Securing a sustainable phosphorus future for Australia:

Implications of global phosphorus scarcity and possible solutions

Stuart White, Dana Cordell and Dustin Moore

Prepared by

Institute for Sustainable Futures, University of Technology, Sydney

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ABBREVIATIONS

EDR	Economic Demonstrated Resource (see Appendix C)
FIFA	Fertiliser Industry Federation of Australia
IFA	International Fertilizer Industry Association
kt	thousand tonnes
Mt	million (metric) tonnes
P	Phosphorus
Reserve	USGS classification of economic and technically feasible part of a mineral resource

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1 INTRODUCTION

Food production is fundamentally dependent on inputs of key natural resources, including water, energy and nutrients. Meeting the needs of a growing world population means agricultural fields will need to expand or intensify, either way requiring more fertilisers, including phosphorus (FAO, 2006). Unlike energy and water resources, there is very little discussion, research and policies that addresses long-term availability and accessibility of phosphorus for global food production. Yet the world's main source of phosphorus – phosphate rock – is declining in both quantity and quality. Indeed, peak phosphorus is anticipated in the coming decades, after which demand will exceed supply.

Phosphorus scarcity will affect regions and countries in different ways, depending on degree of dependence on phosphate, level of food insecurity, degree of phosphorus pollution and other geopolitical and socio-economic factors. While Australia does not suffer from widespread food insecurity, it is a net food-producing country with an agricultural system increasingly dependent on imported phosphate. Australia has some of the world's most naturally phosphorus deficient soils, yet we have simultaneously invested in heavily phosphorus demanding export industries, like beef, sheep and wheat (ABS, 1996). At the same time, phosphorus leaking from agricultural fields and wastewater effluent is the main cause of the growth of algal blooms which can seriously pollute our waterways.

Global phosphorus scarcity is likely to threaten the world's ability to meet growing food demand without changes to the current phosphorus use trajectory (Cordell, 2010). The elemental link to producing food means future phosphorus scarcity may be as significant a global a threat as climate change and water scarcity. Yet our leaders simply don't have a plan for how to respond to phosphorus scarcity, or understand the implications for their citizens, economy, farmers and environment. Australia's policy makers will therefore need to ensure a phosphorus secure future, in addition to an energy- and water-secure Australia.

2 PHOSPHORUS: LIFE'S BOTTLENECK

Phosphorus is one of the most important elements for humanity, because it underpins our ability to produce food. Phosphorus, together with nitrogen and potassium, is an essential element for all living organisms – including plants, animals, bacteria and is a key ingredient in fertilisers (ref). There is no substitute for phosphorus in crop growth. That is, without phosphorus, we cannot produce food.

Historically, most of the world's farmers relied on natural soil-phosphorus to grow crops (with local additions of manures and human excreta). However increased famine and soil degradation particularly in Europe led to a search for external sources of phosphorus fertilisers, including phosphate rock and guano. Phosphate rock was seen as a cheap and infinite source of phosphorus and it became widely used in favour of organic sources. The widespread use of guano and phosphate rock contributed to increased global crop yields and saving billions from starvation over the past half-century. Today, humanity is effectively dependent on mined phosphate rock to maintain high crop yields. Feeding the currently 1 billion hungry mouths in the world plus an additional 3 billion by 2050 is predicted to require at least a doubling of crop yields largely due to intensification of existing agricultural land, which will increase fertiliser needs (FAO, 2006).

3 PEAK PHOSPHORUS: A NEW GLOBAL CHALLENGE FOR FOOD SECURITY

Like oil, phosphate rock is a non-renewable resource and the supply of high-grade reserves are becoming increasingly scarce while demand for phosphorus is expected to increase in the long-term. The element phosphorus is not in itself 'running out' or finite – there will always be the same number of phosphorus molecules circulating the earth. Indeed, phosphorus is the 11th most abundant element in the earth's upper crust. However the amount available to humans for productive use in food production is orders of magnitude smaller, due to physical, energetic, economic, geopolitical, biological and other constraints (Cordell, 2010).

The world's remaining phosphate reserves are more difficult to access, are contaminated with more heavy metals (e.g. Cd, U) and contain lower concentrations of phosphorus (% P_2O_5) (Prud'Homme, 2010). Current reserves are expected to be depleted in 50-100 years (Table 1), depending on future demand increases.

Table 1. Estimates of lifetime of current world phosphate rock reserves by different authors.

Author	Estimated lifetime of reserves	Estimated year of depletion*	Assumptions
Tweeten (1989)	**61 years**	2050	Assumes 3.6% increase in demand; in Runge-Mertzger (1995)
(Runge-Metzger, 1995)	**88 years**	2083	Assumes 2.1% increase, based on 1992 World Bank/FAO/UNIDO/ Industry Fertilizer Working Group
(Steen, 1998)	**60-130 years**	2058 - 2128	Based on range of 2-3% increase demand rates, plus a 'most likely' 2% increase until 2020 and 0% growth thereafter if efficiency and reuse measures are implemented.
(Smil, 2000)	**80 years**	2080	At 'current rate of extraction'
Fixen (2009)	**93 years**	2102	At 2007-2008 production rates
(Smit et al., 2009)	**69-100 years**	2078 - 2109	Assuming 0.7-2% increase until 2050, and 0% increase after 2050.
(Vaccari, 2009)	**90 years**	2099	At 'current rates'

* year of depletion assumes lifetime estimated from date of publish.

