Available online at www.sciencedirect.com

SciVerse ScienceDirect

journal homepage: www.elsevier.com/locate/envsci

Phosphorus flows through the Australian food system: Identifying intervention points as a roadmap to phosphorus security

D. Cordell *, *M. Jackson*, *S. White*

Institute for Sustainable Futures, University of Technology, Sydney, P.O. Box 123 Broadway, NSW 2007, Australia

ARTICLE INFO

Article history:
Received 18 August 2012
Received in revised form
9 January 2013
Accepted 12 January 2013
Published on line 19 March 2013

Keywords:
Phosphorus flow analysis
Australian food system
Phosphorus scarcity
Food security
Efficiency
Recovery

ABSTRACT

Global phosphorus scarcity is likely to threaten the world's ability to produce food in the future if concerted efforts to ensure long-term phosphorus availability and accessibility and to use phosphorus more sustainably in the food system are not taken by policy makers, scientists and industry. Each country is vulnerable to phosphorus scarcity in different ways due to different characteristics of the national food system. However numerous opportunities exist to steer countries on a more sustainable trajectory to buffer food systems against such risks. A country-level phosphorus flow analysis can aid the identification of current inefficiencies, potential points for phosphorus recovery, reduction in losses and facilitate prioritisation of policy measures. This paper presents the findings and implications of a phosphorus flow analysis for Australia. The analysis 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. 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. 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. Key opportunities to increase the resilience of the Australian food system include: increasing manure reuse, phosphorus use efficiency in fertilised pastures, investigate phosphorus recovery from phosphogypsum waste stockpiles and investigating more phosphorus-efficient food and agricultural commodities—particularly to reduce exported and wasted phosphorus whilst maintaining or enhancing productivity.

1. Introduction

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 (Cordell et al., 2009a; Bekunda et al., 2011). Peak phosphorus is predicted to occur this century, possibly as soon as 30 years (Cordell et al., 2009a; Cordell and White, 2011), yet there is no substitute for phosphorus in food production. Fertiliser prices are expected to increase in the future, increasing pressure on up to a billion of the world's farmers who are already restricted in their purchasing power to access fertiliser markets (IAASTD, 2008). Further, the

* *Corresponding author*. Tel.: +612 95144950.
E-mail addresses: Dana.Cordell@uts.edu.au, dana.j.cordell@gmail.com (D. Cordell).
1462-9011/$ – see front matter
http://dx.doi.org/10.1016/j.envsci.2013.01.008

world's remaining high-grade phosphate rock reserves are concentrated in only a few countries, with Morocco alone controlling 70% of the world's share (Jasinski, 2012). This makes phosphate-importing countries vulnerable to geopolitical dynamics in producing countries. In short, global phosphorus scarcity is likely to threaten the world's ability to produce food in the future if concerted efforts to ensure long-term phosphorus availability, accessibility and sustainable use are not made by policy makers, scientists, industry and the community today.

The predominantly one-way movement of phosphorus in the global food system begins when phosphate rock is mined, cleaned and reacted with sulphuric acid to produce a more concentrated and plant-available form of phosphate in fertilisers. Some phosphorus ends up stockpiled onsite in the by-product 'phosphogypsum', while the fertiliser products are traded globally and applied regularly to the world's agricultural fields and pastures. Plant roots and livestock take up only a fraction of the applied phosphorus in fertilisers, resulting in phosphorus leaving the fields in crop harvests, animals' bodies or eroded soil, or remaining in crop residues, soils and manures. Phosphorus-containing crops and animal products are then processed into vegetal and animal based foods such as meat, milk, eggs and fish, some of which are consumed by the human population with the remainder predominantly ending up in organic waste destined for landfills or compost heaps. Almost all of the phosphorus in food consumed by humans leaves the body in urine and faeces. The fate of this phosphorus is therefore largely in oceans, rivers or land via wastewater treatment systems or directly through open defecation. Ultimately, only one-fifth of the phosphorus mined for food production finds its way into the food consumed by the global population (Smil, 2002; Cordell et al., 2009a).

Phosphorus is therefore relevant to many sectors including mining and fertiliser production, agriculture and livestock, food processing, distribution and retail, households, sanitation, environmental protection and waste management sectors. Despite the importance of phosphorus to so many sectors in the food system, long-term availability and accessibility to phosphorus has not been a priority within any sector (Cordell, 2010). However the 800% phosphate price spike in 2008 drew the world's attention to the long-term phosphorus security issue (Cordell et al., 2009a; Gilbert, 2009; Bekunda et al., 2011).

Phosphorus security means ensuring long-term accessibility and availability of phosphorus to ensure all farmers have access to fertilisers, soils are fertile and aquatic environments are protected from excess nutrient loads (Cordell, 2010). Historically there has been very limited awareness and policy debate on global phosphorus scarcity. Unlike other important resources for sustainable food systems and ecosystem functioning, such as carbon, water and land, there has been relatively little research on integrated and sustainable phosphorus use for food security at the national or international scale (Cordell, 2010; Bekunda et al., 2011). Due to the complexity and interconnectedness of many aspects of the food system, long-term phosphorus security is likely to require an integrated approach that reduces dependence on single sources of phosphorus (such as phosphate rock) through diversification, recycles phosphorus from all 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, 2011; Schröder et al., 2011). A systemic inquiry into the sources, flows and fate of phosphorus in a country's food system can facilitate identification of leverage points with which to create a sustainable phosphorus future. A national substance flow analysis (SFA) of phosphorus is a means of doing such an inquiry and was the basis of the study presented in this paper. The Australian food system was selected as a case study because it has a unique combination of characteristics including naturally phosphorus-deficient soils and a strong dependence on imported sources of phosphorus to maintain soil fertility of pastures and crop soils and hence agricultural productivity (Commonwealth of Australia, 2001).

The purpose of this paper is therefore to present the findings from the phosphorus flow analysis in Australia, from which analytical and broader sustainability implications are drawn. The Australian phosphorus substance flow analysis presented in this paper is a first for Australia and provides context within which to locate sectoral studies, a foundation for collaborative problem solving between industries sectors and governments and contributes to the broader knowledge base of the current impacts, opportunities and risks associated with economic, consumer and policy choices associated with this key element of the food system. While each country is vulnerable to phosphorus scarcity in different ways due to different characteristics of national food systems, the lessons from the Australian SFA findings and analysis are relevant to the international community in at least three ways. Firstly, in terms of the methodology applied, which can and is being replicated in other countries to identify phosphorus 'hotspots' and guide appropriate management responses (Cordell et al., 2012), and secondly, the specific findings for those countries with similar characteristics and trends to the Australian context. For example, increasing pressures on existing food-producing countries to expand and intensify production, changes of land use to meet food export demands and changing dietary patterns and increasing demand for fertilisers. Finally, the vulnerability or unsustainable nature of Australian food system has implications for food security in the Asia-Pacific region where much of Australian agricultural commodities are destined.

2. The Australian food system

Australia is heavily dependent on phosphate fertilisers from both domestic and imported sources. Indeed, the country is the world's fifth largest consumer of phosphate fertilisers (Heffer, 2009) despite being only the world's 52nd largest country by population (approximately 22 million people). Historically this phosphorus was sourced from guano mines in the South Pacific such as in Nauru, and more recently from domestic sources supplemented by Moroccan/Western Saharan phosphate rock. This high phosphate consumption is to support the country's agricultural activities that largely occur on naturally phosphorus-deficient soils. Over a century of cropping and grazing following European settlement depleted the little soil phosphorus that naturally existed in Australian soils by the 20th century (ABS, 1996).

Today agriculture is the largest single contributor to Australia's GDP, worth over A$51 billion[1] (excluding forestry) (ABS, 2011a). Consequently, over half of Australia's land area is dedicated to agricultural activities (AIHW, 2012). The largest sectors are beef, wool, wheat and dairy. Of the almost 400 million hectares used for agriculture, 8% is used for cropping while 88% is used for grazing livestock. In dollar terms, the livestock sector is by far the most valuable food industry in Australia.

Most of Australia's agricultural commodities are destined for overseas markets. The Australian food export industry is worth A$23–27 billion (US$24–28 billion), with 26% of this value derived from meats, 28% from grains and oilseeds, 9% dairy, 7% wine (DAFF, 2012). Indeed, Australia is the 14th largest food exporter in the world, producing enough food for approximately sixty million people—almost three times the Australian population (PMSEIC, 2010). North Asia (predominantly Japan and China) is the largest destination for Australian food and agricultural exports (37%), followed by South East Asia (predominantly Indonesia and Malaysia), the US and EU (ABARES, 2011a; DAFF, 2012).

Much of these exports are phosphorus-intensive agricultural commodities, such as wheat, beef and live animals. That is, they require substantial phosphorus inputs to produce a tonne of output relative to other agricultural commodities. Australia exports 64% of its beef and lamb—making the country the world's second largest beef exporter—and exports 45% of its milk (AIHW, 2012).

This dependence on phosphorus and significance of this element for the Australian economy means that while the country does not currently suffer from widespread food insecurity, the food system is vulnerable to changing global drivers related to phosphorus scarcity (Cordell and White, 2010).

While there are an increasing number of phosphorus-related studies within individual sectors in Australia—particularly related to phosphorus use efficiency with specific cropping systems, pasture systems or soil types (Simpson et al., 2011; Weaver and Wong, 2011)—there is a lack of research that integrates the study of phosphorus through the whole food system. That is, research that enables a clear comparison of the relative gains from increasing phosphorus efficiency and recycling in different sectors (such as the mining, agricultural and food processing sectors). This paper facilitates such a comparison and hence identifies the source of the greatest potential for implementing sustainable phosphorus measures.

