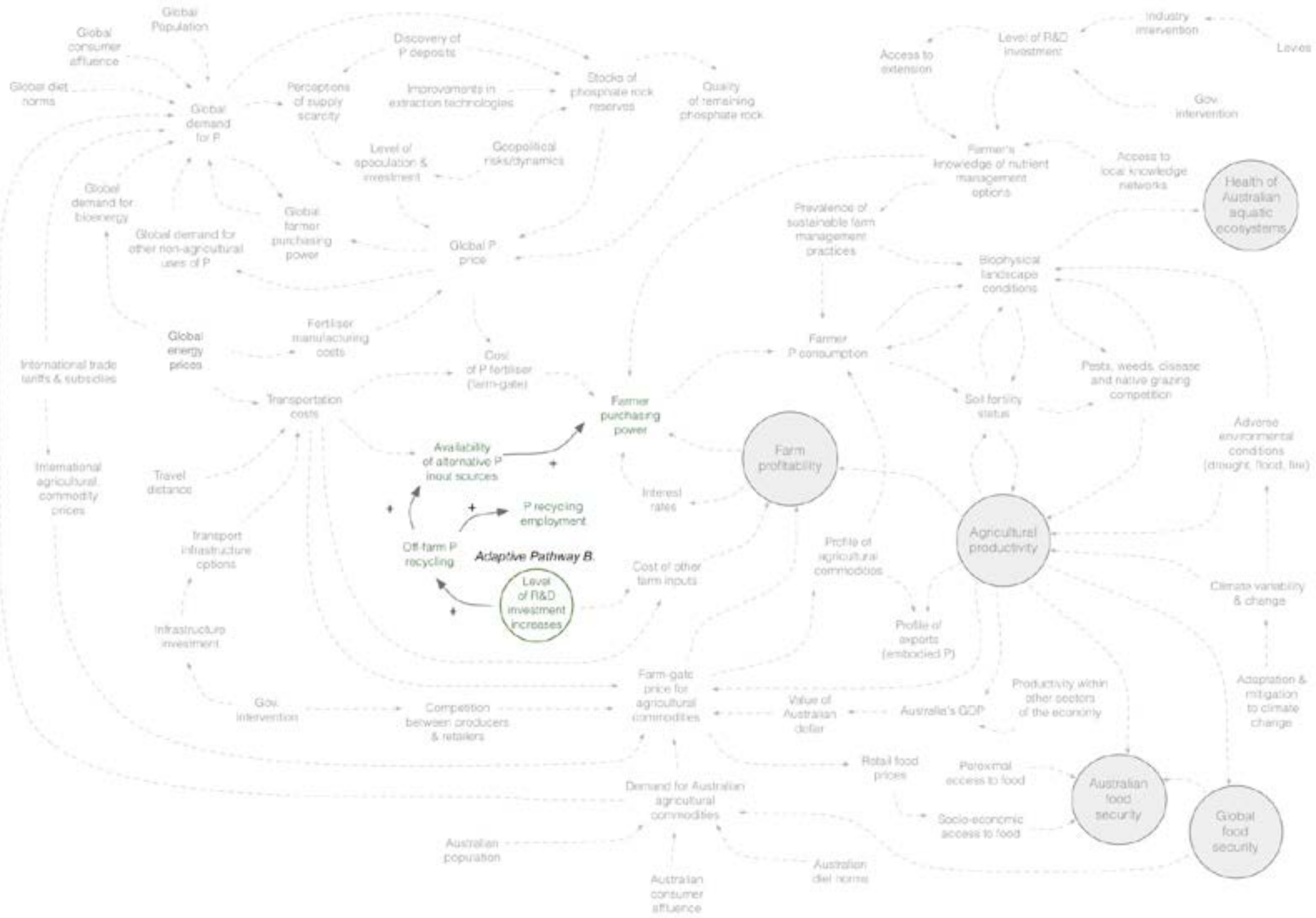

Figure 19: Example of a participant generated adaptive path, beginning with increased investment in off-farm phosphorus recycling.

Figure 19 presents a second adaptive pathway identified during the workshop. While the previous adaptive strategy focused on improving phosphorus use efficiency on farm, this second adaptive pathway focuses on providing farmers with alternative phosphorus inputs, derived from off-farm nutrient recycling. There is an inherent assumption in this strategy that providing farmers with alternative nutrient input sources may be necessary in the future, if fertiliser derived from phosphate rock becomes less affordable, or more difficult to access.

Investment in R&D was again added as a system perturbation, however in this case targeting increasing off-farm nutrient recycling (for example sewage and organic waste; mining industry waste; and animal by-products). Specifically making investments to increase the availability of recovered phosphorus within the Australian farming system, in commercial products that are applicable to small, medium and large-scale agricultural enterprises, across a range of production systems that rely on nutrient inputs.

The emergence of these two adaptive pathways aligns well with the quantitative model produced by this research project (page 9), as the model provides further guidance on the specific on-farm management practices that may yield significant efficiency gains, alongside information about which off-farm nutrient sinks could be targeted for phosphorus recovery and recycling.

Finally, figures 20 and 21 combine some of the key vulnerable and adaptive pathways within one diagram. Causal loop diagrams are more refined systems diagrams that focus in on important feedback loops and paths within the larger system. A core vulnerable feedback loop was the potentially destabilising influence of rising phosphate fertiliser prices.

As phosphorus is both exported off farm in agricultural commodities and may be leached, bound and exported to the environment over time by other means, P fertiliser inputs are currently a key stabilising variable within the Australian agricultural system. If this input source becomes unaffordable for farmers in the longer-term, a runaway feedback loop may occur: *farmer' purchasing power; phosphorus application rates; soil fertility status; agricultural productivity; and farm profitability* (see the 'R' loop in figure 20).

Figure 21 describes how the adaptive pathways identified by the participants may work to restabilise the system and build resilience to this vulnerability, if they are put in place as precautionary measures designed to give Australia a competitive advantage. The plus and minus symbols follow a slightly different logic within the more structured causal loop diagrams, as a plus indicates that the linked variables move together next in the same direction (either increasing together or decreasing together based on a perturbation) and the minus symbol indicates that the variable at the end of the arrow would likely shift in the opposite direction (for example, if the influencing variable increases, the other is likely to decrease and vice versa).

Note, although both government and industry interventions are presented here as potential drivers for innovation, the participants pointed out that industry levies might be a good way to raise investment funding for farm management related R&D and extension. However, this would require phosphorus vulnerability to be recognised by various industry bodies as a future cause for concern.

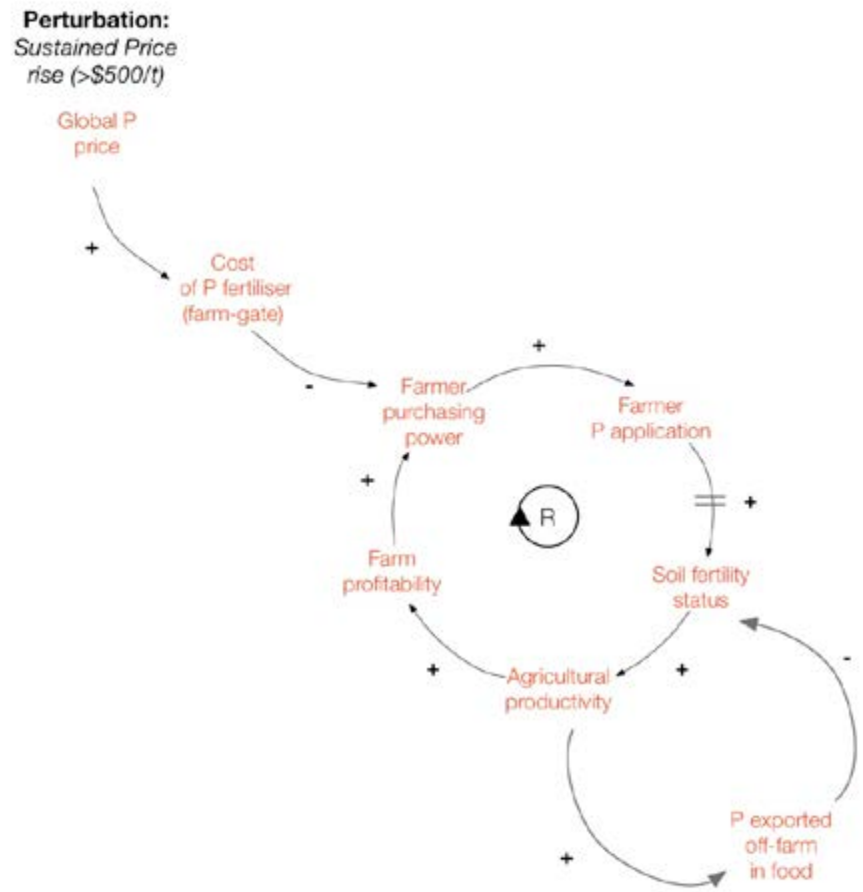

Figure 20: Causal-loop diagram of the vulnerability associated with a sustained global phosphate price increase. 'R' indicates a runaway feedback loop triggered by a reduction in farmers' capacity to purchase phosphate fertiliser. The parallel lines cutting across the arrow between Farmer P application and soil fertility status indicates a time delay, as farmers may have the capacity to rely on the nutrient soil bank in the short term, however over time soil fertility will decline if alternative adaptive strategies are not developed to improve soil fertility.