However, as with oil, the important point is not when 100% of the reserve is depleted, but when the production rate reaches a peak, based on the finite nature of non-renewable resources (Hubbert, 1949). The production of phosphate rock will eventually reach a peak due to the economic constraints of accessing more difficult and lower quality layers. Based on current estimates of reserves, and demand growth, peak phosphorus is estimated to occur around 2035 (figure 1). Whilst the data reliability is disputed and hence the exact timeline of the peak may vary, the underlying problem remains the same. A fundamental notion behind peak theory is that as production of a critical mineral resource shifts from mining the 'cheap and easy' resource, to 'difficult and complex' layers (Giurco et al., 2010) growing and unchecked demand will outstrip the economically available production at some point, despite advances in technology and efficiency. There are currently no alternatives on the market today that could replace the large demand for phosphate rock at any significant scale (Cordell et al., 2009a).

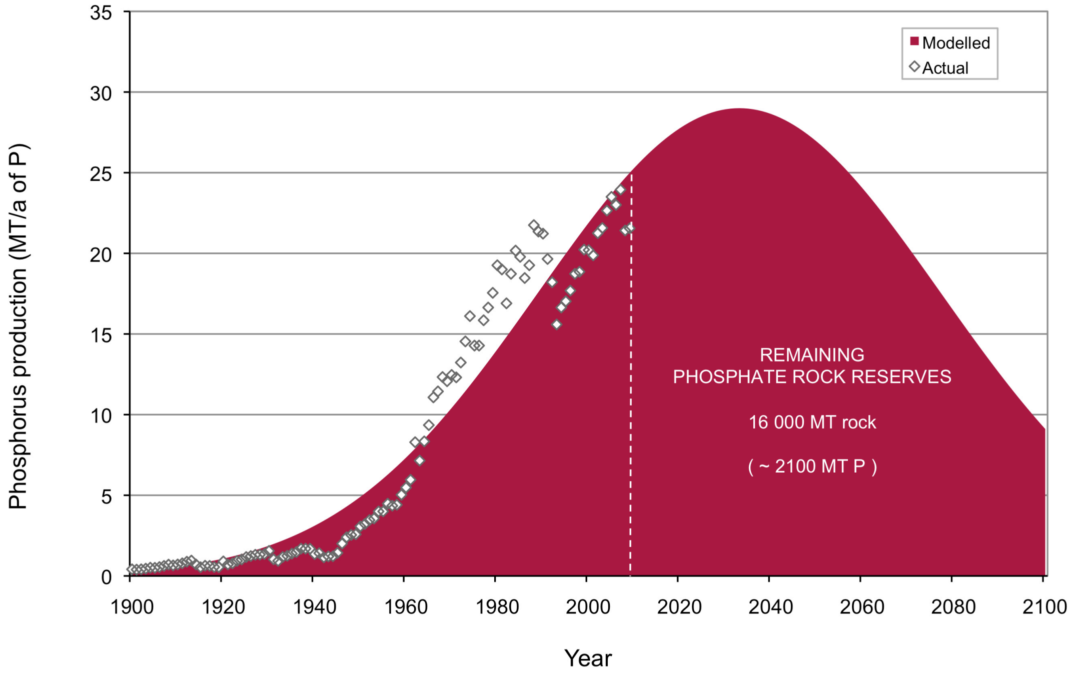

Figure 1: Peak phosphorus: global production of phosphate rock reserves is estimated to peak 2033 at 29 million tonnes of P/yr (equivalent to approximately 220 million tonnes of phosphate rock) while demand will continue to increase. Source: Cordell et al (2009a)

The unprecedented 800% price spike of phosphate rock and other fertiliser commodities in 2008 resulted in increased interest and investment in exploration of new phosphate rock deposits and commissioning of new mines, most notably in Saudi Arabia, Australia and seafloor sediments off the coast of Namibia (Jasinski, 2009; Drummond, 2010; Jung, 2010). While these may increase the overall tonnages of world phosphate rock reserves in the coming years, the quality and accessibility of these reserves are markedly lower than current reserves. Important here is that mining lower grade phosphate rock resources, or phosphate found on continental shelves will involve substantial environmental and economic costs due to difficultly of physical accessibility and/or increased processing resources and costs. That is, extracting the same nutrient value from rock will increasingly require more inputs of energy, raw materials and costs, while resulting in increased volumes of waste and pollution.

There are substantial environmental concerns associated with the mining and use of phosphorus in the global food system. These range from the risk of transferring naturally present radionuclides of uranium and thorium from phosphate rock to agricultural soils; to the generation of a radioactive by-product phosphogypsum during phosphoric acid production which must be stockpiled (USGS, 1999); to the life cycle energy associated with transporting 30 million tonnes of phosphate annually from distant mine to the farm gate[1]; and finally to the widespread pollution of waterways from phosphorus runoff.

The availability of phosphorus is also constrained by a scarcity of *management*. That is, phosphorus is also scarce due to inefficient management throughout the food production and consumption system. For example, while the global population consume around 3 million tonnes of elemental phosphorus in the food we eat, we mine approximately five times this

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[1] For example, phosphate fertilisers applied to Australian agricultural soils may have started as rock in Western Sahara's Boucraa mine, transported to the Moroccan controlled port of Laayoune Plage via the world's longest conveyor belt, shipped to the US for processing into MAP or DAP fertilisers, and subsequently shipped to ports in Australia, then overland to the end-user.

amount (14.9 Mt/a of P) in phosphate rock specifically for food production (Cordell et al., 2009a). Phosphorus is lost during mining and processing, transport, fertiliser application, food processing and retail, food preparation and consumption. While there has been a general awareness of the large losses occurring at the farm, related to phosphorus pollution due to erosion and runoff from fields to waterways, there has been less awareness of losses that occur after the field, with around 50% lost from the global food system after harvest. Substantial amounts of food and organic material are wasted (containing approximately 1.2 Mt/a of P) during food processing, retailing (e.g. supermarkets, restaurants) and consumption (e.g. in households).