3. Methodology

3.1. *Substance flow analysis (SFA)*

Substance flow analysis (SFA) is a material accounting tool that helps assess and understand the sustainability of a particular material in the environment whose quantity and flow paths have been altered by human activity (Brunner and Baccini, 1991). In this case, the substance analysed is phosphorus. SFA is one of several material accounting tools developed in the field of Industrial Ecology to aid environmental management by systematically assessing how materials are used in society (Brunner and Rechberge, 2004). SFA and other such tools (including input–output analysis, material input per unit of service (MIPS), life cycle assessment (LCA) commonly utilise mass balance principles within a systems framework. While the former tools are useful for analysing the relative eco-efficiency of a specific product, SFA is a highly appropriate tool for analysing a key element within the food system such as phosphorus because it enables it to be tracked across disparate sectors, conversion to different goods and the associated magnitude of flows to be compared and analysed on a common unit basis. This quantitative method allows the annual inputs, outputs and accumulation of phosphorus between major sectors within a pre-defined system boundary to be calculated in kilotonnes of phosphorus per year (kt/a of P) (Brunner and Rechberge, 2004). Phosphorus-containing goods (such as fertilisers or food or manure) are identified and analysed via mass balance. For example, an annual phosphorus flow (P) associated with the movement of manure between sector A and sector B is calculated by multiplying the mass of the manure moved between A and B by the concentration of the manure:

$$P_{\text{manure}(A-B)} = \text{mass}_{\text{manure}(A-B)} \times \text{concentration}_{\text{manure}}$$

Major losses, recycling, imports and exports are also identified and calculated. The phosphorus accumulated within each sector over time (in kilotonnes of phosphorus), known as 'stocks' are also typically calculated, however this requires a greater level of data and analysis.

The primary objectives of a phosphorus flow analysis[2] include (Brunner and Baccini, 1991; Brunner and Rechberge, 2004):

1. Define system and identify key phosphorus-containing goods, sectors and flow paths.
2. Identify the major phosphorus flows into, through, and out of elements of the food production-consumption system.
3. Identify the major phosphorus losses/waste streams within and exported from the food system.
4. Determine which phosphorus losses/waste stream flows can be avoided or reduced through demand management measures.
5. Determine which unavoidable phosphorus waste streams can be recovered and reused productively as fertiliser.
6. Identify key data gaps for further research.

Phosphorus is increasingly becoming the subject of substance flow studies, particularly to explicitly address growing concerns regarding phosphorus scarcity and implications for food production. Prior to this, the primary focus of phosphorus flow analyses tended to be pollution and leakage abatement to reduce the risk of phosphorus reaching waterways and causing eutrophication and potentially toxic algal

[1] US$54 billion (as at 14/08/12).

[2] A phosphorus flow analysis can also be described as a phosphorus budget, or phosphorus (stocks and) flows model.

blooms (Tangsubkul et al., 2005; Pellerin, 2011; Cordell et al., 2012).

While many recent national phosphorus flow analyses (from China to France to the US) indicate substantial phosphorus losses and waste streams from the food production and consumption system, the magnitude of these losses and the relative importance of difference sectors can differ substantially from country to country (Gumbo, 2005; Liu, 2005; Cordell et al., 2012; Senthilkumar et al., 2012). This implies a general need to both reduce losses and recover phosphorus effectively and efficiently, and further it stresses the importance of country-specific studies to determine contextual priorities.

In this way, calculating the phosphorus budget of a country allows scientists and policy-makers to identify current inefficiencies, potential points for recovery, reduction in losses and quantify the potential contribution of different technologies and strategies to facilitate prioritisation of policy measures (Brunner, 2010; Cordell, 2010; Pellerin, 2011; Cordell et al., 2012; Senthilkumar et al., 2012).

3.2. Australian phosphorus flow model

The study presented here involved a phosphorus flow analysis for Australia, with the primary output being the Australian Phosphorus Flow Model v1.3.[3] The results, interpretation and initial policy implications are presented in this paper. The intent was to design and develop a model with greater rigour, flexibility and transparency than previous preliminary estimates of phosphorus flows through the Australian food system (McLaughlin et al., 1992; Cordell, 2010; Cordell and White, 2010). For example, the excel-based model provides a clear and accessible interface to increase usability and a flexible structure that allows fields to be updated easily as new data becomes available.

Given phosphorus is used almost entirely for the production of food (approximately 90%), the system boundary for this study was the Australian food system. Seven key sectors were selected and flows associated with the movement of 27 phosphorus-containing goods through these sectors were tracked (see Supplementary Material A for classification and description of flows). These were chosen based on their estimated significance in terms of phosphorus mass and relationship to the food system. Phosphorus goods and flows related to non-food services such as fire retardants were therefore excluded from the study. Key sectors, include:

1. *phosphate rock*: the domestic mining and production of phosphorus rock and imports of commercial phosphate rock;
2. *fertilisers*: the production, domestic distribution, import and export of all commercial grade mineral phosphate fertilisers;
3. *agriculture*: crop-based agricultural systems, including the soil, crops and crop residues (excluding animal-based systems);
4. *livestock*: animal production including aquaculture, pastures and feedlots (excluding wild fish);
5. *food production and consumption*: crop and animal processing for food (i.e. starting from crop harvests in the case of crops, and the abattoir in the case of livestock); and the distribution, retail and consumption of food;
6. *wastewater*: both human excreta and detergents as inputs into the wastewater treatment system; and
7. *organic waste*: solid organic waste generated by the post-harvest key sectors of the food system, such as processing waste from food production and uneaten food scraps; it excludes abattoir waste due to lack of data.

Goods imported into the Australian food system (i.e. those that cross the system boundary) include phosphate rock imports, phosphate fertiliser imports, food/fibre imports. Imported goods also include wild flora and fauna that enter the food system via hunting and gathering and livestock grazing on unfertilised pastures. Goods exported from the food system include fertiliser exports and food/fibre exports. Exported goods also include mine waste, fertiliser waste stockpiles, non-food uses of mined phosphorus (such as detergents), soil eroded from agriculture to non-agricultural soils because they 'leak' from the food system. Table A and B in the Supplementary Material describe goods, sectors and flows in more detail (including inclusions and exclusions). Phosphorus 'stocks', that is, phosphorus accumulated within sectors over time, were not calculated in this study due to lack of access to sufficient time-series data.

To increase the quality, credibility and legitimacy of the outcomes and ensure implementation (Mitchell et al., 2006), key sector experts were engaged in this study though a high-level 'National Strategic Phosphorus Advisory Group' (NSPAG), to provide strategic guidance, review of data and analyses, prioritise science and policy options and ensure findings are designed to be policy-relevant.[4]

3.3. Data sources and quality

Data was sourced from official government statistics, reports and data sets, industry data and scientific studies (Table 1). Where sufficient data was unavailable, values were determined by mass balance, oral information from experts or assumptions generated by the research team.

The general lack of phosphorus data and data sets relative to other important resources (such as carbon, water) is a common identified constraint for undertaking phosphorus substance flow analyses anywhere in the world (Tangsubkul

[3] This forms part of a larger three-year study, the 'Australian Sustainable Phosphorus Futures' project which has an overall aim to deliver sustainable phosphorus adaptation strategies across a range of scenarios to increase the resilience of the Australian food system. http://phosphorusfutures.net/australian-sustainable-phosphorus-futures/37-three-year-project-australian-sustainable-phosphorus-futures.

[4] NSPAG members are representatives of key stakeholder groups and sectors related to phosphorus in the Australian food system (including mineral resources, fertilisers, agriculture, farming, livestock, food nutrition, natural resource management, organic waste, sustainability and wastewater sectors), Members and Terms of Reference can be viewed at: http://phosphorusfutures.net/australian-sustainable-phosphorus-futures/36-national-strategic-phosphorus-advisory-group-nspag.

Table 1 – Data sources and status of data quality for data inputs into the Australian phosphorus flows model. Data quality are categorised as sufficient, poor/questionable or absent. * Indicates a significant flow in terms of magnitude or importance.