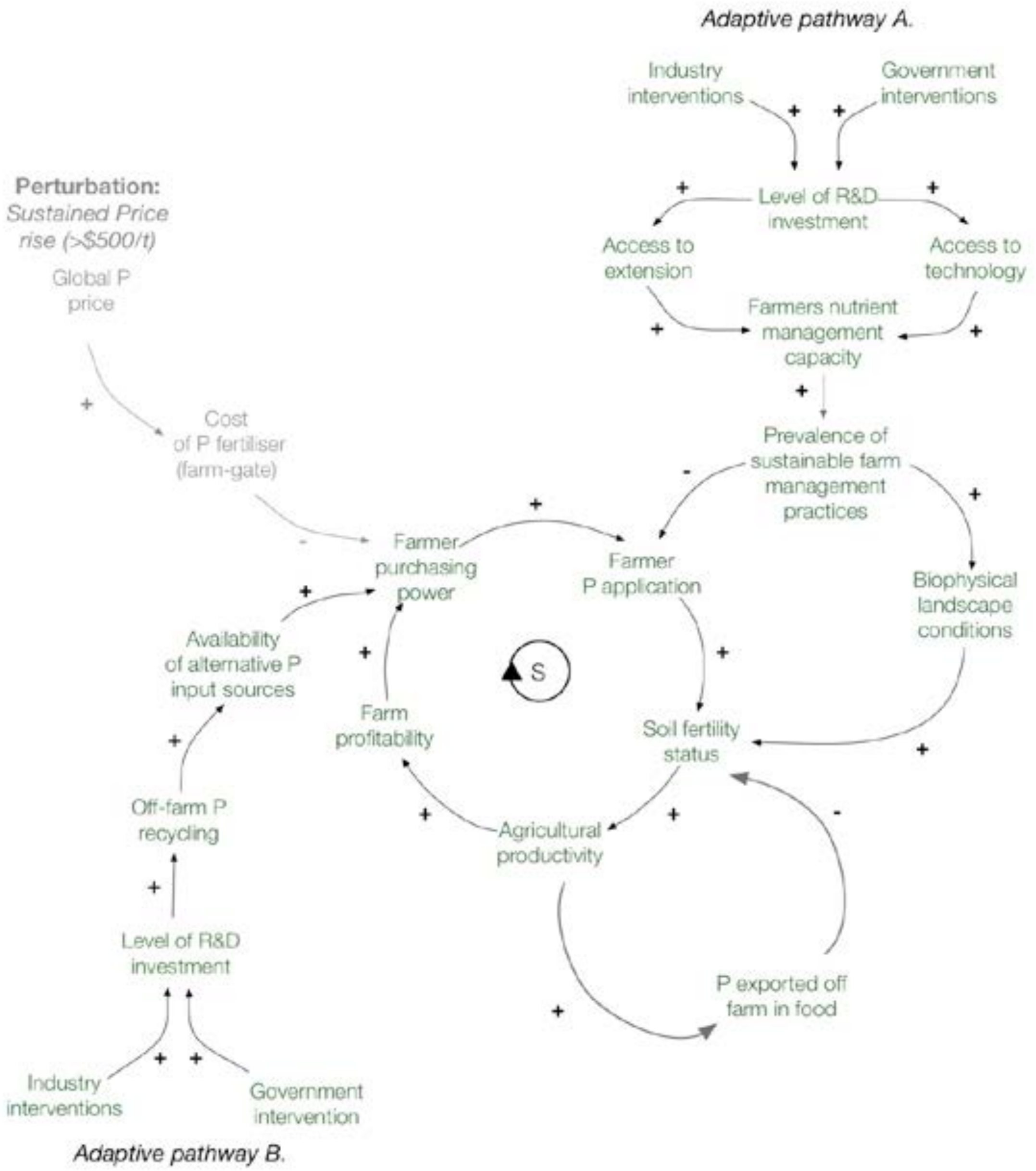

Figure 21: Causal-loop diagram showing potential adaptive pathways to buffer Australian farms against vulnerable fertiliser price increases. 'S' indicates that the core feedback loop has been re-stabilised by the combination of (Adaptive pathway A) on farm practices to improve P application efficiency and (Adaptive pathway B) the availability of alternative sources of recycled P to reduce the systems reliance on imported fertiliser.

Synthesis and Sustainable Pathways

Adaptive capacity and adaptation

Adaptation is defined as actions taken to reduce or moderate or adjust to the expected or actual negative effects of a stress, and take advantage of new opportunities. Adaptation takes place in a dynamic social, economic, technological, biophysical, and political context that varies over time, location and sector (figure 22). Much of the work of the Sustainable Phosphorus Futures project to date has been to identify and characterise the global and national context in which Australia may be vulnerable to changes in the availability and accessibility of phosphorus. The preconditions necessary to enable adaptation are generally termed the system's adaptive capacity. While there is no single conceptual framework or method for assessing adaptive capacity, four broad questions need to be answered that are generic across a range of contexts: What are the likely or current impacts driving adaptation? Who needs to adapt? What are the barriers to or opportunities arising from adaptation? What appears to enable adaptation processes?

For social systems, adaptive capacity is also considered as the component of vulnerability most amenable to influence, and therefore provides an entry point for adaptation planning. One practical conceptualisation of adaptive capacity is to define it in terms of available resources and the ability of individuals, communities or organisations to use these resources to adapt to change or reorganise following a substantial shock.

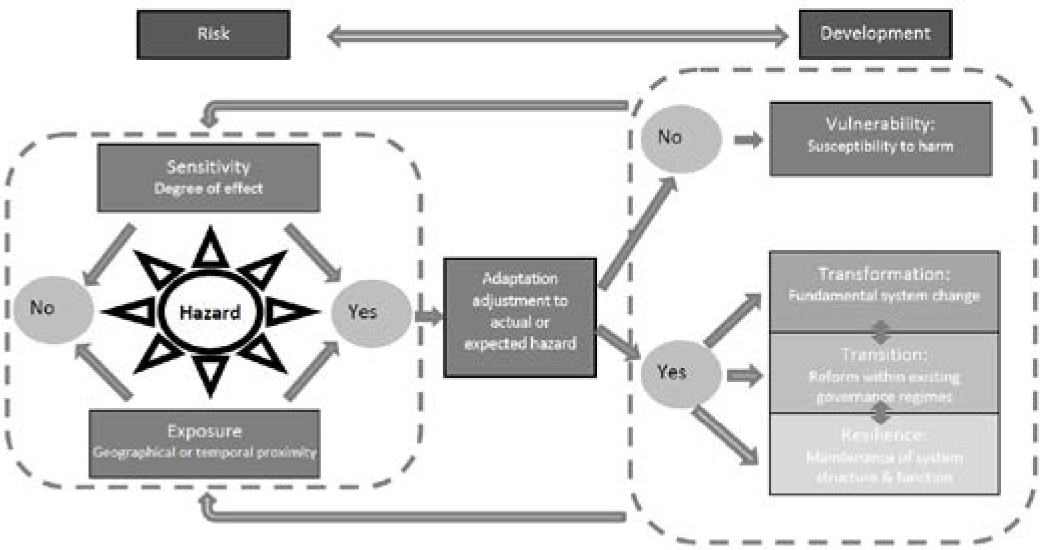

Figure 22: The conceptual relationship between the risks posed by sensitivity and exposure to a hazard, the resilience, transition or transformation pathways of adaptation, and persistent vulnerability where adaptation fails (after Pelling 2011).

Because adaptation is often influenced by the perception of a hazard, constrained by local context and distributed across many actors in social systems integrated approaches are best that focus on the needs of the decision-maker as the point where action can be taken (figure 22). Two approaches, sustainable livelihoods framework and adaptive pathways, are particularly useful in understanding the capacity to adapt to global phosphorus vulnerability. The sustainable livelihoods framework (Ellis, 2000) uses a framework of five capitals (or asset classes) to link an assessment of contextual vulnerability to the need for change among local actors, such as farmers. In the sustainable livelihoods framework people are depicted as pursuing their livelihoods by drawing upon a portfolio of livelihood assets to make a living. These assets or resources are commonly categorised as:

- **human capital**, e.g. levels of education, health and ability to labour
- **social capital**, e.g. connections to community and society
- **natural capital**, e.g. stock, flows and security of natural resources
- **physical capital**, e.g. level and type of infrastructure
- **financial capital**, e.g. wealth, personal income and debt levels.