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

Geopolitical scarcity can further restrict the availability of phosphorus resources in the short- or long-term. For example, while all farmers need access to phosphorus, 85% of the world's remaining phosphate rock reserves are controlled by five countries, mainly Morocco and China (figure 2) (Jasinski, 2010). In 2008 China imposed a 135% export tariff to secure domestic supply for food production (Fertilizer Week, 2008); a move which essentially halted exports from the region overnight. The US is expected to deplete its own high-grade reserves in the coming decades and increasingly imports rock phosphate from Morocco. However Morocco currently occupies Western Sahara and controls that region's extensive reserves in defiance of UN resolutions (Corell, 2002). Trading with Moroccan authorities for Western Sahara's phosphate rock is condemned by the UN, and importing phosphate rock via Morocco has been boycotted by several Scandinavian firms (Hagen, 2008).

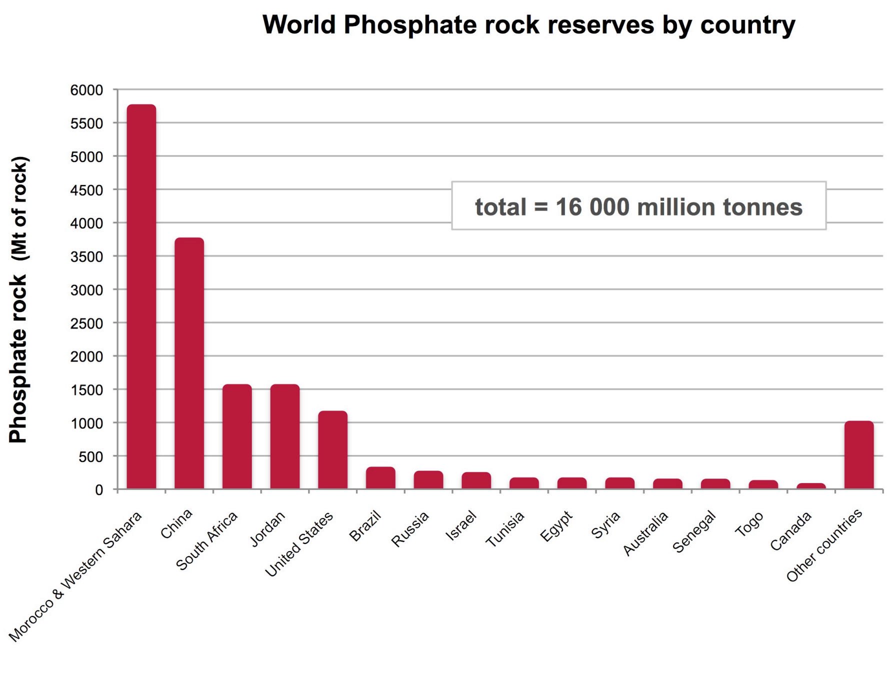

Figure 2: Geographical distribution of remaining phosphate rock reserves, indicating 85%

controlled by Morocco, China, South Africa, Jordan and United States. Data: USGS 2010.

Finally, *institutional* scarcity is also inhibiting the productive use of phosphorus by humans. That is, there is a lack of effective policies and actors explicitly governing global phosphorus resources to ensure availability and accessibility of phosphorus for food security, both in the short- and long-term (Cordell, 2010). There is a concerning lack of available, reliable and consistent data on global phosphorus resources and consumption patterns in the global food system upon which a) researchers, scientists and observers can base analyses and b) phosphorus users, producers and policy-makers can make informed decisions. The information that is available is not independent, transparent or trustworthy (Cordell, 2010).

The lack of effective global governance is compounded by a lack of stakeholder consensus on the issues and fragmentation of institutional arrangements. While phosphorus is relevant to numerous different sectors (for example, a 'commodity' in the mining sector, a 'pollutant' in the water and wastewater sector) phosphorus *scarcity* is currently not a priority within any sector, and hence long-term phosphorus security has no obvious home in any sector. Phosphorus is by default governed by the market system, which may be appropriate for efficiency of trade, but is not sufficient to adequately address the much broader sustainability requirements, such as access to phosphorus for all farmers, the finite nature of phosphate rock resources and long-term security (Cordell, 2010).

Global demand for phosphorus is expected to increase over the medium term at 2-3% p.a. (FAO, 2007; Heffer and Prud'homme, 2008). While fertiliser demand has been stabilizing in the developed world due to previous decades of over application, the demand in emerging and developing economies like China, India and Brazil is anticipated to soar over the coming decades, resulting in an increased demand for phosphorus globally. This increase in the future overall global demand for phosphorus is due to increasing:

- global population (9 billion expected by 2050 (UN, 2007);
- per capita phosphorus demand – (largely due to changing diets towards more phosphorus-intensive foods such as meat and dairy products) (FAO, 2008);
- fertiliser demand for non-food uses such as biofuels production (IFA, 2008);
- soil fertility needs[2]; and
- need for farmer access to fertilisers[3].

If no action is taken now to ensure long-term phosphorus availability and accessibility, a hard-landing response to phosphorus scarcity is likely to result in a situation of increased: energy and raw material consumption; production and processing costs; waste and pollution; short-term price spikes; long-term phosphate prices; geopolitical tensions; and a reduction in farmer access to fertiliser markets, which in turn will lead to reduced global crop yields and increased global hunger (Cordell, 2010).