Sector	Data sources	Data quality		
		Sufficient[a]	Poor/questionable[b]	Absent[c]
Phosphate rock	ABARES (2010b,c, 2011b), IFA (2012), Prud'Homme (2010), and USGS (2010)	• Phosphate rock trade (production and imports)	• Proportion of total phosphate rock used for industrial use • *P content of phosphate rock (in annual production and reserves)	P in detergents produced and consumed in Australia • *P in mining waste • *Phosphate rock production and reserves on Christmas Island
Fertilisers	ABARE (2007a, 2008, 2009, 2010), FIFA (2007, 2008, 2009, 2010, 2011), and Pers. Comm. InvitecPivot(3/2/2012)	• P concentration of P2O5 and all commercial grade fertilisers • Phosphate fertiliser trade • Processing losses to the environment (excludes phosphogypsum)	• *P_2O_5 content in dry waste storage of phosphogypsum • *Proportion of domestically used fertiliser applied to crops (versus pastures)	N/A
Agriculture (crop systems)	ABS (2011b), DEWHA (2006), McLaughlin et al. (1992), and Recycled Organics Unit (2007)	• Fertiliser application in cropping systems (by fertiliser type)	• *P losses via soil erosion to non-agricultural uses and water associated with fertiliser/manure	• *P in non-food agricultural products (such as pet food, clothing, oils) • *% P lost from pastures vs. cropping systems to non-ag land • *P inputs in aquaculture (e.g. fish feed, added nutrients) and outputs (fish stocks and waste)
Livestock	ABARE (2007b, 2010), ABS (2007), ALFA (2007), DEWHA (2006), FAOSTAT (2011), FIFA (2009, 2010), Hoffman & Beaulieu (2001), LivecorpPers.Comm 21/2/12, McLaughlin et al. (1992), Prud'Homme (2010), and NSW DPI (2007)	• P in animal feed broken down by grain type and animal type • Live export by head numbers • Average weight per animal	• *P in manure that is reused in agriculture • *P content of live animals (%P), particularly sheep • *%P in edible versus non-edible carcass parts	• *P in feed supplements for livestock • *% P lost from pastures versus cropping systems to non-ag land
Food production	ABARES (2010b,c), ABS (2007–2010), DAFF (2007), FAO (unknown), McLaughlin et al. (1992), NHMRC (2003), and Prud'Homme (2010)	• Crop production by crop type (kt/a) • Fisheries production, exports and consumption • Imported food and fibre (kt/a)	• The proportion of purchased food which is actually consumed • P in imported food • *P in exported food • *P concentration of food/crop types	• P in food additives for human consumption • Proportion of P in non-food products versus food products • Aquaculture inputs and outputs • Wild animal catches
Wastewater	ANZ Biosolids Partnership (2009), CEEP (1993), Crawford et al. (2006), GE Power & Water (2012), FAO (1992), Lenntech (2011), Lindquist (2003), Mekala et al. (2008), and NWC (2008)	• Wastewater generation (GL) • Fate of biosolids (landfill, reuse in ag, reuse in non-ag)	• *Fate of recycled effluent in Australia (e.g. proportion recycled to residential/ industrial uses vs. recycled to ag soil vs. recycled to non-ag soil) • P removed from different treatment processes • *P excreted per person	N/A

Table 1 (*Continued*)

Sector	Data sources	Data quality		
		Sufficient[a]	Poor/questionable[b]	Absent[c]
Organic waste	Recycled Organics Unit (2007), FAO (2006), and Hyder Consulting (2008)	• Food waste generated in municipal and commercial/industrial sectors • Food waste sent to landfill versus recycled	• *P in organic waste and the fate-blood and bone	• Proportion of seafood ending as organic waste (pre-consumer and post-consumer) • Proportion of 'Green Organics' assumed to be associated with food production and consumption • *P in blood and bone reused in agriculture as fertiliser

Data sources: ABARE (2007a,b), ABARE (2008), ABARE (2009), ABARE (2010), ABARES (2010a,b,c), ABARES (2011b), ABS (2007–2010), ABS (2011b), ABS (2006–07), ANZ Biosolids Partnership (2009), ALFA (2007), CEEP (1993), Crawford et al. (2006), DAFF (2007), DEWHA (2006), FAO (1992), FAO (2006), FAO (unknown), Fisheries Research and Development Corporation (2011), FAOSTAT (2011), FIFA (2007), FIFA (2008), FIFA (2009), FIFA (2010), FIFA (2011), GE Power & Water (2012), Hoffman & Beaulieu (2001), Hyder Consulting (2008), IFA (2012), Lenntech (2011), Lindquist (2003), Livecorp (2012), McLaughlin et al. (1992), Mekala et al. (2008), NWC (2008), NHMRC (2003), NSW DPI (2007), Prud'Homme (2010), Recycled Organics Unit (2007), USGS (2010).

[a] 'Sufficient data'—data that are of high or reasonable quality.

[b] 'Poor data'—data which is known to be of poor quality from the original source, or, is a questionable proxy for the specific parameter (e.g. if an international figure has been used as a proxy for Australia, or 10–15 year old data).

[c] 'Absent data'—data for which assumptions were made in the absence of any data.

et al., 2005; Pellerin, 2011). The Australian case is no exception: data availability at the national level are low or extremely low, for most flows associated with informal sectors such as organic waste reuse (see Supplementary Material B). Table 1 also indicates the quality of data used to undertake the phosphorus flow analysis.

4. Results

4.1. *Overall Australian phosphorus budget*

The Australian Phosphorus Flow Model v1.3 (Fig. 1) indicates the major phosphorus inputs, outputs and internal flows of phosphorus through the Australian food system for the year 2007.

Despite being a net food exporter, Australia is a net *importer* of phosphorus, with a net of 80 kt P[5] imported into the country each year (Fig. 2a). Approximately 214 kt/a of P are imported into the country via imported fertilisers and phosphate rock, while approximately 134 kt/a of P are exported via fertiliser and food exports.

At the same time, Australia has a net phosphorus deficiency from the food system of approximately 106 kt P each year (Fig. 2b). 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,[6] 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).

4.2. *Sector phosphorus budgets*

This section summarise the key phosphorus budgets (inflows and outflows) for key sectors. Australia mines phosphate rock domestically for fertiliser production (approximately 288 kt/a of P produced by a single mining company in Queensland), and supplements this with phosphate rock imports (predominantly from Morocco/Western Sahara) amounting to approximately 64 kt/a of P (Fig. 3a). All of this phosphate rock is currently consumed domestically, with the largest share (80%) used for fertiliser production. Smaller amounts are used for livestock feed additives, food additives and industrial purposes (such as detergents, fire retardants, matches and medicines).

Phosphorus fertilisers applied to Australian soils come from both domestically produced phosphate[7] (256 kt/a of P) and imported phosphate[8] (149 kt/a of P) (Fig. 3b). As noted in Section 1, phosphate fertilisers are produced by reacting

[5] Kilotonnes of phosphorus.

[6] Domestic phosphate rock production is included in the food system, because this essentially represents Australia's phosphate mine at Phosphate Hill, owned by fertilisers company Incitec Pivot Ltd. and operated for the purpose of producing fertilisers for agricultural use.

[7] As single superphosphate (SSP), diammonium phosphate (DAP) and monoammonium phosphate (MAP).

[8] Mainly as monoammonium phosphate (MAP).

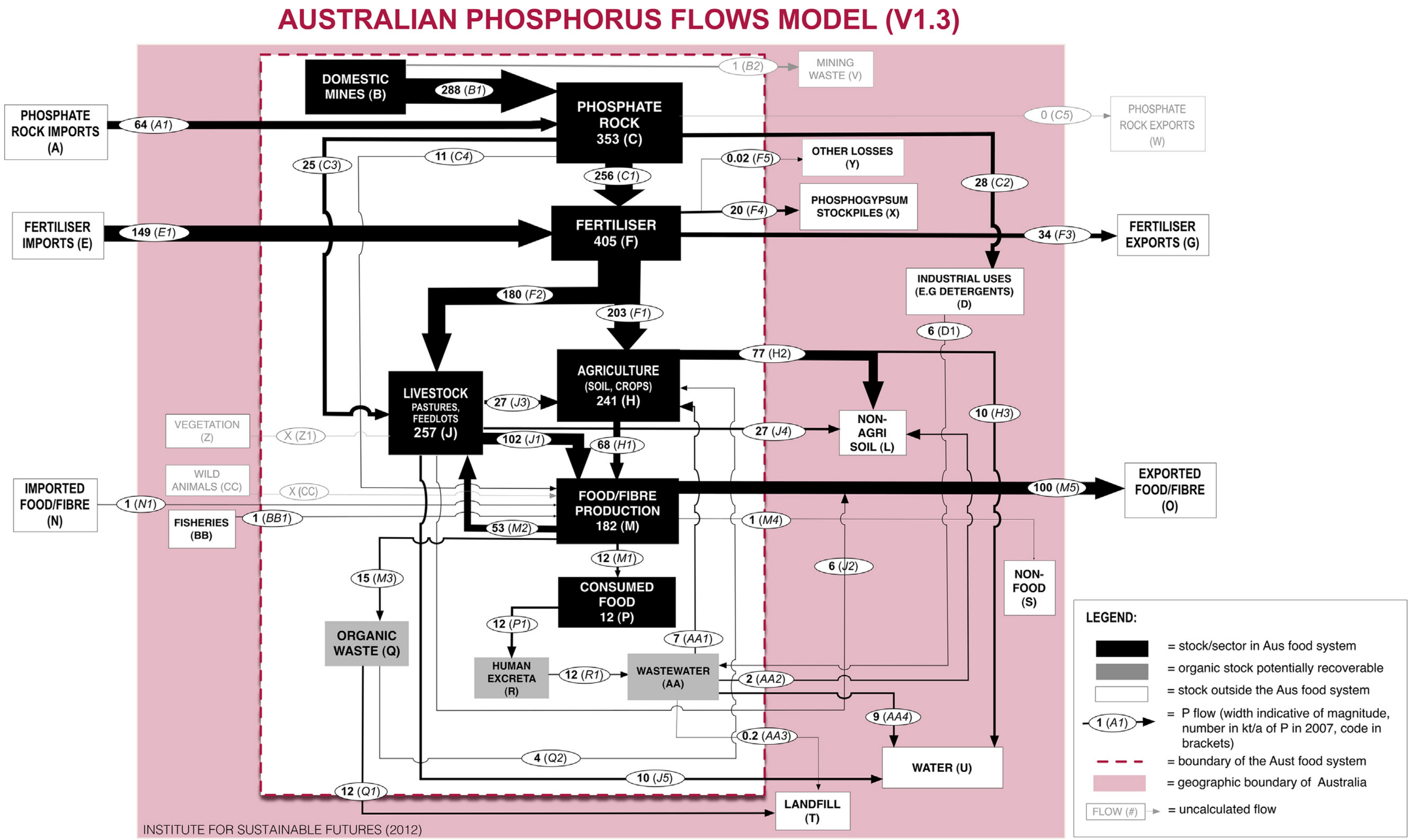

Fig. 1 – Phosphorus flows through the Australian food system (units are in kt/a of P). (Black arrows indicate the flow of phosphorus in kt of P for the year 2007, where width represents the relative order of magnitude of flows; the red dotted line indicates the boundary of the Australian food system, and the pink shaded box indicates the country boundary. Greyed out boxes and flows implies no data exists or data has not been found.)