The amount and balance of the capitals in an individual's, community's or organisation's portfolio are important. Those with larger portfolios have more livelihood options, and less vulnerability, than those with fewer assets. For example, in many regions of Australia agricultural livelihoods are critical to regional prosperity and could be adversely affected by changes to phosphorus availability and accessibility. Agricultural livelihood strategies are based on the access to and transformation of natural capital. Farmers make a living by using crops and livestock to transform natural capital (water, soil fertility, sunshine) into commodities for sale. Their sale creates income (financial capital) which can then be transformed into other types of capital: an education for their children (human capital), innovative technology and farming equipment (physical capital), and membership of clubs and social networks (social capital).

Governments play a major role in changing the ability of individuals and communities to access, combine and transform capital, through laws, policies and other governance frameworks. In the case of agricultural livelihoods, laws that regulate land clearing and surface water extraction are examples of ways governments act to modify access to resources, and thereby the livelihoods strategies of farmers, thus influencing livelihood outcomes.

Adaptive pathways approaches were developed to aid decision making for climate change under deep uncertainty (Stafford Smith, 2011). Adaptive pathways allow decisions to be grouped or 'bundled' around systems components and for the separation of short-term coping strategies within an existing system from long-term and durable transformational change to a system (Kates et al, 2012). Decisions with the potential to result in trajectories that traverse boundary conditions for system sustainability, or maladaptive pathways, can also be identified. Using adaptive pathways can assist in testing the reactions of decision-makers to changes in system drivers. The pathways chosen by an individual decision maker would be influenced by their perception of vulnerability and their adaptive capacity.

Figure 23 illustrates an example of a potential on-farm phosphorus adaptive pathway in response to increasing phosphorus prices and drought. The yellow line shows one possible pathway for introducing different options to address changes in the system drivers – not necessarily the preferred or ideal pathway. 'Incremental change' is effectively coping within the existing phosphorus system; 'transformational change' is system adaptation to long term changes in phosphate fertiliser related drivers. Imposing drought on the system either from seasonal variability or climate change will modify the adaptive pathway. Individual farmer vulnerability will also modify the adaptive response. In practice, the system might undergo a series of cycles around improving farm performance and improving phosphorus efficiency before it transformed to a modified farming system. The hypothetical pathway also would likely dip into alternative phosphorus sources depending on relative prices and availability.

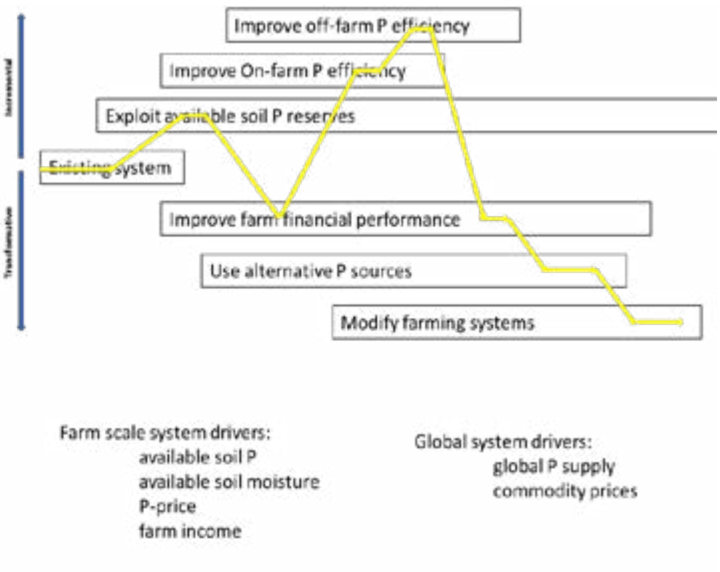

Figure 23: Example of on-farm phosphorus adaptive pathways.

National adaptive phosphorus pathways

The concept of adaptive pathways can also be applied at the national level. The national phosphorus adaptive pathways concept (the ‘P wormhole’ conceptualised in figure 24) can help navigate future phosphorus pathways without exceeding important and co-existing thresholds/boundaries. The four boundaries shown in figure 24 correspond to the sustainability goals and worldviews identified in section *Mapping vulnerability in the Australian phosphorus system,* that is, related to agricultural productivity, ecological integrity, farmer/rural livelihoods and food security. Figure 24 indicates a theoretical adaptive path between the present and future, that breaches the ecological threshold by way of example (e.g. this could be excess nutrient pollution of a water body resulting in a significant algal bloom) and thus mal-adapts before its’ path is corrected to continue inside the ‘safe operating space’ of the P wormhole.

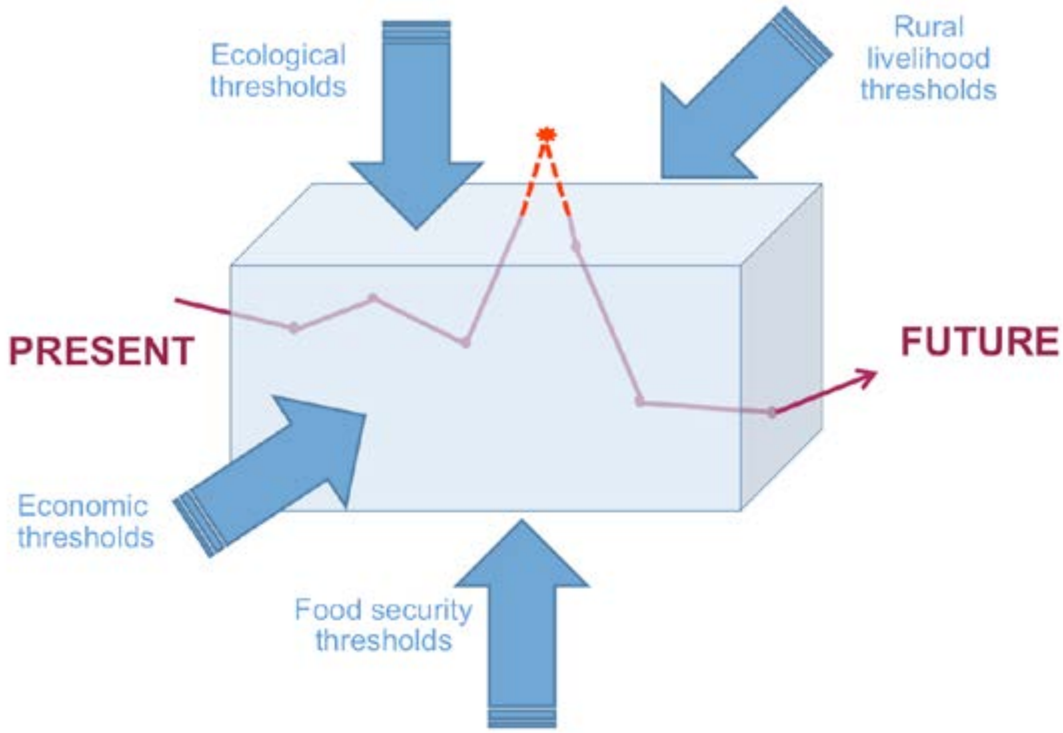

Figure 24: Conceptualising national adaptive phosphorus pathways in a 'safe operating space' bounded by 4 sustainability thresholds: economic, ecological, livelihood and food security.

The conceptual framework for exploring future national adaptive pathways was developed and road-tested during the national stakeholder workshop. The matrix in Table 3 provides an additional framework to guide analysis and hence synthesis of the trade-offs between greatest gains in phosphorus efficiency (outputs from the model) and the adaptive capacity for national system changes. The framework proved a useful cognitive tool for grappling with such trade-offs in the face of multiple competing goals. It also allowed for a preliminary identification of external barriers to adaptation (such as institutional barriers imposed by existing policies) and constraints to capacity imposed through a lack of resources under the capital framework. Action to promote adaptation would be designed to catalyse a change process if the key capacity constraints were removed.

Table 3: Matrix to facilitate the analysis of the trade-off between gains in phosphorus sustainability and the resources that can be deployed for adaptation (capacity).

Sustainable phosphorus measures (output from model)	P saved or yielded (kt/a of P)	Current national capacity to adapt (5 capitals)	Barriers & opportunities?	Implications for 4 sustainability goals/groups?	Who could/would take action?
AD1.4—Soil testing					
LD1.7—phytase enrichment					
AD2.1—plant selection (P-efficient crop selection/breeding)					
FS1.1—phosphogypsum (recovery)					
PD2.1—reduce P-intensive diets					
WS1.6—struvite					
PS1.1—food waste (supply-chain)					

The below provides specific worked examples based on the stakeholder workshop of the trade-offs between phosphorus sustainabiltiy gains (kt/a of P saved or yielded), current national capacity to adapt and barriers and opportunities.