Averting a crisis, or a 'hard landing', is possible, but will likely require substantial physical and institutional changes. There is no single solution to meeting future phosphorus needs for global food production, rather, an integrated approach will be required that seeks to combine a range of supply- and demand-side measures. A preliminary future scenarios analysis (Cordell et al., 2009b) indicated that if the business-as-usual global phosphorus demand could

[2] Many of the world's agricultural soils are phosphorus deficient, and FAO estimate that 80% of the growth in food production will need to come from intensification of existing farmland (i.e. improving productivity), rather than clearing natural landscapes for farming (FAO 2006). Significant phosphorus applications will be required to ensure all the world's soils have reached optimal or 'critical' levels, after which it will only be necessary to apply what is taken away in harvests (Koning et al 2008)

[3] There are many farmers today that currently cannot access fertiliser markets due to low purchasing power. However many of these farmers are working with phosphorus deficient soils, hence representing a significant 'silent demand'.

be reduced by around 70% (through demand-side measures of changing diets and phosphorus use efficiency in agriculture and the food chain), the remaining 30% could be met through a high recovery and reuse rate of all sources of phosphorus (manure, human excreta, crop residues, food waste etc).

4 VULNERABILITY OF AUSTRALIA TO PHOSPHORUS SCARCITY

While Australia does not suffer from widespread food insecurity per se, it is still vulnerable to future global phosphorus scarcity in a number of ways, including ecologically, economically, geopolitically and environmentally.

Australia is a net food-producing country, feeding approximately 60-70 million people a year (ABS, 1996; Williams, 2010). While agriculture represents only 3% of GDP, Australian agricultural exports play an important role in the global trade of agricultural commodities (ABS, 1996). However many of these agricultural export commodities (such as beef and live sheep exports) require substantial amounts of phosphate fertiliser input per unit output (demonstrated in section 5.X). According to ABARE (2009), red meat production and live exports[4] alone account for approximately 22-29% of the total gross value of Australian agricultural production. Australian agriculture is therefore currently dependent on phosphorus-intensive agricultural exports. This vulnerability is compounded by the fact that most Australian soils are naturally phosphorus-deficient due to extensive weathering, fragile soils and shallow top soils (Commonwealth of Australia, 2001), and thus require substantial additions of phosphate fertilisers derived from both domestic and imported phosphates.

This unsustainable phosphorus use patter began when European settlers arrived in Australia centuries ago and continued Northern Hemisphere agricultural practices, rather than observing and learning from the land practices of Australia's indigenous population. These European practices were more appropriate for richer soils. By the 20th Century, continual harvesting and grazing had depleted the little soil phosphorus that naturally existed in most Australian soils (ABS, 1996).

Cheap, high-grade, and readily available Nauruan guano[5] phosphate was subsequently discovered and developed by the British Phosphate Commission[6] and Australia's agricultural productivity was 'revolutionised' (Garrett, 1996). This led not only to exploitation of 80% of Nauru's non-renewable guano deposits but also resulted in the displacement of local populations to other Pacific islands. Superphosphate processed from guano became the most commonly used fertilisers in Australia to replenish soil phosphorus. Indeed, Australia's fertiliser use for many decades was almost entirely dependent on imported phosphate from Nauru (and Christmas Island), as indicated in figure 3. The Australian government offered fertiliser subsidies to boost agricultural exports in the post World War II era and fertiliser demand increased rapidly[7] (Lodi News-Sentinel, 1974). Agricultural production doubled between 1950 and 1980.

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[4] Red meat includes beef cattle, sheep, goats and buffalo; live exports include sheep and cattle.

[5] Guano is the excreta from bird and bats that have been deposited over thousands of years, first discovered off the Peruvian Coast.

[6] The British Phosphate Commission was a joint venture between New Zealand, Australia and Britain.

[7] The two troughs in fertilizer use in the early 1970's may have been influenced by the temporary removal of the fertiliser subsidy by the Whitlam Government in 1973 (Lodi News-Sentinel, 1974).