Fig. 2 – (a) The country-scale phosphorus mass balance indicates Australia is a net importer of phosphorus (net 80 kt/a P) and (b) At the food system scale, Australia has a net deficit of phosphorus (net 106 kt/a P).

phosphate rock with acid to produce a more soluble form, phosphoric acid. This process results in the generation of five tonnes of phosphogypsum by-product for everyone tonne of phosphate. Approximately 10% of phosphorus in domestically produced fertiliser ends up in phosphogypsum waste stockpiles (20 kt/a of P) with a small amount in waste streams discharged to the environment (0.02 kt/a of P). The remaining fertiliser is either applied to pastures (180 kt/a of P), cropping systems (203 kt/a of P) or exported (34 kt/a of P). Fertiliser exports also vary widely from year to year (ranging from 34 to 106 kt/a of P between 2006 and 2010).

Phosphorus inputs into agricultural cropping systems[9] include fertilisers (203 kt/a of P), manure (27 kt/a of P), organic waste (4 kt/a of P) and recycled biosolids/effluent from wastewater (7 kt/a of P) (Fig. 3c). Some phosphorus applied to soils is dissolved in soil solution and taken up by crop roots. Some phosphorus for crop growth also comes from the soil stock (from both natural sources and previous fertiliser applications). Phosphorus leaves the agriculture sector as crop harvests (68 kt/a of P) for food, feed or fibre processing, or is lost to non-agricultural soil (77 kt/a of P) or water via wind or water erosion (10 kt/a of P). The remaining phosphorus either accumulates within the soil stock or remains in situ as crop residues.

Phosphorus inputs into the livestock sector include fertilised pastures for grazing (180 kt/a of P), feed (53 kt/a of P), and feed additives (25 kt/a of P) (Fig. 3d). Cattle alone account for 53% of feed demand, and 72% of all feed is from grains. A large share (almost 50%) of Australia's phosphorus fertiliser demand is attributed to pastures. When phosphorus in feed and feed additives are included, the livestock sector accounts for 257 kt/a of P demand compared to the cropping sector (excluding crops produced for animal feed) which accounts for 150 kt/a of P. Outputs from the livestock sector include phosphorus contained in live animals sent to abattoirs,[10] eggs and milk (102 kt/a of P) and live animals for export (6 kt/a of P). Outputs also include phosphorus contained in manure that is either reused as fertiliser in other crop systems (27 kt/a of P), or, treated or untreated manure that is 'lost' from the livestock sector to non-agricultural soil (27 kt/a of P) e.g. through spreading manure on non-agricultural land or lost to water via leakage (10 kt/a of P). The majority of phosphorus entering the livestock sector either accumulates in manure, animal bodies (bones, blood) or to a lesser extent exits the sector as meat and milk products. Approximately 700 kt P is excretedin livestock manure in Australia annually. Most of this manure (67%) is generated by grazing cattle, and hence not directly recoverable via feedlots. Indeed, only 64 of 700 kt/a of P is estimated to leave the livestock sector each year, the rest accumulates in soil.

Phosphorus inputs into the food/fibre production system include agricultural and livestock primary produce such as crops, animals/carcasses, eggs, milk, fish, food additives as well as inputs from imported food (Fig. 3e). The largest inputs into food production include animal products (102 kt/a of P) and harvested crops (68 kt/a of P). Inputs into fisheries include wild catches and inputs into aquaculture (which include fish feed and nutrients). Most phosphorus in fish accumulates in fish bones and scales (rather than flesh). Some of the flesh is also wasted between production and consumption. The food/fibre production sector includes many processes from primary processing of agricultural and livestock products, food processing, food wholesaling, distribution, retailing and food preparation to the point of purchase/consumption (AIHW, 2012). The most significant phosphorus outputs from Australia's food/fibre production sector are exported food/fibre (100 kt/a of P) and livestock feed (53 kt/a of P). Other outputs include organic waste (15 kt/a of P), non-food products[11] (1 kt/a of P), and consumed food[12] (12 kt/a of P).

The Australian population together generates approximately 12 kt/a of P in urine and faeces which largely goes to wastewater. Added to this is approximately 6 kt/a of P in detergents. Almost all of these two phosphorus sources enter a centralised or decentralised wastewater treatment system, ranging from septic tanks to tertiary treated wastewater. Phosphorus outputs from wastewater treatment are either in the liquid fraction (effluent) or solids (biosolids). The fate of effluent and biosolids range from discharge to waterways, reuse in agriculture or forestry, or disposal to landfill (Fig. 4). Ultimately, most phosphorus ends up discharged to oceans (and rivers), reused in agriculture or spread on non-agricultural land (Fig. 3f). Approximately 9 kt/a of P is permanently lost via ocean outfalls nationally.

Phosphorus is present in all organic waste at different concentrations. Phosphorus enters the organic waste sector as food waste from households, the retail or wholesale sectors and food processing waste from the food-manufacturing sector. It includes both avoidable food waste (such as spoilt

[9] Livestock systems are analysed separately.

[10] For the purpose of this study, abattoirs are considered part of the 'food production' sector, rather than the livestock sector, hence the large phosphorus flow leaving the livestock sector. Abattoir waste, including blood and bone reuse has not however been indicated in the model due to lack of data.

[11] Phosphorus contained in non-food products was estimated and hence an uncertain figure.

[12] The food consumption sector includes food that is literally consumed by humans in Australia.

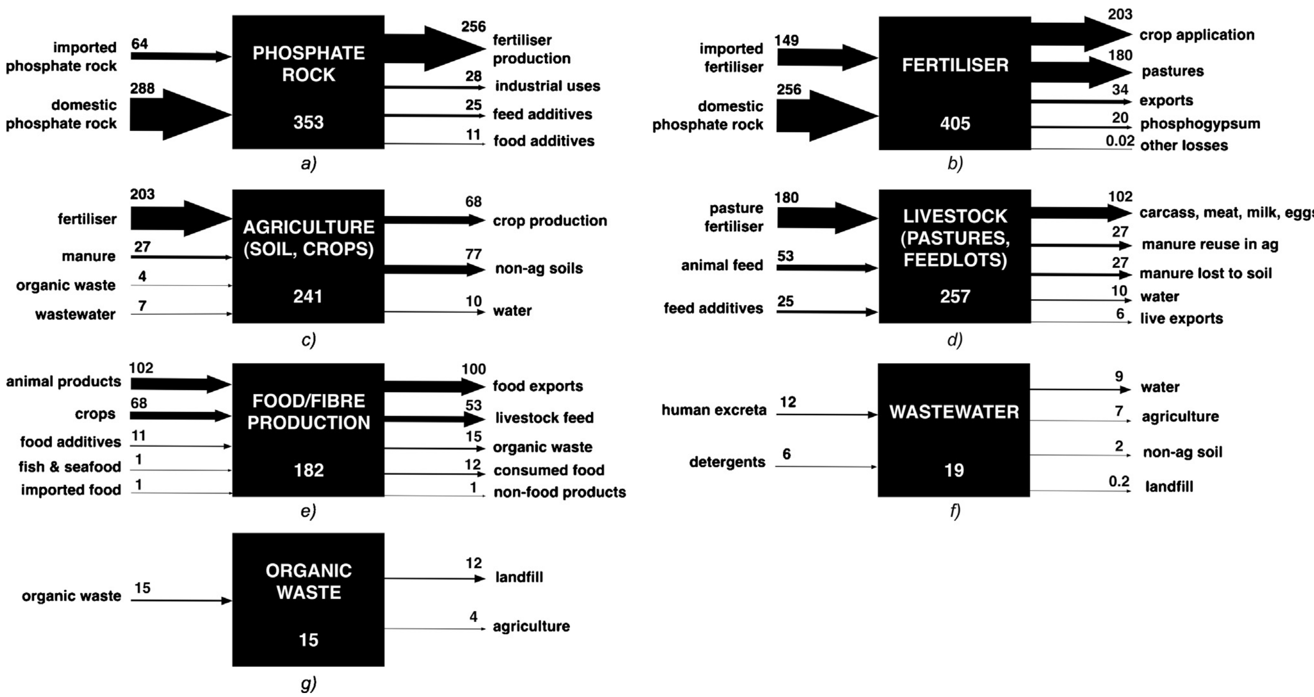

Fig. 3 – Phosphate budgets (inputs and outputs) for individual sectors: (a) phosphate rock; (b) fertiliser; (c) agriculture (cropping systems); (d) livestock (pastures and feedlots); (e) food and fibre production; (f) human excreta and wastewater, (g) organic solid waste. Units are in kt/a of P. Note: The net balance of each sector (calculated as input minus output) in most cases does not equal zero due to: (a) an annual accumulation or deficit (e.g. more phosphorus is being removed from the sub-system than is being inputted, or vice versa); (b) data reliability was low; and (c) inaccurate assumptions (e.g. inaccurate co-efficient use, missing minor input or output flow).