AD1.4 - Soil testing:

Increasing the prevalence of soil testing in Australia was perceived to be a farm management practice with the potential to significantly improve phosphorus use efficiency by enabling farmers fertiliser application rates to better match soil needs - if farmers' capacity to test can be increased. The participants' perception of the significant potential efficiency gains align with recent findings of Wong *et al.* (2012)[4]. Wong et al. suggest widespread over application of phosphorus in Australia, which was also echoed by the workshop participants. Wong et al. go on to explain that only one third of the properties sampled conducted soil testing, and although some producers may have tested in other years, there appears to be significant efficiency gains to be made from improving soil testing rates and then translating knowledge of this into better application rates (as opposed to applying fixed amounts of fertiliser across properties without a detailed understanding of soil fertility status). Participants provided a detailed example describing dairy farms where phosphorus is applied across properties, even though the manure distribution patterns on dairy farms (associated with regular milking paths) results in some areas being consistently over fertilised. Identified barriers to soil testing adaptation are the cost of soil testing and the need to incentivise the practice. Greater R&D could reduce the cost of testing, for example as has been the case with water monitoring technology, which has become more cost effective over the last 20 years (although long-term dry conditions were a significant driver for improvements in water monitoring technology). A further identified barrier is the gap between soil testing and farmers actually taking the step of changing application rates according to results. The latter is hard for farmers to change as there are upfront financial costs and need for R&D investment.

[4] Wong et al (2012) explain that: "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."

AD2.1 Plant selection:

Lupins are a clear example of the potential efficiency gains to be had from implementing the plant selection measure. The human and technical capacity is relatively high – that is, there are already cultivars in Australia that require less phosphorus to produce and famers know how to grow these, which could result in phosphorus efficiency gains if substituted for other Australian crops. However in terms of the barriers to change, knowledge surrounding crop production is not a constraint, nor are Australia's environmental conditions (lupins grown essentially anywhere), rather the barriers may predominantly relate to social capital, as when inputs are available to grow the other crops that consumers prefer to eat, then those varieties will be cultivated in greater abundance, as there is a higher profit margin associated with their production due to the greater demand. As an adaptive strategy to bypass these social constraints, crops which require less phosphorus to produce, such as lupins, could possibly be substituted with other cultivars grown to produce animal feed, providing that the newly substituted crops were deemed to provide an adequate nutrient substitution. If the price of fertiliser dictated that more efficient varieties were necessary to feed the Australian population, shifting to these varieties might not be difficult for Australian farmers, providing that consumer demand was no longer a constraint under this scenario.

FS1.1 – Phosphoygypsum recovery:

The potential efficiency gains (i.e kt/a of P) from the measure of recovering phosphorus from phosphogysum stockpiles are very high. Each year, approximately 20 kt of P is added to Australia's phosphogysum stockpile – an amount almost double that of the phosphorus contained in food consumed by the entire Australian population. However the current capacity to adapt is low and several barriers were identified. First, the logistical capacity to transport the bulky and low-grade phosphogypsum from the source – at the remote Phosphate Hill near Mt Isa in Australia's north, to where it is needed by farmers, is low. While the phosphorus content could potentially be extracted from the stockpile onsite, making transport far more economically feasible, the current technical capacity for such extraction is near non-existent. Social and institutional capacity for phosphogypsum recovery is also low, due to the perceived or real health risks associated with the radioactivity of phosphogysum and hence around its potential reuse. The waste is generated during the fertiliser production process, to remove the radionuclides of uranium and thorium present in phosphate rock. There is still a debate internationally regarding the acceptable level of risk associated with these stockpiles (IPGWG, 2010; Wissa, 2003). If the health risks were to be managed, an identified opportunity regarding phosphogypsum recovery is the potential to co-produce, that is, seek other benefits from reusing phosphogypsum, e.g. for its calcium or gypsum qualities.

PD2.1 – Reduce phosphorus-intensive diets:

In general, meat and dairy-based diets can demand 2-3 times more phosphorus fertiliser than a vegetarian-based diet (Cordell et al 2009b). However the efficiency gains associated with reducing phosphorus-intesive diets of Australian consumers may be potentially low-to-medium, given most of Australia's food and agricultural commodities are destined for overseas markets. Conversely this means that the potential efficiency gains associated with changing diets in countries importing Australian food is higher. Despite the medium-high potential efficiency gains, the social capital of consumers awareness and willingness to shift diets due to environmental/sustainability reasons such as climate change is currently relatively low (especially related to phosphorus). Besides communication programs such as Meat Free Monday, the institutional capacity to influence diets towards more sustainable food is also relatively low. While there may be an opportunity to consume fish as more phosphorus-efficient alternative to meat, the implications for the environment are potentially large. Wild fish stocks are in decline globally, and intensive aquaculture has significant associated environmental costs, such as the inputs of hormones, antibiotics, nutrients, feed and potential risks of pollution from such intensive fish farms and risk of contaiminating the wild fish gene pool. Exploration of this measure demonstated the need to navigate the P wormhole in the 'safe space' without mal-adapting and breaching a threshold (ecological threshold in the case of intensive fish farming).

WS1.6 – Struvite recovery (or biosolids) from wastewater treatment:

The maximum efficiency gains associated with recovering phosphorus from excreta (regardless of the technical process) are relatively small (in the order of 10 kt/a of P compared to Australia's phosphorus demand in the order of 450 kt/a of P), because most phosphorus in food is consumed – and hence excreted – overseas. The technical capacity for phosphorus recovery from wastewater treatment plants exists (e.g. currently around 50% of generated biosolids are today applied to agricultural fields). There are over 30 processes for the recovery of phosphorus from wastewater streams that are being developed or already commercialised (particularly in Europe and North America) ranging from struvite recovery[5] to ash incineration (Sartorius et al. 2011). However the viability of a specific technology depends on the current wastewater treatment process, which varies across the country. Nearly 90% of the Australian population live in coastal urban areas, creating an opportunity as cities are 'phosphorus hotspots' in human excreta that can theoretically be recovered. However the economic capacity to capture and reuse phosphorus is currently limited in this country, partly because capital costs tend to be very high (e.g. Sydney's Malabar WWTP would require approximately $2 billion to upgrade for phosphorus recycling). Further, local fertiliser market opportunities are crucial to sell and/or transport the recovered phosphorus to. Given phosphorus recovery from wastewater will be an important measure for the future, an identified opportunity to stimulate such recovery is to focus on avoided costs. The Malabar example shows there are few financial gains to be made by investing in an upgrade, as the effluent is currently discharged through deep ocean outfalls. However for some inland wastewater treatment plants, where there is a real or environmental cost associated with effluent discharges into rivers, recovering phosphorus for reuse could prove more cost-effective. This indicates an opportunity for phosphorus recovery to be driven by other incentives and levers in the system.

PS1.1 – food/organic waste recycling:

Similar to wastewater, phosphorus recovery from food waste is likely to be relatively small in Australia in terms of kt/a of P, compared to efficiency gains 'upstream' in the livestock and agriculture sectors. However an important trade-off was identified here. The social capital required for food waste recycling could be large, owing to the direct human connection: everyone eats, and everyone wastes food (the same could be said for excreta – everyone eats and excretes, which may be a reason why the idea of urine diversion has captured people's imagination and hence helped to raise awareness of the phosphorus sustainability issue). That is, people may be more receptive to measures that directly relate to them, providing citizens and consumers with a social imperative or clear 'so what?'. Institutional and political capacity is however currently lacking to implement such measures. However the social capital may provide politicians with 'permission' to make decisions regarding food waste recovery. Opportunities to trigger organic/food recycling could include increasing landfilling costs. This could be an incentive for improved reuse of not just food and organic waste, but biosolids or other forms of recovered phosphorus. If less than the cost of landfilling, waste managers could deliver recovered phosphorus to farmers free of charge. This would also be a positive for local labour community, hence a potential win-win-win. This also highlighted the idea that if the waste problem is continually given to waste managers, the solutions are more likely to be around 'waste', where as if the waste problem is given to business managers to resolve, the latter are more likely to come up with resource solutions and business incentives.

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[5] Struvite is magnesium ammonium phosphate. Struvite can readily form in advanced wastewater treatment processes permanently clogging pipes if not removed. The reaction is magnesium-limited and can be exploited to produce an efficient slow release fertiliser (Uysala et al., 2010).