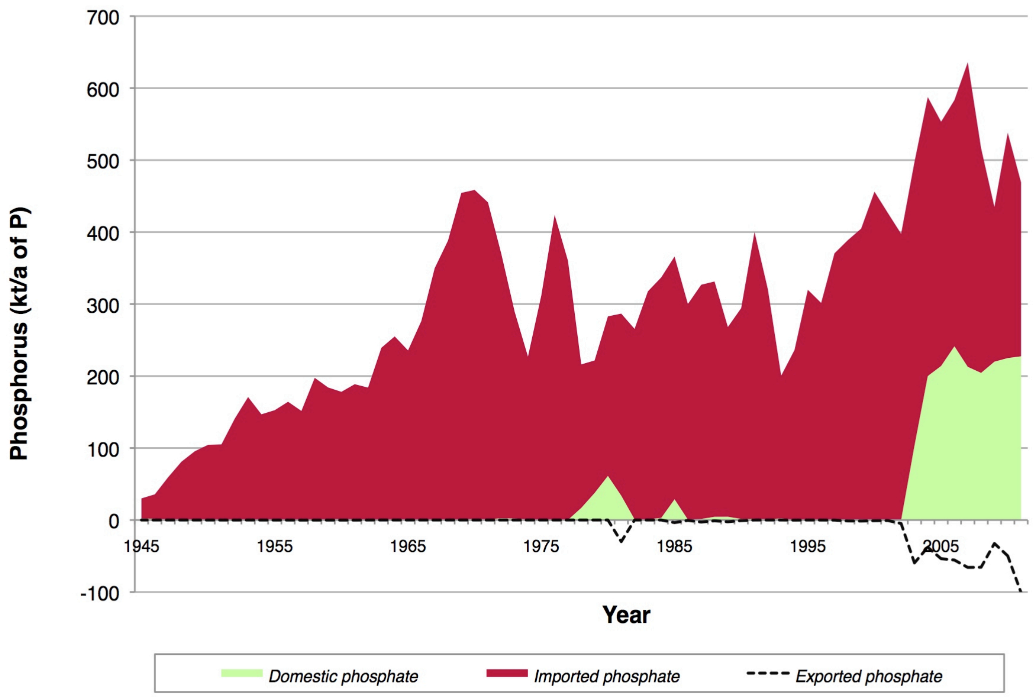

Figure 3: Historical phosphate trade, indicating Australia's substantial dependence on phosphate imports (largely from Nauru) through to 2008. Data sources: Various mineral statistics (see Appendix A-1).

However this agricultural boom was relying on a finite resource, and when the high quality phosphate from guano had been exhausted (figure 4) and the operation was no longer economically viable, Australia had to find another source of high-grade phosphorus, to maintain its high agricultural output[8]. Phosphate rock was discovered in Australia at the turn of the 20th Century, however serious exploration and mining commenced in the 1960's, and production dramatically increased in 1999 (mainly at Phosphate Hill). Production from these reserves provides approximately half of Australia's current demand for phosphorus (Geoscience Australia, 2008; FIFA, 2006b; Government of South Australia, 2009).

[8] Meanwhile the Nauruan economy collapsed because it had been dependent on the royalties from phosphate mining. There is still uncertainty today about whose responsibility it is to rectify the environmental, social and political devastation caused by the phosphate mining.

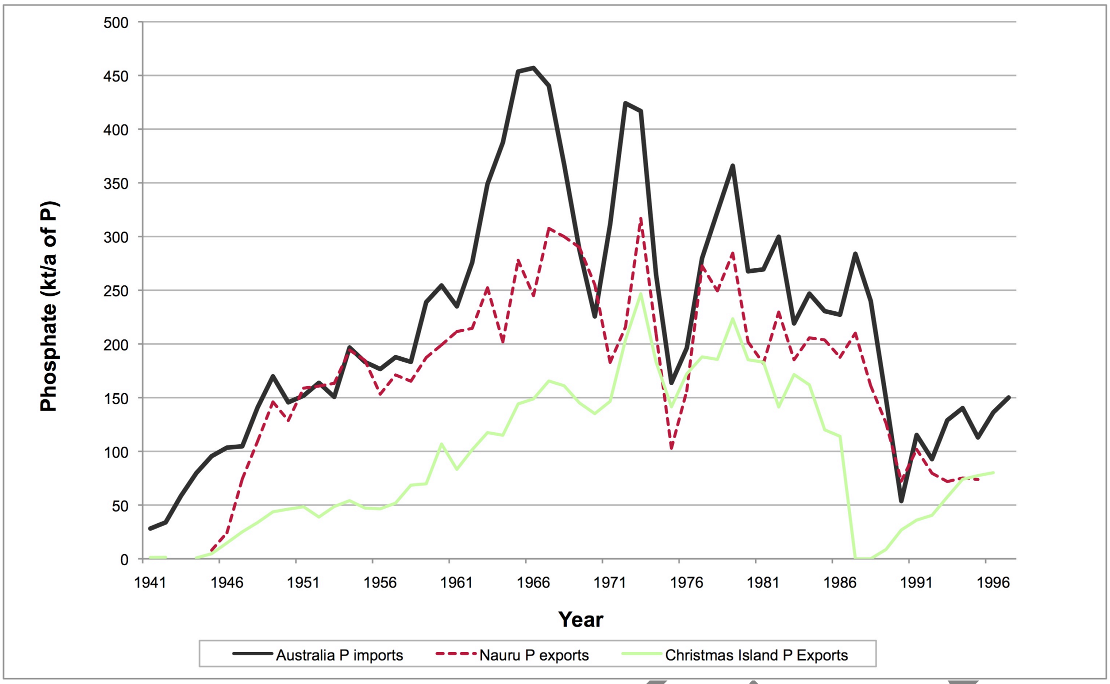

Figure 4: Historical production of phosphate on Christmas Island, Nauru (indicating a peak in the early 1970s), and imports into Australian Source: Various mineral statistics (see Appendix A-2)

Imports also increased from other regions, namely Northern Africa. A substantial amount of fertilisers applied by Australian farmers originates from phosphate rock mines in Western Sahara and Morocco (ABARE, 2007). While these are the largest high quality reserves in the world, importing phosphorus from this region carries a significant embodied ethical burden and potential security risk (as noted in section 2): Australian companies, their shareholders and customers are indirectly supporting the occupation. Further, heavy reliance on phosphate rock from this politically sensitive region could put Australian food production at risk should there be an interruption in supply from the region (Kamal Fadel, 2008, Polisario, pers. comm. 14th November). Notably, one of the major importers of Western Saharan phosphate into Australia, Westerfarmers, committed to reducing their dependence on phosphate rock from Western Sahara[9] (WSRW, 2009).

Today, Australia is still dependent on phosphate rock from imported and domestic sources for food and feed production to feed the Australian population, support the economy through agricultural exports and contribute to feeding the world. It is estimated the national fertiliser bill at the farm gate now exceeds AU$10 billion (Zero Waste Australia, 2008) and FIFA conservatively estimate the value of the fertiliser industry to the Australian economy is around AU$8 billion (FIFA, 2005).