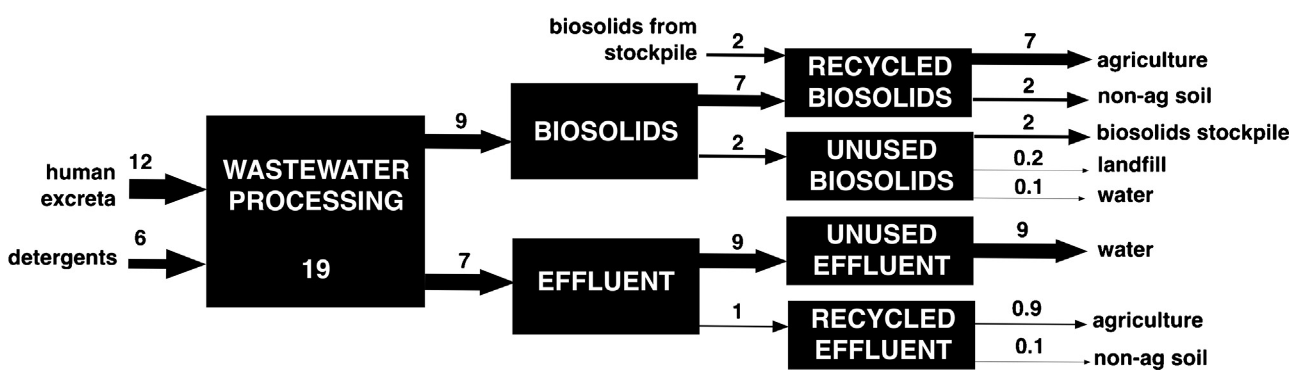

Fig. 4 – Detailed phosphorus flows into, through and from the wastewater treatment process. Units are in kt/a of P.

prepared food) and unavoidable food waste (such as banana peels and egg shells). On average, this amounts to some 15 kt/a of P (Fig. 3 g). Because most of Australia's food/fibre production is exported as primary agricultural commodities (such as wheat and live exports), this means most of the associated organic waste is generated overseas, and hence the embodied phosphorus not available for recovery and reuse.

4.3. *Phosphorus losses and recovery rates*

The analysis indicates substantial phosphorus losses—and some recycling—in almost all key sectors (Table 2). The greatest losses from the food system in absolute terms occur as permanent losses via soil and manure loss from the agriculture and livestock sectors respectively, and, to lesser extent as a temporary loss in phosphogypsum stockpiles from the fertiliser production process. The former is permanent in the sense that the phosphorus cannot be recovered for productive reuse in the food production system. The latter is temporary in the sense that phosphorus can theoretically be extracted from phosphogypsum stockpiles. Recovery rates of phosphorus also vary from sector to sector, with the greatest recycling of phosphorus for productive reuse in agriculture occurring in the livestock sector (40%) via manure reuse.

Table 2 – Summary of losses and recovery rates of phosphorus for each key sector (in absolute and percentage terms).

Sector	P losses from sector[a]		P recycled to agriculture[a]		Comments
	kt/a P	Loss (%)[b]	kt/a P	Recycled (%)[c]	
Mining	1	0.5%	N/A	N/A	This loss is not representative (and likely to be much larger based on international studies) as data on losses from mining were not available and some internal recovery of phosphorus within the mining sector could occur
Fertiliser	20	5%	N/A	N/A	Estimate associated with phosphogypsum stockpiles. This is a temporary loss. Recycling within the fertiliser sector was not determined
Agriculture	86	56%	N/A	N/A	Losses are mainly due to soil erosion. Recycling included in Food production sector below; excludes crop residues recirculated within agriculture sector
Livestock	36	21%	27	42%	Includes manure lost or recycled outside of the livestock sector (i.e. excludes manure recycled within the livestock sector); excludes abattoir waste
Food production	12	7%	4	26%	Losses exclude organic waste associated with food production overseas from exported agricultural commodities; excludes abattoir waste due to lack of data
Wastewater	11	61%	7	39%	Includes P in effluent and biosolids either lost to water/landfill/non-soil, or recycled to agriculture
Organic waste	12	74%	4	26%	Caution: double counting with losses/recovery flows from food production, i.e. these are the same absolute flows (kt P/a) as the food production sector, however percentages are expressed as proportion of the organic waste sector

[a] The magnitude (kt/a P) indicates the importance of this flow relative to others in terms of potential measures to improve efficiency, while the loss or recovery rate (expressed as %) indicates the potential scope for increasing phosphorus reuse. It is important to note that these losses and recovery rates only represent outflows from sectors, not losses or recycling that occurs within each sector. For example, recovery rates within agriculture are not included because either crop residues are recirculated with the sector, or, harvested crops recovered as organic waste is calculated in the food production sector.
[b] Loss expressed as a percentage of the *total* outflow from that sector.
[c] Recycling expressed as the percentage of *waste* outflow from that sector that is recirculated to agriculture (as opposed to lost).

4.3.1. *Analytical limitations and opportunities for improvement*

This section highlights aspects that were outside the scope of this study and discusses analytical drawbacks and implications in terms of opportunities for subsequent versions of the model.

Due to the importance of adequate baseline data from which policy recommendations can be made, the quality analysis in Table 1 facilitates future priority data collection. That is, prioritising further collection of data which is indicated as 'insufficient' and starred as important in Table 1, including: phosphorus in mining waste, phosphate rock production and reserves on Christmas Island; changes in percentage phosphorus in fertilisers applied to crop versus pasture systems; percentage phosphorus lost from pastures as crop systems; phosphorus inputs into aquaculture; phosphorus in manure which is reused productively in agriculture; phosphorus content of live animals; phosphorus content of abattoir waste and the proportion that is recycled as blood and bone fertiliser. It is important to note however that SFAs can still be used to draw conclusions even where data availability is poor (Tangsubkul et al., 2005).

While stocks were not calculated in this study, some sectors are likely to have significant stocks. For example, the mining sector has a stock of phosphate rock reserves, currently being depleted at an annual rate of 352 kt/a of P; the agricultural sector's soil stock currently accumulating at a rate of 77 kt P annually; and the livestock sector's accumulation of phosphorus in manure, currently at a rate of 635 kt/a of P. There will also be a significant stock of phosphorus in phosphogypsum stockpiles (the by-product from phosphate fertiliser production) accumulating at some 20 kt/a of P. Stocks that are accumulating over time imply potential opportunities for tapping into these as an alternative source of phosphorus such as soil and phosphogypsum. Stocks that are depleting (such as high grade phosphate rock) imply a need to monitor these sources so that alternative sources can be established before the current sources are depleted. Further, the geospatial variation and biochemical nature of the phosphorus soil stock will affect whether the element can be accessed for its fertiliser value (Schröder et al., 2011; Simpson et al., 2011).

While country-scale SFAs represent national averages, in reality the phosphorus quantities in the Australian food system can also vary geospatially. There can be large discrepancies between the phosphorus use efficiency per unit of land for different types of cropping systems (such as broadacre where grain crops cover large expanses of land relative to horticulture which has a higher rate of fertiliser application over a smaller land area) (FAO, 2007). Further, across different cropping systems and bio-regions of

Australia, soil can have a phosphorus accumulation in some areas, and a deficiency in other areas. There are also large variations in phosphorus inputs, accumulation and phosphorus use efficiency ratios within Australia's livestock sector. These can range from northern grazing systems, which have little to no phosphorus inputs over large expanses of land, to intensive cattle feedlots which have high phosphorus inputs and yields in terms of tonnes per hectare (McIvor et al., 2011; Simpson et al., 2011). Therefore future analyses could subdivide cropping and livestock systems into at least three categories each (such as broadacre, horticulture and 'sustainable compact farming' for the former, and feedlots, fertilised pastures and northern grazing systems for the latter).

Phosphorus use can also vary temporally. While the year 2007 was selected as the static model year due to highest data availability, significant annual variations can occur, particularly within the fertiliser and agricultural sectors. For example, 2007 was a drought year in Australia and hence less fertiliser was applied and wheat production was lower than earlier and latter years (Kirkegaard and Hunt, 2010).

Finally, phosphorus can vary in terms of quality. While an SFA is designed to track the quantity of phosphorus flows, the form of phosphorus (its chemical speciation) will have significant implications in terms of efficiently, cost-effectively and safely producing phosphate fertilisers from virgin or recycled sources. For example, the feasibility of recovering phosphorus from waste or wastewater will be determined not only by the potential magnitude in kt/a of P, but also by its bioavailability and toxicity to plants (Cordell et al., 2011). Even in natural systems, phosphorus chemistry in soils can determine the extent to which phosphorus will be strongly bonded to other compounds in the soil (and hence unavailable to plant roots) versus dissolved in soil solution and hence readily available to plant roots. Therefore an analysis of other such important factors related to quality of phosphorus is a logical next step to complement an SFA. While this was outside the scope of this study, it is a recommended next step.

4.3.2. *Implications for increasing phosphorus security in Australia*

This section discusses the broader sustainability and policy implications of the study. While the previous section has outlined some drawbacks of the current analysis and possible means to overcome them, it is important to balance the need for a solid foundation of current baseline phosphorus flows, whilst simultaneously taking a future-oriented outlook.

The SFA identified that Australia is a net *importer* of phosphorus despite being a net food *exporter*. 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. The results from the Australian Phosphorus Flows model v1.3 are important in identifying intervention points in the system that

Table 3 – Matrix of actions (sustainable phosphorus measures) and goals (phosphorus security in Australia).