Implications for stakeholders

Phase 2 of this project both identified high-level paths of phosphorus vulnerability in the Australia food system, and, potential sustainable measures and strategies by which Australia could adapt in win-win scenarios for productivity, the environment and rural livelihoods.

Research implications

The study found that the future trajectory of phosphorus use in this country is highly uncertain, in terms of business-as-usual, possible scenarios, and a shared preferred future scenario. This uncertainty is due to lack of existing research and policy debate, lack of baseline data, and a lack of consensus on what a shared trajectory would look like taking into account multiple and potentially competing goals.

Despite the importance of phosphorus to Australia's economy, rural livelihoods, environmental integrity and food security both in Australia and abroad, there is a serious lack of knowledge and data on key attributes of the current system. For example, there is a lack of sufficient quality data on important model assumptions regarding complete and transparent data sets on Australia's phosphate reserves and production; and the breakdown of phosphorus use in this country for pastures vs cropping vs supplements in the food sector, and industrial uses of phosphorus.

The lack of consensus and existing policy/research debate on preferred phosphorus future scenarios was addressed through the development and collaborative exploration of 'What If' scenarios with stakeholders in the national phosphorus workshop. The process used in the workshop to elicit implications of potential future perturbations and prioritise sustainable strategies and pathways was novel and has great potential for future workshops. It enabled the collective deliberation of promising sustainable strategies, whilst acknowledging the presence of competing/co-existing goals – agricultural productivity, rural/farmer livelihoods, food security and ecological integrity.

The uncertainty was further managed by designing the sustainable future measures model with a high-level of user-interactivity. The interactive model is an excellent platform from which a more comprehensive and user-friendly interface scenario model can be developed (as a new project), including costing of sustainable measures. Such an interactive model can be used to: a) directly engage key stakeholders in real-time with the implications of different scenarios (such as investment in soil testing versus renewable phosphate fertilisers, b) improve the quality of the quantitative analysis of long-term sustainable options (to more accurately reflect the phosphorus savings/yields and costs); c) support decision-making for the agricultural/farming industry, government and non-government groups. This is further elaborated on in the Recommendations section.

Policy implications

The research findings and stakeholder workshop highlighted the need to consider phosphorus in the broader context of the food system and other resources. Firstly, that non-phosphorus related incentives and avoided costs might be more strategic levers to trigger many of the sustainable phosphorus initiatives (such as avoided landfill levies or pollution costs as highlighted in the WS1.6 struvite and PS1.1 food/organic waste examples). Secondly, much can be learnt from effective strategies in water, carbon and climate change in relation to navigating a sustainable future trajectory. Thirdly, there are numerous potential phosphorus synergies in terms of mitigation/adaptation strategies for other resources such as carbon that need to be identified to ensure win-wins and avoid mal-adaption. For example, ensuring soil carbon strategies leave phosphorus in a plant-available form, or that the development of bioenergy doesn't increase phosphate fertiliser demand for biofuel crops or permanently remove phosphorus from the field in agricultural wastes.

The research and stakeholder workshop also highlighted how the concept of adaptive capacity can guide adaptation pathways at the national level, in addition to its more typical application at the local level. The national adaptive pathways concept introduced in this research demonstrated a need to navigate future phosphorus pathways without exceeding important and co-existing thresholds/boundaries (related to food security, livelihoods, ecosystem integrity and the economy).

Finally, the research found that while there are sustainable initiatives already underway within specific sectors (that have a direct or indirect positive influence on phosphorus management), there is a strong need to integrate across sectors to assess trade-offs, identify synergies, prioritise strategies and ensure that co-existing boundaries are not exceeded. In turn, there is a strong need for participation from all sectors and perspectives to co-define and co-navigate this future space. Ongoing and expanded stakeholder/sector inclusion in the research will be crucial (e.g. representing key sub-sectors with agriculture and livestock, such as dairy industry, grains, horticulture).

Recommendations

If adopted, this research will guide prioritisation and investment in both R&D and implementation of appropriate sustainable phosphorus measures and strategies for Australia to increase the resilience of the food system in the long-term.

Recommended improvements to the current research study include:

- Coordinate research around improved data across all key sectors (prioritising the 'red' list identified as poor quality and important/significant parameter)
- Develop an interactive visualised interface for the Model and make this available as a user-friendly web-based application (similar to v2.0 http://phosphorusfutures.net/australian-sustainable-phosphorus-futures/35-interactive-future-phosphorus-scenarios)
- Apply/use the interactive visualised model in future stakeholder workshop settings to further test/validate the model, seek stakeholder assumptions and increase stakeholder engagement and learning in the area of integrated sustainable phosphorus measures.

Recommended future research and policy priorities as part of the 3 year Sustainable Phosphorus Futures project include:

9. **Costed policy options:** a framework for systematically assessing and comparing selected sustainable phosphorus measures as a means to determine the least-cost sustainable phosphorus options ($/kt P saved or yielded) for Australia, as described in section *Framework for developing costed phosphorus policy options*;

10. **Adaptive phosphorus pathways**:
    - further explore national phosphorus vulnerability and adaptive pathways, to investigates how Australia can govern phosphorus to ensure long-term food security, farmer livelihoods, soil fertility and environmental protection (building on the process developed in Phase 2, e.g. figure 24 and table 3). That is, to identify vulnerable regions and sectors within the Australian food system to the threat of phosphorus scarcity, assess in what ways they are vulnerable, co-define sustainable adaptive pathways (including indicators of boundary thresholds), and prioritise polices and approaches to build national adaptive capacity; and
    - explore on-farm (bottom-up) phosphorus vulnerability and adaptive pathways through participatory means focusing on identified priority areas, such as soil testing and fertiliser application rate/time/placement ("4Rs"); explore farmer preferences, needs, vulnerability to phosphorus scarcity in specific regions and implications for sustainable phosphorus options

11. **Geospatial analysis of phosphorus hotspots:** Geospatial model indicating dynamic relationship between phosphorus 'hotspots' across Australia (phosphorus sources, demand and 'sinks'), and the energetic and economic feasibility of transporting fossil versus recycled phosphorus;

12. **Phosphorus-carbon inter-linkages:** Assess the inter-linkages between phosphorus and carbon, in terms of physical and institutional flows (that is, around the intersections of their physical flows through the food system (e.g. in food waste, algae, soil) and synergistic and adverse impacts of management responses (such as soil carbon sequestration, bioenergy, influencing diets);

13. **Implications of low phosphorus-intensive diets:** Examine the dietary trends of Australians and overseas consumers of Australian food and agricultural commodities and implications for Australian phosphorus and food system. Analysis of the 'P footprints' of key Australian animal

and crop-based food products (i.e. phosphate rock mined to produce a kg of grazed beef, sheep, eggs, milk, wheat, vegetables etc);

14. **Expanded sub-sector stakeholder engagement:** Engage more stakeholders in sub-sectors (e.g. within the livestock sector include stakeholders from dairy, feedlot, grazed livestock; within agricultural sector include grains, horticulture, organic sectors; within food sector include food processors, retailers, organic/food waste stakeholders; and so on). Within sectors, address how barriers to efficiency gains could be overcome and opportunities for improved technology e.g. exploring more cost-effective soil-testing (through R&D) and improved technology to both reduce costs and increase uptake of soil testing;

15. **Participatory development of future scenarios:** Continue to engage stakeholder via participatory development of future scenarios (e.g. collaborative input of user assumptions in model); and

16. **Policy forum:** Further, a policy forum is recommended to raise the profile and understanding of the issue among policy-makers and support the development of policies and initiatives to improve phosphorus use. Such a forum could be supported by costed policy options from Recommendation 1 above, and/or the use of the national and local adaptive phosphorus pathways with multiple-thresholds concept.

Appendices

A1: Australian Sustainable Phosphorus Measures Model

A2: Descriptions of measures in model

A3: Data assumptions and sources for Sustainable Phosphorus Measures model

A4: National stakeholder workshop – agenda and participants

A1: Sustainable Phosphorus Measures Model

Excel model available from RIRDC upon request.