Widespread use of fertilisers, together with land use changes, gully and stream erosion and sewage effluent, eutrophied susceptible waterways leading to cyanobacteria (blue-green algal bloom) outbreaks in inland and coastal waterways. Toxic algal blooms can affect river and lake health, poison or reduce the quality of human and animal drinking water supplies, reduce the quality of recreational waters and lead to large fish kills with substantial costs for the fishing industry in addition to aquatic ecosystem health. In 2000, the annual cost of algal blooms in Australia was estimated at $180-$240 million per year (Atech 2000 in DEWHA, 2006). The fertiliser and agriculture industry responded to pressures to improve efficiency of

[9] CSBP has previously imported 60-70% of its imports from Western Sahara.

fertiliser application and uptake and to reduce losses, as their Northern counterparts were doing. For example, the Fertiliser Industry Federation of Australia has developed a voluntary initiative, *Fertcare*, to assist farmers in the efficient use of fertilisers (FIFA, 2006a). Whilst efficient fertiliser use benefits the environment through reduced pollution, it does not fully address the emerging phosphate scarcity issue (Cordell and White, submitted).

Despite decades of fertiliser application, many Australian cropping and pasture systems today have phosphorus-deficient soils due to natural deficiencies, sub-optimal fertilizing strategies, and sub-optimal land use practices leading to erosion. The National Land and Water Resource Audit has highlighted nutrient depletion as a major issue, however there is no discussion about where additional nutrients will come from to ameliorate the problem in the future (Commonwealth of Australia, 2001).

In 2008, the price of phosphate rock spiked at an unprecedented US$430/tonne, 800% higher than relatively stable price of US$50/tonne before 2007 (figure 5). This occurred roughly at the same time as the spike in commodity prices for food, agricultural commodities, oil and other fertilisers. The phosphate fertiliser price spike was thought to be due to a combination of market tightness between supply and demand, speculation, and increasing raw material prices (IFA, 2008). Short-term supply was unable to keep up with increasing demand due to increased global meat and dairy consumption (especially in growing economies like China and India) which results in demand for significantly more phosphorus fertiliser per capita (Cordell et al., 2009a). Phosphate rock production and especially trade is linked directly and indirectly to the price of oil. The recent sharp increase in biofuel production not only competes with food crops for productive land, but also for phosphorus fertilisers.

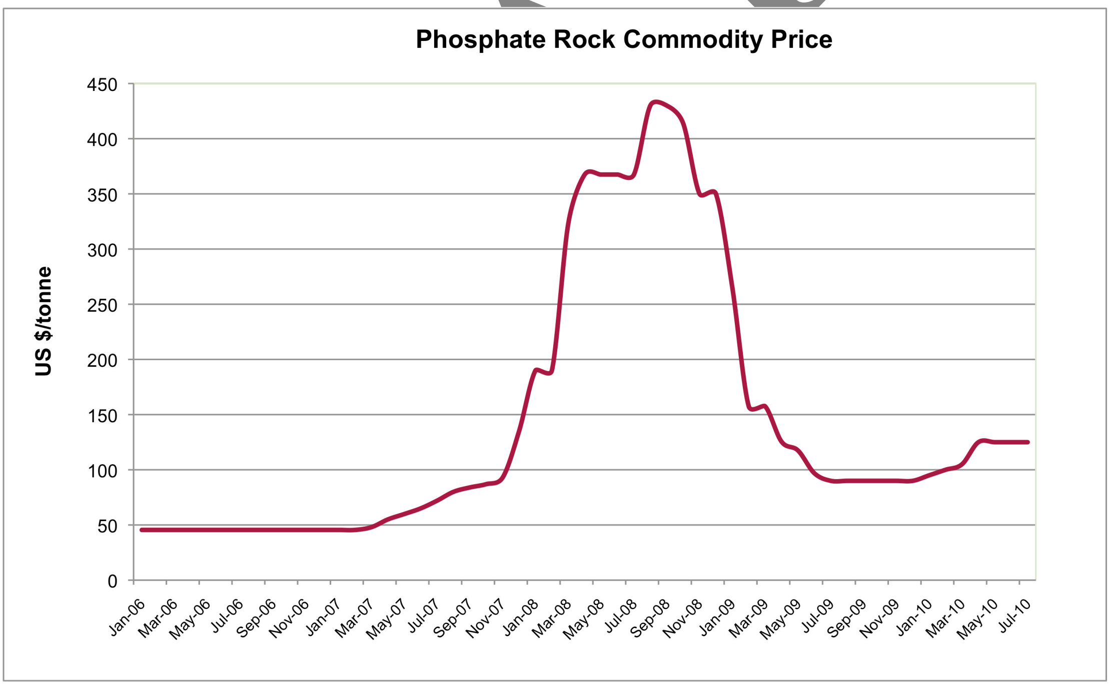

Figure 5. Phosphate rock commodity price (Casablanca) between January 06 to July 10, indicating an 800% price increase (Source: updated from Cordell, 2010; data: Worldbank, Minemakers).