GOALS: phosphorus security in Australia	ACTIONS: sustainable phosphorus measures				
	Reconsider profile of agriculture (including exports)	Diversify P sources (i.e. P from rock and other organic sources)	Reconsider diets towards P-efficient foods	Increase phosphorus use efficiency	Increase recycling and reuse of phosphorus
Reduce Australia's dependence on P imports (thereby increasing long-term access to P)	X	X	X	X	X
Reduce Australia's total P demand while maintaining food/ag output (or increase number of people fed per tonne P input)	X		X	X	
Reduce losses and wastage		X		X	X
Reduce eutrophication and pollution				X	X
Ensure healthy soils				X	X
Ensure farmers needs are met (e.g. maintaining or increasing productivity; access to P)	X	X		X	

would increase the resilience, efficiency and 'closed-loop' nature of the food system through measures identified in Table 3. It is important to note that losses can vary widely in degree of their permanence (permanent to temporary), their cause (unavoidable to avoidable), and in turn, the most appropriate management response (efficiency and/or recycling). Schröder et al. (2010, p. 33) provides a typology of phosphorus losses from the food system and sustainable management responses. In general, it is more energy and economically efficient to reduce avoidable losses and increase efficiency first, and implement measures to recycle phosphorus second, as is the case for many resources (von Weizsacker, 1998).

The analysis in the Australian Phosphorus Flows model v1.3 also enables individual sectors and associated stakeholders to assess the key sources and fate of phosphorus within their sector for sector-specific responses. The following paragraphs highlight how such sectors could consider addressing sustainable phosphorus measures to achieve phosphorus security.

The largest phosphorus-demanding sector in Australia is the livestock sector. This represents 63% of total phosphorus demand in Australia.[13] The manure of the 211 million strong head of livestock (ABS, 2007; ALFA, 2007) in Australia together contains 60 times more phosphorus than that in food consumed by the entire Australian population. At the sector level this implies opportunities in the livestock sector to increase phosphorus use efficiency in pastures and feed systems, in addition to a greater need to increase the productive recovery of phosphorus in manure. At a broader system level, this implies a need to reconsider the future role and size of the livestock sector in Australia given the sector's very large phosphorus footprint.

Overall, the embodied phosphorus of meat products is estimated to be three times higher than vegetal products (White et al., 2010). Australia's livestock systems are often regarded as being more resource efficient than their counterparts in Europe or North America because Australian livestock are predominantly grazed on pastures or native grasses rather than lot-fed (Archer, 2011). While Australia's northern grazing systems are indeed phosphorus-efficient because phosphorus inputs are negligible or very low, on the whole, Australia's pasture-fed livestock systems are phosphorus intensive in that large quantities of imported and mined phosphorus fertilisers are required to replenish Australia's naturally phosphorus deficient soils. This suggests a need to further investigate the phosphorus footprint of the key animal products produced in Australia (such as beef, lamb, kangaroo, wool, milk, eggs) and evaluate the benefits and costs to Australian agriculture and the environment of shifting towards more phosphorus-efficient animal products.

The majority of the phosphorus in agricultural commodities produced in Australia is exported. This makes the Australian food system vulnerable because: (a) the phosphorus physically or virtually[14] embodied in the exports cannot be recovered for reuse, and, partly as a consequence of this, (b) substantial quantities of phosphorus must be continually imported into the Australian food system in order to replenish what is exported. This dependence on phosphorus imports into the system means any disruption to the supply of phosphate from international sources could threaten the viability, stability and productivity of the Australian agricultural sector. To mitigate against such a threat, Australia may need to rethink the future profile of the agricultural export industry to improve the overall phosphorus efficiency of such exports. That is, to reduce the phosphorus input required per unit output of export.

The wastewater sector represents a very small fraction (4%) of phosphorus relative to Australia's total phosphorus demand, however this still represents a phosphorus 'hotspot' and a substantial opportunity for sustainable phosphorus management in Australia. This is because the phosphorus is concentrated in toilets, pipes and treatment plants compared to the dispersed nature of phosphorus in soils. Further, nearly 90% of this phosphorus is concentrated in coastal urban areas where the majority of the Australian population reside, creating both a problem in terms of eutrophication risk for estuarine and coastal waters (Tangsubkul et al., 2005), and an opportunity for recovery and reuse. For example, approximately 4 of the 9 kt of P discharged from wastewater treatment plants to the ocean each year comes from a single major city. However it is also important to note that because most of the food and agricultural products produced in Australia are exported and hence consumed overseas, most of the phosphorus consumed and excreted by consumers of Australian food is discharged into wastewater systems in other countries and hence not available for reuse within the Australian food system.

While there is insufficient data on current losses and recovery rates in Australia's phosphate mining sector, opportunities for increased efficiency are likely to exist in Australia and should be investigated. At the global scale, current phosphate mining efficiency has been estimated at approximately 50–80% (Prud'Homme, 2010; Schröder et al., 2010).

In the fertiliser industry, more phosphorus was estimated to be added to phosphogypsum waste stockpiles each year than is consumed in food by the entire Australian population. The magnitude and 'temporary' nature of this phosphorus loss in phosphogypsum indicates a vast opportunity. However due to high radioactivity levels of phosphogypsum,[15] there is a need to explore safe and efficient phosphorus recovery technologies before such hazardous waste can be even considered for safe phosphorus recovery in agriculture. A second potential opportunity in the fertiliser sector is to support and develop a market for renewable phosphate fertilisers (Tilley, 2010). Currently phosphate-rock-based fertiliser producers dominate the Australian phosphate fertiliser industry (White et al., 2010).

Within the agricultural sector the biggest challenge arises from the dependence on fertilisers to maintain soil fertility and crop growth. Although data showed annual trends which

[13] Including phosphorus used to fertilise pastures and feed associated with dairy and beef cattle and broilers.

[14] Virtual phosphorus refers to the amount of phosphorus mined or sourced otherwise to produce a food or agricultural product.

[15] Australian phosphogypsum has 226Ra concentrations of approximately 500 Bq kg^{-1} (Rutherford et al., 1994).

varied significantly in amounts of fertiliser applied, the overall magnitude of phosphorus inputs through fertiliser compared with naturally or locally derived sources such as manure and organic waste was significant. From a supply side approach, alternative forms of fertilisers such as application of manures and creating incentives for recycling of nutrients onsite could not only reduce the vulnerability of farmers to geopolitical shocks such as unexpected price hikes for fertilisers, but also contribute to new business opportunities. On the demand-side, losses can be minimised and phosphorus use efficiency improvements to farm management techniques such as soil testing (Schröder et al., 2011) through education, training and sharing of knowledge such as through communities of practice in conjunction with other land and water management needs will build the capacity of vulnerable groups to respond to possible future challenges.

Apparent losses associated with the production, processing, retail and consumption of food are relatively low compared to upstream sectors, however a substantial part of these losses are likely to be due to avoidable wastage such as spoilage (AIHW, 2012), and hence this presents an opportunity for reducing food processing and prepared food waste. Reducing such food waste also has substantial benefits for other sustainability drivers, such as reducing life-cycle energy and water consumption, costs and other food processing inputs (Institute for Sustainable Futures, 2011). However there will always be some organic waste generated (such as banana peels, rice husks and egg shells) which can be efficiently recovered for its phosphorus and other resource value. Indeed, exploration at the local government level for integrated waste management solutions is increasing, through food waste programmes, waste to energy and community agriculture and gardens (Institute for Sustainable Futures, 2011). This trend provides significant opportunities to investigate more holistically the opportunities for nutrient capture and reuse.

Finally, at the broader policy scale, once intervention points in the food system have been identified and prioritised, appropriate policy instruments (such as targets, regulations, taxes) can be implemented to facilitate recycling and efficiency measures. Further, the assessment of incentives and barriers to farmers, food producers, and all other key sectors to appropriately manage phosphorus within their sector is required. Appropriate infrastructure, institutional arrangements, economic structures and information all need to be addressed. These approaches need to be systemic and collaborative across industry, government, research and academic institutions and communities to identify synergies with other nutrient and pollutant management, land management and water management opportunities.

5. Conclusions

This paper has presented findings from an Australian phosphorus flow analysis—a valuable approach to systematically identifying intervention points in the Australian food system. Conclusions from this study can be drawn both for the Australian situation specifically and the international context generally.

Regarding Australia-specific conclusions, the results of this study indicate that despite being one of the world's few phosphate rock producers and a net food exporter, Australia is still a net phosphorus importer. A significant nutrient resource is therefore being lost from the Australian food system unable to be replenished, increasing the dependency on fertilisers and imports. The majority of phosphorus is used to support Australia's substantial livestock and agricultural export sectors. The PSFA allows potential policy interventions and management options to be identified to address key 'hotspots' of phosphorus losses and waste within the system for this valuable resource. Key opportunities to reduce dependence on imports and reduce losses identified include: increasing manure reuse, phosphorus use efficiency in fertilised pastures, investigating phosphorus recovery from phosphogypsum waste stockpiles and investigating more phosphorus-efficient food and agricultural commodities—particularly to reduce exported and wasted phosphorus whilst maintaining or enhancing productivity.

The study also highlighted that further research is necessary to improve data sets at this scale and therefore the knowledge base of phosphorus flows through key Australian sectors and across different geographic regions and will help facilitate appropriate phosphorus management and mitigation actions.

The findings are relevant to the international context in at least three ways: firstly, with respect to the methodology applied, secondly in relation to implications for other countries with similar food system characteristics and finally, with respect to Australia's role in food security in the Asia-Pacific region.

There is a strong need to assess how countries and regions can respond to the challenge of global phosphorus scarcity. Undertaking country-specific phosphorus flow analyses is important as the nature of phosphorus use, magnitude of flows and fate in a given food system will differ from country to country and differ in terms of key intervention points. Further there is a strong need for an integrated assessment of phosphorus flows between sectors (such as fertiliser, food and sanitation sectors) in order to decrease losses and increase efficiency and recycling of phosphorus in the most appropriate places within the food system. The approach taken in this study can and is being used in other countries and regions to support national phosphorus management strategies.