A2: Descriptions of measures in model

Category	Measure	Description
Production		
Mining	Growth in conventional phosphate rock mining	The current growth rate in phosphate rock production in Australia (excluding Christmas Island)
Intelligent Mining	fraction of waste stockpiles mined	Percentage of the waste stockpiles created that are being mined (so if 100 tonnes of waste stockpiles exists in year x and correspondingly 1 tonne is mined the value should be 1%)
Intelligent Mining	Phosphogypsum - fraction chemical extracted	Percentage of the phosphogypsum stockpiles created that are being mined (so if 100 tonnes of phosphogypsum stockpile exists in year x and correspondingly 1 tonne is mined for chemical conversion the value should be 1%). Chemical extracted means extracting a safe phosphorus compound out of the phosphogypsum and applying that to the land as opposed to using the phosphogypsum directly on the soil
Intelligent Mining	Basic slag - fraction chemically extracted	Percentage of the slag stockpiles created that are being mined (so if 100 tonnes of slag dumps exists in year x and correspondingly 1 tonne is mined (and chemically altered to extract out phosphorus) the value should be 1%.
Direct Mining	Phosphogypsum - fraction direct application	Similar to the chemical extraction only here it is being placed on the soil directly without some treatment process
Direct Mining	Basic slag -fraction direct application	Similar to the chemical extraction only it is being placed on the soil directly without a treatment process
Renewable Harvesting	Algae	Amount of phosphorus that is being harvested from algae, hypothetically in terms of inland waterways remediation - remove the algae from the waterway and put it on the land as a fertiliser
Renewable Harvesting	Seaweed	Similar concept to algae harvesting, except more likely harvesting seaweed from the coastal fringe (so the seaweed that is exposed at low tide is some areas)
Mining Efficiencies		
Intelligent Mining	% phosphate rock mining losses	% phosphate rock mining losses, so 10% would mean for every 100 tonnes of phosphate rock that is sold, 10 tonnes of phosphate rock wastes are generated
Intelligent Manufacturing	% phosphate fertiliser production/processing losses	% phosphate fertiliser production losses, including phosphogypsum, spillages, etc
Demand Efficiency		
Cropping; Horticulture; Irrigated cropping.	Erosion reduction	Erosion reduction reduces the amount of erosion per square meter. So say 100 g/m2 of soil is lost in 2010, and in 2040 erosion reduction percentage is 10% then 90g/m2 of soil is lost in 2040
Grazing modified pasture; Irrigated modified pasture; Remote cattle stations.	Erosion reduction	Erosion reduction reduces the amount of erosion per square meter. So say 100 g/m2 of soil is lost in 2010, and in 2040 erosion reduction percentage is 10% then 90g/m2 of soil is lost in 2040

Category	Measure	Description
Cropping; Horticulture; Irrigated cropping.	Improved soil characteristics	Increases the percentage of available P in soil by that percentage. So assume 1% of P is available in the soil (without this measure) and the measure is set to 10% in 2040 then percentage of P available in the soil is 1.1%
Grazing modified pasture; Irrigated modified pasture; Remote cattle stations.	Improved soil characteristics	Increases the percentage of available P in soil by that percentage. So assume 1% of P is available in the soil (without this measure) and the measure is set to 10% in 2040 then percentage of P available in the soil is 1.1%
Cropping; Horticulture; Irrigated cropping.	Plant selection - increasing maximal yield	This increases the theoretical max yield of the plants (i.e. selecting plants that are better at converting available soil P to P in the plant). The actual yield changes based on the available P in the soil
Grazing modified pasture; Irrigated modified pasture; Remote cattle stations.	Plant selection - increasing maximal yield	This increases the theoretical max yield of the plants (i.e. selecting plants that are better at converting available soil P to P in the plant). The actual yield changes based on the available P in the soil
Cropping; Horticulture; Irrigated cropping.	Better fertiliser application practices (rate, timing, placement, soil testing)	This measure and microbial inoculants below add together, so if this value is 5% and microbial inoculants is 15% total effect is 20%. This 20% then increases the plant yield by 20% (so what was a yield of 1 tonne is now a yield of 1.2 tonnes)
Grazing modified pasture; Irrigated modified pasture; Remote cattle stations.	Better fertiliser application practices (rate, timing, placement, soil testing)	This measure and microbial inoculants below add together, so if this value is 5% and microbial inoculants is 15% total effect is 20%. This 20% then increases the plant yield by 20% (so what was a yield of 1 tonne is now a yield of 1.2 tonnes)
Cropping; Horticulture; Irrigated cropping.	Improved soil - microbial inoculants	see comment above interacts with better application practices
Grazing modified pasture; Irrigated modified pasture; Remote cattle stations.	Improved soil - microbial inoculants	see comment above interacts with better application practices
Cropping; Horticulture; Irrigated cropping.	Plant selection - increasing P fraction in food	This is the percentage of P that is in the edible part of the plant. So say the plant yield is 100t and the percentage is 80% then 80t of P is in the crop that is converted to food/feed to feedlot animals etc and 20t is lost to crop wastes.
Grazing modified pasture; Irrigated modified pasture; Remote cattle stations.	Animal selection - less fussy eater	This is the percentage of P in the crop yield that the animal actually then eats. So the assumption here is that there is no crop wastes (what the animal doesn't eat is directly/naturally recycled into the soil). Note feedlot animals are assumed to eat everything that they are provided with
Grazing modified pasture; Irrigated modified pasture; Remote cattle stations.	Animal Selection - better P uptake	Animal eats say 100 t of P in grass/hay, of that 100t, from the bio availability of Grass percentage (say 80%) 80t of P is available to the animal then this measure is say X% of the 80t of P that was capable of being absorbed actually made it into the animal

Category	Measure	Description
Feedlots	Animal Selection - better P uptake	Animal eats say 100 t of P in grass/hay, that of that 100t, from the bio availability of Grass percentage (say 80%) 80t of P is available to the Animal then this measure is say X% of the 80t of P that was capable of being absorbed actually made it into the animal
Feedlots	Phytase supplements in non ruminant animals	The percentage of P in the animals feed that is reduced through the use of phytase supplements
Grazing modified pasture; Irrigated modified pasture; Remote cattle stations.	Animal Selection - more P in meat fraction	The percentage of phosphorus in the meat portion of the animal versus the rest of the animal (blood, bone, carcass)
Feedlots	Animal Selection - more P in meat fraction	The percentage of phosphorus in the meat portion of the animal versus the rest of the animal (blood, bone, carcass)
Grazing modified pasture; Irrigated modified pasture; Remote cattle stations.	Animal Selection - Bio-availability of Grass/Hay (all animals)	The % of P in the fodder that is bioavailable to the animal
feedlots	Animal Selection - Bio-availability of Grain (ruminants)	The % of P in the fodder that is bioavailable to the animal
feedlots	Animal Selection - Bio-availability of Grain (non-ruminants, no phytase)	The % of P in the grain that is bioavailable to the animal
feedlots	Animal Selection - Bio-availability of bone (non-ruminants)	The % of P in the bonemeal that is bioavailable to the animal
feedlots	Animal Selection - Bio-availability of blood (non-ruminants)	The % of P in the bloodmeal that is bioavailable to the animal
feedlots	Animal Selection - Bio-availability of supplements (non-ruminants)	The % of P in the supplements that is bioavailable to the animal
Manufacturing Efficiency		
Food Manufacturing	Food losses associated with supply chain	Food losses associated with supply chain (i.e. pre-consumer), as % of wasted relative to consumed
Food Manufacturing	Food losses associated with distances in supply chain	Food losses associated with distances in supply chain (e.g. spoilage in transport)
Food Manufacturing	Food losses associated with consumers	Food losses associated with consumers (post-retail)
Food Manufacturing	P in food additives	P in food additives (e.g. in fizzy drinks)
Other Manufacturing	P in detergents	P in detergents
Other Manufacturing	P in matches	P in matches
Other Manufacturing	P in lithium ion batteries	P in lithium ion batteries
Lifestyle Efficiency		

Category	Measure	Description
Dietary Change	Per capita change in meat consumption relative to 2010	Per capita change in meat consumption relative to 2010
Lifestyle Change	% P consumed in food relative to 2010	% P consumed in food relative to 2010
Lifestyle Change	% P absorbed in food relative to 2010	% P absorbed in food relative to 2010
Recycling Efficiency		
Wastewater process	P permanently lost from wastewater due to sewer exfiltration from cracked/leaky pipes etc	P permanently lost from wastewater due to sewer exfiltration from cracked/leaky pipes etc
Wastewater process	P permanently lost from wastewater due to sewer overflows	P permanently lost from wastewater due to sewer overflows
Wastewater process	% P in wastewater that ends up in biosolids vs effluent	% P in wastewater that ends up in biosolids vs effluent
Recycling		
Grazing modified pasture	% P in manure generated that is productively reintegrated into pasture soils	% P in manure generated in grazing modified pasture systems that is productively reintegrated into pasture soils
Irrigated modified pasture	% P in manure generated that is productively reintegrated into pasture soils	% P in manure generated in irrigated modified pasture systems that is productively reintegrated into pasture soils
Remote cattle stations	% P in manure generated that is productively reintegrated into pasture soils	% P in manure generated in remote cattle stations that is productively reintegrated into pasture soils
Feedlot	% of manure generated in feedlots that is recycled as fertiliser for crop growth in Australia	% of manure generated in feedlots that is recycled as fertiliser for crop growth in Australia
Livestock	% of bones generated that are recycled as fertiliser	% of bones generated that are recycled as fertiliser (e.g. in Blood & Bone) in Australia
Livestock	% of blood generated that is recycled as fertiliser in Australia	% of blood generated that is recycled as fertiliser in Australia
Livestock	% of bones generated that are recycled as feed in Australia	% of bones generated that are recycled as feed in Australia
Livestock	% of blood generated that is recycled as feed in Australia	% of blood generated that is recycled as feed in Australia
Livestock	% of P in carcass (excluding edible, blood and bone fractions) that is recycled as fertiliser	% of P in carcass (excluding edible, blood and bone fractions) that is recycled as fertiliser
Agriculture	% of crop waste reused	% of crop waste reused (either direct onsite or offsite processing)