Most farmers and policy-makers were completely unaware prior to the fertiliser price spike, hence no preparations were made. Following the price escalation, a Senate Inquiry was held into the drivers and impacts of the global fertiliser market on Australia and the nature of potential monopolistic and cartel behaviour by the fertiliser industry and price manipulation

(Commonwealth of Australia, 2009). The Inquiry concluded that there is need for effective competition in the industry and for greater transparency. A few large players dominate the current market and this in turn seriously compromises effective competition in the industry and has implications for the pricing of fertiliser products in Australia. Serious concerns were raised during the Inquiry regarding the degree of protection available to farmers and others from anti-competitive practices and exploitation of market powers by fertiliser companies (Commonwealth of Australia, 2009). It is believed that the powers of the ACCC need strengthening in order to fulfil its role in promoting competition and fair trading, and that ABARE should collect and publish international input price information on fertiliser products to ensure farmers are well positioned to make judgements about the timing and quantity of their purchases (Commonwealth of Australia, 2009).

Whilst the Senate Inquiry was an important initiative, the sustainability issues facing Australia extend far beyond the scope of the Senate Inquiry. Hence, further national investigation and action is still required that goes further than the current focus on fertiliser market structures to determine in what ways the Australian food system is vulnerable to short- and long-term phosphorus scarcity, and to identify mechanisms that can increase Australia's resilience and adaptability to such an anticipated future.

5 AUSTRALIA'S PHOSPHORUS BALANCE

In order to prioritise Australia's policy and management responses to phosphorus scarcity (such as investing in phosphorus use efficiency in agriculture, phosphorus recovery from wastewater and food waste), it is instructive to better understand the magnitude and fate of phosphorus flows through the Australian economy. That is, the inputs, outputs and stocks (in tonnes P per year) between all key sectors (not just agriculture): including mining and fertiliser, agriculture and livestock, food production and consumption, and solid waste and wastewater sectors. Such quantification can aid the identification of current inefficiencies, potential points for recovery, reduction in losses and facilitate prioritisation of measures. A simplified analysis of the major phosphorus flows through the Australian food production and consumption system is presented in figure 6 in thousand tonnes of phosphorus per year ('000 t/a of P).[10]

[10] This analysis builds on Cordell and White (forthcoming-a). Flows are indicative rather than precise, due to poor data availability. Further, no complete dataset exist for a given year, care has been taken to use 2006-7 data where possible, and extrapolated from earlier years where such data is not available. Data for each form of phosphorus has been obtained from multiple sources, as indicated in the following sections. Oral information with key Australian stakeholders was also used in some instances to triangulate or compliment existing data due to a lack of publically available data and is referenced as such. Remaining figures were based on material balance calculations (ie. inputs = outputs + accumulation) by working both forwards from the start of the food chain and backwards from excretion and consumption up the chain.

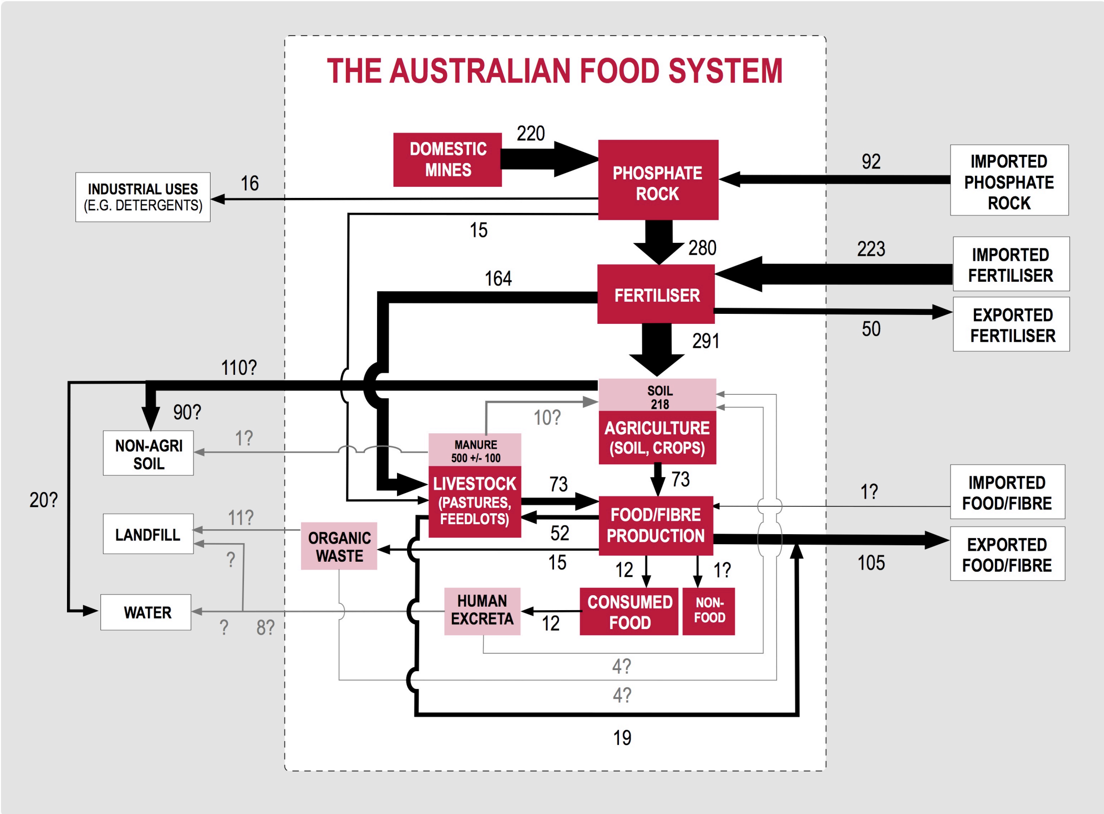

Figure 6. Australia's phosphorus budget. Major phosphorus flows through the Australian food production and consumption system – from mine to field to fork. Units are kt/a of P (Source: updated from Cordell 2010).