This research highlighted the valuable role a national substance flow analysis can play to identify and value losses and waste within a national food system allowing country-specific intervention points to be identified. While specific results from one country are not directly transferable to another country (as noted above), some general conclusions can be made for other countries. For example, there is likely to be a need in all countries to reduce losses, increase recycling and improve efficiency to some extent. Further, more explicit parallels relating to risks and opportunities for sustainable management may also be drawn for countries with similar characteristics and trends to Australia, such as: dependency on imports, net food producer, the profile and importance of agriculture to the economy, land-use patterns, exports and meat and livestock production.

Finally, Australia's substantial dependency on phosphate imports leaves the country's role in the region as a 'foodbasket' vulnerable to future phosphorus scarcity. It is unclear whether Australia could continue to feed three times its' population in a phosphorus-constrained (and climate varied) future under the business-as-usual food production model. Sustainable phosphorus measures need to be implemented (supported by appropriate policy) to increase the resilience of the Australian food system both for domestic food production and food security in export partner countries, particularly in North and South East Asia.

Acknowledgements

This research was funded by the Rural Industries Research & Development Corporation (RIRDC), a Mercedes-Benz Banksia Environmental Research Award and through in-kind support from the University of Technology, Sydney. In addition to these supporters, the authors would like to thank the members of the National Strategic Phosphorus Advisory Group for generously offering their time, expertise, discussion and review. Finally, the authors would like to thank the other members of the Phase 1 of the Australian Sustainable Phosphorus Futures project on which this paper was based, including: Chris Cooper, Louise Boronyak, Dr Steve Mohr, Monique Retamal and Dustin Moore.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.envsci.2013.01.008.

REFERENCES

ABARE, 2007a. Australian mineral statistics December quarter 2007, Commonwealth of Australia.

ABARE, 2007b. Feedgrains, Regional demand and supply in Australia, Table 11, p. 14.

ABARE, 2008. Australian mineral statistics December quarter 2008, Commonwealth of Australia.

ABARE, 2009. Australian mineral statistics December quarter 2009, Commonwealth of Australia.

ABARE, 2010. Australian mineral statistics December quarter 2010, Commonwealth of Australia.

ABARES, 2010a. Australian mineral statistics September quarter 2010, Commonwealth of Australia, p. 32, available at: http://adl.brs.gov.au/data/warehouse/pe_abares99001765/AMS10.4_Septqtr_REPORT.pdf accessed 17 January 2012.

ABARES, 2010b. Agricultural Commodity Statistics, p. 154.

ABARES, 2010c. Australian Commodity Statistics. Table. 111, p. 110.

ABARES, 2011a. Agricultural Commodity Statistics 2011. Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES), Department of Agriculture, Fisheries and Forestry, Australian Government, Canberra.

ABARES, 2011b. Australian mineral statistics 2011: tabular data, Commonwealth of Australia, available at: http://adl.brs.gov.au/data/warehouse/pe_abares99001797/ams_dec10_tables.xls, accessed 17 January 2012.

ABS, 1996. 4606.0—Sustainable Agriculture in Australia, 1993–94. Australian Bureau of Statistics (ABS), Canberra Available: http://www.abs.gov.au/AUSSTATS/abs@.nsf/mf/4606.0.

ABS, 2007–2010 Agricultural Commodities Australia. Available at ttp://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/7121.02009-10?OpenDocument.

ABS, 2007. Agricultural Commodities, Australia, 2006–07, ABS 7121.0. Australian Bureau of Statistics, Australian Government, Canberra.

ABS. 7121.0—Agricultural Commodities, Australia, 2006–07.

ABS, 2011a. Agricultural Commodities, Australia, 2009–10. ABS cat. no. 7121.0. Australian Bureau of Statistics (ABS), Canberra.

ABS, 2011b. 3218.0 Regional Population Growth, Australia. Table 8. Estimated Resident Population, State and Territory Summary. Available at http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/3218.02009-10?OpenDocument.

AIHW, 2012. Australia's Food & Nutrition 2012. Cat. no. PHE 163. Australian Institute of Health and Welfare, Australian Government, Canberra, ISBN: 978-1-74249-323-7, 250pp.

ALFA, 2007. ALFA/MLA Feedlot Survey. Australian Lot Feeders' Association (ALFA) and Meat and Livestock Australia (MLA) National Accredited Feedlot Survey, Sydney.

Archer, M., 2011. Ordering the vegetarian meal? There's more animal blood on your hands. The Conversation. http://theconversation.edu.au/ordering-the-vegetarian-meal-theres-more-animal-blood-on-your-hands-4659/.

Australia New Zealand Biosolids Partnership, 2009. Biosolids Production and End Use in Australia, Australian Water Association. Available at http://www.biosolids.com.au/bs-australia.php

Bekunda, M., Cordell, D., Corman, J., Rosemarin, A., Salcedo, I., Syers, K., Lougheed, T., 2011. Phosphorus & Food Production, UNEP Yearbook: Emerging issues in Our Global Environment, 2011. United Nations Environment Programme, Paris. , In: http://www.unep.org/yearbook/2011.

Brunner, P., Baccini, P., 1991. Metabolism of the Anthroposphere. Springer, Berlin/Heidelberg/New York.

Brunner, P.H., 2010. Substance flow analysis as a decision support tool for phosphorus management. Journal of Industrial Ecology 14 (6), 870–873.

Brunner, P.H., Rechberge, H., 2004. Practical Handbook of Material Flow Analysis. Lewis Publishers, Boca Raton, FL, ISBN: 1-5667-0604-1, 2003, 332 pages.

CEEP (Centre European d'Etudes des Polyphosphates), 1993, Phosphorous removal from wastewater in the EU: Chapter 4—The impact of phosphorus removal from wastewater, pp. 31-35. Imperial College London.

Commonwealth of Australia, 2001. Australian Agriculture Assessment 2001. National Land and Water Resources Audit c/o Land & Water Australia, Canberra. , In: http://www.anra.gov.au/topics/agriculture/pubs/national/agriculture_contents.html.

Cordell, D., 2010. The story of phosphorus: sustainability implications of global phosphorus scarcity for food security. Doctoral Thesis, Institute for Sustainable Futures, University of Technology, Sydney (UTS) & Department of Thematic Studies—Water and Environmental, Linköping University, Sweden, Linköping University Press, No. 509, ISBN: 9789173934404.

Cordell, D., Drangert, J.-O., White, S., 2009a. The story of phosphorus: global food security and food for thought. Global Environmental Change 19 (May), 292–305.

Cordell, D., Neset, T.-S., Prior, T., 2012. The phosphorus mass balance: identifying 'hotspots' in the food system as a roadmap to phosphorus security. Current Opinion in Biotech, http://dx.doi.org/10.1016/j.copbio.2012.03.010.

Cordell, D., Neset, T.S.S., White, S., Drangert, J.-O., 2009b. Preferred future phosphorus scenarios: A framework for