Category	Measure	Description
Livestock	% P in a fish that is inedible and recycled as fertiliser/fishmeal etc	% P in a fish that is inedible and recycled as fertiliser/fishmeal etc (rather than eaten or disposed of)
Food	of P in pre-consumer waste generated, % P recycled	of P in pre-consumer waste generated, % P recycled
Food	of P in consumer waste generated, % P recycled	of P in consumer waste generated, % P recycled
Wastewater process	% of P in urine that is recycled directly as fertiliser in crop growth	% of P in urine that is recycled directly as fertiliser in crop growth
Wastewater process	% of P in faeces that is recycled directly (e.g. via composting) as fertiliser in crop growth	% of P in faeces that is recycled directly (e.g. via composting) as fertiliser in crop growth
Wastewater process	% of P in treated effluent that is recycled as fertiliser in crop growth	% of P in treated effluent that is recycled as fertiliser in crop growth (by any means - direct application, struvite etc)
Wastewater process	% of P in biosolids recycled as fertiliser in crop growth	% of P in biosolids recycled as fertiliser in crop growth
Mineral processes	% of P in Li-ion batteries recovered and recycled in new batteries	% of P in Li-ion batteries recovered and recycled in new batteries

A3: Data assumptions

Variable	Value in 2010		Reference/Comment
Recoverable Resources of phosphate rock	64.4	Mt P	492.1 Mt of phosphate rock Accessible EDR assumed 30% P2O5 content. GA (2012)
Production of phosphate rock	261	kt P/y	USGS (2013)
Size of tailing dumps	39	kt P	assuming international figures 15% mining waste, 261 kt of P in phosphate rock mined in Australia (Mohr and Evans 2013)
Size of basic slag stockpile	17.8	Mt P	ASA (2012) amount put into storage from 2008 to 2011 and P content is ~1% Kaul (2013),
Phosphogypsum stockpile	8.8	Mt P	Walter (2012), Kwonpongsagoon et al 2007
Basic slag generated	28.6	kt P/y	Australasian slag association market survey (2011) and P content is ~1% (Personal Communication with Harold Kaul from BlueScope Steel)
Population in Australia	22.2	Million People	UN (2013)
P in livestock products consumed by the Australian population	0.22	kg P/person.yr	ISF 2010 (CSIRO report)
P in crops consumed by the Australian population	0.19	kg P/person.yr	ISF 2010 (CSIRO report)
P in fish consumed by the Australian population	0.14	kg P/person.yr	ISF 2010 (CSIRO report)
Wild fish produced in Australia	0.57	kt P/y	ABARES (2012) with a P content of 0.2 g/85 grams estimated from Davita (2013)
Land for to (C)	222	(000) km^2	Australian Agriculture Assessment 2001
Land for to (H)	3.5	(000) km^2	Australian Agriculture Assessment 2001
Land for to (IC)	9.5	(000) km^2	Australian Agriculture Assessment 2001
Land for to (GMP)	185	(000) km^2	Australian Agriculture Assessment 2001
Land for to (IMP)	10.8	(000) km^2	Australian Agriculture Assessment 2001
Land for to (RCS)	3520	(000) km^2	ABS and DAFF
P conc. in soils (C)	251	ppm (mass)	Australian Agriculture Assessment 2001
P conc. in soils (H)	284	ppm (mass)	Australian Agriculture Assessment 2001
P conc. in soils (IC)	292	ppm (mass)	Australian Agriculture Assessment 2001
P conc. in soils (GMP)	263	ppm (mass)	Australian Agriculture Assessment 2001
P conc. in soils (IMP)	230	ppm (mass)	Australian Agriculture Assessment 2001
P conc. in soils (RCS)	150	ppm (mass)	Estimate
Depth of soils (C)	1.08	m	Australian Agriculture Assessment 2001
Depth of soils (H)	1.06	m	Australian Agriculture Assessment 2001
Depth of soils (IC)	1.22	m	Australian Agriculture Assessment 2001
Depth of soils (GMP)	0.96	m	Australian Agriculture Assessment 2001
Depth of soils (IMP)	1.16	m	Australian Agriculture Assessment 2001
Depth of soils (RCS)	0.25	m	Estimate
P erosion in soils (C)	249	t soil/km^2	Australian Agriculture Assessment 2001
P erosion in soils (H)	249	t soil/km^2	Australian Agriculture Assessment 2001
P erosion in soils (IC)	85	t soil/km^2	Australian Agriculture Assessment 2001

Variable	Value in 2010		Reference/Comment
P erosion in soils (GMP)	24	t soil/km^2	Australian Agriculture Assessment 2001
P erosion in soils (IMP)	24	t soil/km^2	Australian Agriculture Assessment 2001
P erosion in soils (RCS)	450	t soil/km^2	Australian Agriculture Assessment 2002
Density of soils (C)	1.35	t/m^3	Australian Agriculture Assessment 2001
Density of soils (H)	1.35	t/m^3	Australian Agriculture Assessment 2001
Density of soils (IC)	1.34	t/m^3	Australian Agriculture Assessment 2001
Density of soils (GMP)	1.35	t/m^3	Australian Agriculture Assessment 2001
Density of soils (IMP)	1.35	t/m^3	Australian Agriculture Assessment 2001
Density of soils (RCS)	1.36	t/m^3	Australian Agriculture Assessment 2001
P supplements given to non ruminant animals (F)	25	kt P/y	ISF 2012

C = Cropping, H = Horticulture, IC = Irrigated cropping, GMP = Grazing modified Pasture, IMP = Irrigated modified pastures, RCS = Remote cattle stations, F = Feedlots. Conc. =Concentration

Variable	Value		Reference/Comment
Max bio-avail. of soils (C)	200	ppm	Dumas et al 2011 – HWS, DAFF (2012)
Max bio-avail. of soils (H)	200	ppm	Dumas et al 2011 – HWS, DAFF (2012)
Max bio-avail. of soils (IC)	200	ppm	Dumas et al 2011 – HWS, DAFF (2012)
Max bio-avail. of soils (GMP)	200	ppm	Dumas et al 2011 – HWS, DAFF (2012)
Max bio-avail. of soils (IMP)	200	ppm	Dumas et al 2011 – HWS, DAFF (2012)
Max bio-avail. of soils (RCS)	200	ppm	Dumas et al 2011 – HWS, DAFF (2012)
Midpoint bio-avail. of soils (C)	200	ppm	Dumas et al 2011 – HWS, DAFF (2012)
Midpoint bio-avail. of soils (H)	200	ppm	Dumas et al 2011 – HWS, DAFF (2012)
Midpoint bio-avail. of soils (IC)	200	ppm	Dumas et al 2011 – HWS, DAFF (2012)
Midpoint bio-avail. of soils (GMP)	200	ppm	Dumas et al 2011 – HWS, DAFF (2012)
Midpoint bio-avail. of soils (IMP)	200	ppm	Dumas et al 2011 – HWS, DAFF (2012)
Midpoint bio-avail. (RCS)	200	ppm	Dumas et al 2011 – HWS, DAFF (2012)
power term bio-avail. soils (C)	0.15	-	Dumas et al 2011 – HWS, DAFF (2012)
power term bio-avail. soils (H)	0.15	-	Dumas et al 2011 – HWS, DAFF (2012)
power term bio-avail. soils (IC)	0.15	-	Dumas et al 2011 – HWS, DAFF (2012)
power term bio-avail. soils (GMP)	0.15	-	Dumas et al 2011 – HWS, DAFF (2012)
power term bio-avail. soils (IMP)	0.15	-	Dumas et al 2011 – HWS, DAFF (2012)
power term bio-avail. soils (RCS)	0.15	-	Dumas et al 2011 – HWS, DAFF (2012)
rate bio-avail. soils (C)	0.0008	1/ppm	Dumas et al 2011 – HWS, DAFF (2012)
rate bio-avail. soils (H)	0.0008	1/ppm	Dumas et al 2011 – HWS, DAFF (2012)
rate bio-avail. soils (IC)	0.0008	1/ppm	Dumas et al 2011 – HWS, DAFF (2012)
rate bio-avail. soils (GMP)	0.0008	1/ppm	Dumas et al 2011 – HWS, DAFF (2012)
rate bio-avail. soils (IMP)	0.0008	1/ppm	Dumas et al 2011 – HWS, DAFF (2012)
rate bio-avail. soils (RCS)	0.0008	1/ppm	Dumas et al 2011 – HWS, DAFF (2012)
initial constant bio-avail. soils (C)	1	-	Dumas et al 2011 (Estimated)