meeting long-term phosphorus needs for global food demand. In: Mavinic, D., Ashley, K., Koch, F. (Eds.), International Conference on Nutrient Recovery from Wastewater Streams Vancouver, 2009. IWA Publishing, London, ISBN: 9781843392323.
Cordell, D., Rosemarin, A., Schröder, J.J., Smit, A.L., 2011. Towards global phosphorus security: A systems framework for phosphorus recovery and reuse options. Chemosphere 84 (6), 747–758.
Cordell, D., White, S., 2010. Securing a sustainable phosphorus future for Australia. Farm Policy Journal 7 (3), 1–17.
Cordell, D., White, S., 2011. Peak phosphorus: clarifying the key issues of a vigorous debate about long-term phosphorus security. Sustainability 3 (10) 2027–2049, 2071–1050In: http://www.mdpi.com/journal/sustainability.
Crawford, G., Daigger, G., Erdal, Z. 2006. Enhanced Biological Phosphorous removal within membrane bioreactors, WEFTEC 06. Paper online: http://www.environmental-expert.com/Files/5306/articles/8912/146.pdf.
DAFF. (2007). Australian Food Statistics, 2006.
DAFF, 2012. Australian food statistics 2010–11. Department of Agriculture, Fisheries and Forestry, Canberra.
DEWHA. (2006). Australia State of the Environment 2006, 7.2 Assessment of river health.
FAO, 2007. Fertistat Fertiliser Use Statistics: Australia 2000 (Application rates). Food & Agricultural Organisation of the United Nations, In: http://www.fao.org/ag/agp/fertistat/index_en.htm.
FAO. (1992). Wastewater treatment and use in agriculture. Food and Agriculture Organization of the United Nations, Rome.
FAO. (2006). Plant nutrition for food security: A guide for integrated management, FAO fertilizer and plant nutrition bulletin 16, Food and Agriculture Organization of the United Nations, Rome.
FAO. (unknown). The composition of fish. Available at: http://www.fao.org/wairdocs/tan/x5916e/x5916e01.htm.
FAOSTAT. (2011).Online database for live animal data. Accessed December 2011, available at: http://faostat.fao.org/site/573/DesktopDefault.aspx?PageID=573#ancor.
Fisheries Research and Development Corporation. (2011). Response to the National Food Plan issues paper, p8.
FIFA. (2007). Fertiliser Industry Environment Report 2006.Available at: http://www.fifa.asn.au/default.asp?V_DOC_ID=1000.
FIFA. (2008). Fertiliser Industry Environment Report 2007.Available at: http://www.fifa.asn.au/default.asp?V_DOC_ID=1001.
FIFA (2009). Fertilizer Industry Environment Report 2008, Fertilizer Industry Federation of Australia, Inc., Table. 4, p. 11, available at http://www.fifa.asn.au/files/pdf/publications/2008%20Fertilizer%20Industry%20Environment%20Report.pdf.
FIFA. (2010). Fertilizer Industry Environment Report 2009, Fertilizer Industry Federation of Australia, Inc., Table. 4, p. 11, available at http://www.fifa.asn.au/files/pdf/publications/Fertilizer%20Industry%20Environment%20Report%20%202009.pdf.
FIFA. (2011). Fertiliser Industry Environment Report 2010. Available at: http://www.fifa.asn.au/default.asp?V_DOC_ID=1002.
GE Power & Water, 2012, ZeeWeed Membrane Bioreactor, http://www.gewater.com/products/equipment/mf_uf_mbr/mbr.jsp.
Gilbert, N., 2009. The Disappearing Nutrient. Nature 461 (October), 716–718.
Gumbo, B., 2005. Short-cutting the phosphorus cycle in urban ecosystems. PhD thesis, Delft University of Technology and UNESCO-IHE Institute for Water Education, Delft.
Heffer, P., 2009. Assessment of fertilizer use by crop at the global level. International Fertilizer Industry Association (IFA), Paris, January 2009, AgCom/09/28.
Hoffman, N., Beaulieu, M. (2001). A Geographical Profile of manure production in Canada, 2001. Table A1.
Hyder Consulting. (2008). Waste and Recycling in Australia Report. Prepared for the Department of Environment, Water, Heritage and Arts.
IAASTD, 2008. International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD), agreed to at an Intergovernmental Plenary Session in Johannesburg, South Africa in April, 2008, http://www.agassessment.org.
IFA. (2012) 'Conversion factors', International Fertilizer Industry Association, available at http://www.fertilizer.org/ifa/HomePage/STATISTICS/Conversions-factors.
Institute for Sustainable Futures, 2011. National Food Waste Data Assessment. Institute for Sustainable Futures, University of Technology Sydney, prepared for the Department of Sustainability, Environment, Water, Population and Communities, Sydney. , In: http://www.environment.gov.au/wastepolicy/publications/food-waste.html.
Jasinski, S.M., 2012. Phosphate rock, mineral commodity summaries. US Geological Survey, January 2012.
Kirkegaard, Hunt, 2010. Increasing productivity by matching farming system management and genotype in water-limited environments. Journal of Experimental Botany 61 (15), 4129–4143.
Lenntech, 2011, Phosphorous Removal from Wastewater, http://www.lenntech.com/phosphorous-removal.htm.
Lindquist, A. 2003, About Water Treatment, Kemira, Sweden, 2003.
Liu, Y., 2005. Phosphorus flows in China: physical profiles and environmental regulation. PhD thesis, Wageningen University, Wageningen, ISBN 90-8504-196-1.
Livecorp. (2012) Pers. Comm. 21/2/2012.
McIvor, J.G., Guppy, C., Probert, M.E., 2011. Phosphorus requirements of tropical grazing systems: the northern Australian experience. Plant Soil 2011 349, 55–67.
McLaughlin, M., Fillery, I., Till, A., 1992. Operation of the phosphorus, sulphur and nitrogen cycles. In: Gifford, R., Barson, M. (Eds.), Australia's Renewable Resources: Sustainability and Global Change. Bureau of Rural Resources Proceedings No. 14, pp. 67–116.
Mekala, G.D., Davidson, B., Samad, M., Boland, A.M. 2008. Wastewater reuse and recycling systems: A perspective into India and Australia. Colombo, Sri Lanka: International Water Management Institute. 35p.(IWMI Working Paper 128).
Mitchell, R.B., Clark, W.C., Cash, D.W., Dickson, N.M., 2006. Global Environmental Assessments: Information and Influence. MIT Press, Cambridge.
National Water Commission, 2008, National Performance Reports data, http://www.nwc.gov.au/__data/assets/pdf_file/0014/11462/NPR_Part_A_complete.pdf.
NHMRC. (2003). Dietary Guidelines for Australian Adults. Prepared for the Commonwealth of Australia, 2003. Weighted average of P intake, p7.
National Health and Medical Research Council. NSW DPI. (2007) Primefacts 522, Mineral Contect of Common Ruminant Stockfeeds, Crops and Pastures. Table 1. Mineral analysis of feeds.
Pellerin, S., 2011. Designing phosphorus cycle at country scale. European Scientific Workshop, Bordeaux, France, July 5–6, 2011, http://www.bordeaux-aquitaine.inra.fr/tcem_eng/seminaires_et_colloques/colloques/designing_phosphorus_cycle_at_country_scale.
PMSEIC, 2010. Australia and Food Security in a Changing World: Can we feed ourselves and help feed the world in the future?

Report of the PMSEIC Expert Working Group, Canberra, October.
Prud'Homme, M., 2010. World phosphate rock flows, losses and uses. In: Phosphates 2010 International Conference. International Fertiliser Industry Association, Brussels.
Recycled Organics Unit. (2007). Organics Recycling in Australia: Industry Statistics 2007. Report prepared for Compost Australia by the Recycled Organics Unit. http://www.recycledorganics.com/publications/surveyreports/Organics%20recycling%20in%20Australia%202007%20final.pdf.
Rutherford, P.M., Dudas, M.J., Samek, R.A., 1994. Environmental impacts of phosphogypsum. Science for the Total Environment 149 (1–2), 1–38.
Schröder, J.J., Cordell, D., Smit, A.L., Rosemarin, A., 2010. Sustainable Use of Phosphorus. EU Tender ENV.B.1/ETU/2009/0025, Plant Research International Report 357.
Schröder, J.J., Smit, A.L., Cordell, D., Rosemarin, A., 2011. Improved phosphorus use efficiency in agriculture: a key requirement for its sustainable use. Chemosphere 84 (6), 822–831.
Senthilkumar, K., Nesme, T., Mollier, A., Pellerin, S., 2012. Conceptual design and quantification of phosphorus flows and balances at the country scale: the case of France. Global Biogeochemical Cycles 26, GB2008.
Simpson, R., Oberson, A., Culvenor, R.A., Ryan, M., Veneklaas, E., Lambers, H., Lynch, J., Ryan, P., Delhaize, E., Smith, A., Smith, S.E., Harvey, P., Richardson, A., 2011. Strategies and agronomic interventions to improve the phosphorus-use efficiency of farming systems. Plant & Soil 349, 89–120.
Smil, V., 2002. Phosphorus: global transfers. Encyclopedia of Global Environmental Change, 3 'Causes and consequences of global environmental change', Prof Ian Douglas (Ed), 536–542.
Tangsubkul, N., Moore, S., Waite, T.D., 2005. Incorporating phosphorus management considerations into wastewater management practice. Environmental Science and Policy 8, 1–15.
Tilley, E., 2010. Phosphorus and sanitation. In: Neset, T.S., Cordell, D. (Eds.), Phosphorus and Global Food Security: A synthesis, International workshop proceedings, Global Phosphorus Research Initiative. Linköping University, 12/24/2010In: http://www.ep.liu.se/ecp_home/index.en.aspx?issue=053.
US Geological Survey. (2010) U.S. Geological Survey Minerals Yearbook—2010. http://minerals.usgs.gov/minerals/pubs/country/2010/myb3-2010-as.pdf.
von Weizsacker, E.U., 1998. Factor Four: Doubling Wealth, Halving Resource Use—A Report to the Club of Rome. Earthscan, London.
Weaver, D.M., Wong, M.T.F., 2011. Scope to improve phosphorus (P) management and balance efficiency of crop and pasture soils with contrasting P status and buffering indices. Plant Soil 349, 37–54.
White, S., Cordell, D., Moore, D., 2010. Securing a sustainable phosphorus future for Australia: implications of global phosphorus scarcity and possible solutions, prepared by the Institute for Sustainable Futures, University of Technology, Sydney, for CSIRO Sustainable Agriculture Flagship, Sydney.

Dr Dana Cordell is a research principal at the Institute for Sustainable Futures, University of Technology Sydney. She co-founded the Global Phosphorus Research Initiative (GPRI) www.phosphorusfutures.net in 2008 with colleagues in Sweden and Australia as an outcome of her doctoral research on the 'Sustainability implications of global phosphorus scarcity for food security'. In addition to undertaking interdisciplinary research, GPRI aims to facilitate networking and awareness-raising among policy-makers, industry, other scientists and the public regarding sustainable phosphorus use and food security. Dana also has 11 years of sustainability research experience leading and undertaking interdisciplinary sustainable water, sanitation and waste management projects.

Melissa Jackson is a senior researcher at the Institute for Sustainable Futures, University of Technology Sydney. Melissa project manages the Australian Sustainable Phosphorus Futures research project at the Institute and helped establish the National Strategic Phosphorus Advisory Group. Melissa has 8 years of experience managing and undertaking sustainability projects as a researcher, consultant and strategist. Her expertise in energy and climate change mitigation and adaptation, futures studies and change management is applied to transdisciplinary sustainability projects such as behaviour change for energy, food, transport and waste with the aim of creating sustainable future through reduced consumption.

Professor Stuart White is the director of the Institute for Sustainable Futures at the University of Technology, Sydney. He has researched and published on resource efficiency issues for over 20 years, with a focus on the potential of efficiency measures to reduce demand for resources. He was a co-founder of the Global Phosphorus Research Initiative. His interest in the sustainable use of phosphorus started with growing up on a farm in Western Australia.