Variable	Value		Reference/Comment
initial constant bio-avail. soils (H)	1	-	Dumas et al 2011 (Estimated)
initial constant bio-avail. soils (IC)	1	-	Dumas et al 2011 (Estimated)
initial constant bio-avail. soils (GMP)	1	-	Dumas et al 2011 (Estimated)
initial constant bio-avail. soils (IMP)	1	-	Dumas et al 2011 (Estimated)
initial constant bio-avail. soils (RCS)	1	-	Dumas et al 2011 (Estimated)
max yield from (C)	5	t (crop)/ha	Dumas et al 2011
max yield from (H)	100	t (crop)/ha	Assumption based on the estimated yield in 2001 of 27.5.
max yield from (IC)	5	t (crop)/ha	Dumas et al 2011
max yield from (GMP)	23	t (crop)/ha	Assumption based on the estimate that the yield in 2010 was 5.4 which it was in 2001 see ABARE
max yield from (IMP)	23	t (crop)/ha	Assumption based on the estimate that the yield in 2010 was 5.4 which it was in 2001 see ABARE
max yield from (RCS)	15	t (crop)/ha	Assumed remote cattle station yield is lower.
initial yield from (C)	0.98	-	Dumas et al 2011 Barley yield data
initial yield from (H)	0.98	-	Dumas et al 2011 Barley yield data
initial yield from (IC)	0.98	-	Dumas et al 2011 Barley yield data
initial yield from (GMP)	0.98	-	Dumas et al 2011 Barley yield data
initial yield from (IMP)	0.98	-	Dumas et al 2011 Barley yield data
initial yield from (RCS)	0.98	-	Dumas et al 2011 Barley yield data
yield rate from (C)	0.22	1/ppm	Dumas et al 2011 Barley yield data
yield rate from (H)	0.22	1/ppm	Dumas et al 2011 Barley yield data
yield rate from (IC)	0.22	1/ppm	Dumas et al 2011 Barley yield data
yield rate from (GMP)	0.22	1/ppm	Dumas et al 2011 Barley yield data
yield rate from (IMP)	0.22	1/ppm	Dumas et al 2011 Barley yield data
yield rate from (RCS)	0.22	1/ppm	Dumas et al 2011 Barley yield data
% of P in plants grown by (C)	0.33%	%	cereals 0.33% P (FAO)
% of P in plants grown by (H)	0.33%	%	vegetables 0.04%, fruits 0.02% (FAO)
% of P in plants grown by (IC)	0.33%	%	cereals 0.33% P (FAO)
% of P in plants grown by (GMP)	0.20%	%	Ranges 0.21 to 0.59 (dry matter) (FAO)
% of P in plants grown by (IMP)	0.25%	%	Ranges 0.21 to 0.59 (dry matter) (FAO)
% of P in plants grown by (RCS)	0.05%	%	Guess
P conc. in new soils (C)	0.015%	% (mass)	Based on ASRIS (2013), plus assumption that it will be lower than current soils
P conc. in new soils (H)	0.015%	% (mass)	Based on ASRIS (2013), plus assumption that it will be lower than current soils
P conc. in new soils (IC)	0.015%	% (mass)	Based on ASRIS (2013), plus assumption that it will be lower than current soils
P conc. in new soils (GMP)	0.015%	% (mass)	Based on ASRIS (2013), plus assumption that it will be lower than current soils
P conc. in new soils (IMP)	0.015%	% (mass)	Based on ASRIS (2013), plus assumption that it will be lower than current soils
P conc. in new soils (RCS)	0.015%	% (mass)	Based on ASRIS (2013), plus assumption that it will be lower than current soils
Density of new soils (C)	1.300	t/m^3	Estimated

Variable	Value		Reference/Comment
Density of new soils (H)	1.300	t/m^3	Estimated
Density of new soils (IC)	1.300	t/m^3	Estimated
Density of new soils (GMP)	1.300	t/m^3	Estimated
Density of new soils (IMP)	1.300	t/m^3	Estimated
Density of new soils (RCS)	1.300	t/m^3	Estimated
Depth of new soils (C)	0.25	m	ASRIS (2013)
Depth of new soils (H)	0.25	m	ASRIS (2013)
Depth of new soils (IC)	0.25	m	ASRIS (2013)
Depth of new soils (GMP)	0.25	m	ASRIS (2013)
Depth of new soils (IMP)	0.25	m	ASRIS (2013)
Depth of new soils (RCS)	0.25	m	ASRIS (2013)
Efficiency of Phytase - rate (F)	300	1/%	Estimate
Efficiency of Phytase max uptake (F)	51%	%	ISF, 2012 model; Selle, P. H., Walker, A. R., & Bryden, W. L. (2003).
Fraction of P in Bone compared to P in Bone + Blood + non edible carcass (GMP)	55%	%	ISF 2012; Peterson, 2013
Fraction of P in Bone compared to P in Bone + Blood + non edible carcass (IMP)	55%	%	ISF 2012; Peterson, 2013
Fraction of P in Bone compared to P in Bone + Blood + non edible carcass (RCS)	55%	%	ISF 2012; Peterson, 2013
Fraction of P in Bone compared to P in Bone + Blood + non edible carcass (F)	55%	%	ISF 2012; Peterson, 2013
Fraction of P in Blood compared to P in Bone + Blood + non edible carcass (GMP)	5%	%	ISF 2012; Peterson, 2013 (Estimated)
Fraction of P in Blood compared to P in Bone + Blood + non edible carcass (IMP)	5%	%	ISF 2012; Peterson, 2013 (Estimated)
Fraction of P in Blood compared to P in Bone + Blood + non edible carcass (RCS)	5%	%	ISF 2012; Peterson, 2013 (Estimated)
Fraction of P in Blood compared to P in Bone + Blood + non edible carcass (F)	5%	%	ISF 2012; Peterson, 2013 (Estimated)
Fish wastes relative to edible fish	50%	%(P in wastes relative to P in edible fish)	ISF, 2012; FRDC, 2011
P in urine versus faeces	67%	%	Johansson et al 2001
average life of a Li-ion battery	10	years	ISF lithium paper (Mohr et al 2012).

A4: National Sustainable Phosphorus workshop

NATIONAL STRATEGIC PHOSPHORUS ADVISORY GROUP

WORKSHOP 2: AGENDA

Date: Friday 6th September

Time: 10:00am - 3:00pm

Venue: Level 2, 15 National Circuit, Barton,
Rural Industries R&D Corporation (RIRDC)
Phone: 02 6271 4100; Map: http://www.rirdc.gov.au/publications/forms/contact-us

Hosted by: Institute for Sustainable Futures, University of Technology, Sydney

Time	Item
10:00 - 10:15	Project background, objectives & introductions
10:15 - 11:00	Sustainable Phosphorus Measures model
11:00 - 11:20	Morning tea
11:20 - 12:50	Mapping phosphorus vulnerability: influence diagram, validation, *What if*? scenarios
12:50 - 1:30	Lunch
1:30 - 2:30	Sustainable pathways: priorities, balancing trade-offs, synthesis
2:30 – 3:00	Priorities & next steps

Participants:

1. Nick Drew	Executive Manager, Fertiliser Australia
2. Graham Turner	Principal Research Fellow, Melbourne Sustainable Society Institute, University of Melbourne
3. Allison Britt	Commodity Specialist (phosphate) Geoscience Australia
4. David Gough	Strategy Manager, Servicing & Asset Strategy Sydney Water
5. Adrienne Ryan	Policy Officer Soil Policy Section, Sustainable Resource Management Division Department of Agriculture Fisheries And Forestry (DAFF)
6. Ronnie Harding	Senior Visiting Fellow, Institute of Environmental Studies, UNSW & Wentworth Group of Concerned Scientists
7. Gerry Gillespie	Chairman, Zero Waste Australia & Office Of Environment & Heritage
8. Phil Graham	Technical Specialist Livestock Systems, Agriculture NSW
9. Lauren Oehme	Research Program Co-ordinator Rural Industry Research & Development Corporation
10. Tim Wright	Field Service Manager, AG*n*VET Services
11. Dana Cordell 12. Stuart White 13. Brent Jacobs	Institute For Sustainable Futures, University Of Technology, Sydney

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