5.1 Phosphate rock & fertilisers: imports, exports, production, consumption

Roughly half of the 455 kt/a of P in fertilisers applied to Australian soils comes from domestic rock (the remainder comes from imported rock or finished fertiliser products). Most domestically sourced phosphate rock is mined at Phosphate Hill in Queensland, (supplying approximately 220 kt/a of P with a concentration of around 24% P_2O_5 (Geoscience Australia, 2007; Geoscience Australia, 2008)[11]. Other domestic production of phosphate rock occurs on Christmas Island in the Indian Ocean (for which there is no available public data[12]), and South Australia (mainly for non-fertiliser industrial purposes) (Geoscience Australia, 2008).

Domestic phosphate rock reserves are not as high quality as those in Northern Africa, and thus Australia also imports phosphate rock (containing approximately 92 kt/a of P) (FIFA, 2007). According to the Fertiliser Industry Federation of Australia, all Australian fertiliser manufacturers import significant quantities of phosphate rock (FIFA, 2003). Table 2 indicates the country of origin and supplier of imported phosphate products, including phosphate rock (most of which is processed domestically into marketable fertilisers), single superphosphate and monoammonium and diammonium phosphates. Most imported phosphate rock is processed into finished phosphate fertilisers by Incitec Pivot in Queensland or CSBP[13] in

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[11] P_2O_5 contains exactly 44% P.

[12] Production (input) and export (output) of phosphate rock from Christmas Island has been excluded from this analysis due to lack of consistent data. These inputs and outputs essentially cancel each other out as most phosphate rock mined on the Island is exported to South East Asia.

[13] wholly owned by Westfarmers.

Western Australia for sale on the domestic market. Approximately 223 kt/a of P is also imported into Australia in finished fertilisers from the US, Morocco, China and South Africa. Comparatively less P (approximately 50 kt/a of P) is exported as phosphate fertilisers (mainly DAP and MAP produced by Incitec Pivot) (FIFA, 2010).

Table 2: The country of origin and companies supplying phosphate rock and phosphate fertiliser products to the Australian market[14] (excluding Christmas Island and Nauru). Source: FIFA (2010)

Product	Origin	Supplier
Phosphate rock	Morocco	OCP
	Togo	SNTP
	China	Wengfu
		Kaolin
Single Superphosphate	Israel	ICL
	China	Wengfu
Monoammonium phosphate (MAP) **Diammonium phosphate (DAP)**	USA	The Mosaic Company
		Mississippi Phosphates Corporation
		CF Industries
		PCS
	Morocco	OCP
	China	Wengfu
		Kaolin
	South Africa	Foskor

5.2 Phosphate farm budget: fertiliser application, crop uptake, soil stocks, losses

Of the 455 kt/a of P in fertilisers applied to Australian agricultural soils, only a small fraction is taken up by crops in the same year. This can be as low as 20-30% uptake, according to the Australian Soil Fertility Manual (Richardson et al., 2009; Wakelin et al., 2004) and FAO (2006) (approximately 70 kt/a of P). This leaves in the order of 220 kt/a of P which either remains in a temporary soil 'stock' (a small proportion of which is taken up by crops in subsequent years), or is permanently lost to waterways or non-agricultural land via erosion of top soil. McLaughlin et al. (1992) estimate the annual rates of nutrient loss from Australia through soil erosion is 6-32 kt, while the Australian State of the Environment Report 2006 (SoE) predicts that nearly 19 kt of P is exported down rivers to the coast each year from areas of intensive agriculture (Commonwealth of Australia, 2006)[15]. Because phosphorus is so readily and tightly adsorbed to clay and other organic particles, very little phosphorus is typically lost via leaching in Australian soils (ABS, 1996).

As discussed earlier, phosphorus transported to inland and coastal waters adsorbed to eroded agricultural soil particles can cause eutrophication leading to toxic algal blooms that can poison aquatic ecosystems, and cause economic damage to the fishing, tourism and recreation industries (Chudleigh and Simpson, 2000). Agricultural runoff along the Queensland coast is even causing damage to the Great Barrier Reef (Commonwealth of Australia, 2001).

During harvest, some organic phosphorus in crop residues remains on the farm is eventually mineralised and added to the soil phosphorus reservoir.

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[14] The breakdown of suppliers is not static and can change due to market and geopolitical factors.

[15] It is unclear what proportion of exported phosphorus, in terms of farm nutrient loss, corresponds directly to fertiliser use and application. In any case, improved agricultural efficiency and farm soil management could reduce these significant annual rates, and potentially assist in minimising unnecessary fertiliser applications.

5.3 Livestock & manure: phosphorus feed additives, feed, manure generation, recovery and losses

The Australian livestock sector includes cattle (meat and dairy), sheep, poultry (broilers and layers), goats, pigs and turkeys for both the domestic and export markets. This sector represents a significant part of Australian agriculture (22% of the total value in 2007-2008) (ABARE, 2009). Most of Australian sheep and cattle are grazed rather than feedlot fed due to large available land areas (unlike European livestock for example). For example, around 14% of cattle (or around 3 500 000 head) are feedlot in Australia (ABS, 2007; ALFA/MLA, 2007). As with agricultural cropping soils, pastures and grazelands in Australia are also naturally phosphorus deficient, however McLaughlin et al. (1992) note a declining use of phosphorus on pastures since the mid 1970s. Nevertheless, reasonably high and increasing levels of phosphorus fertilisers are applied to dairy pastures, which are mostly in high rainfall areas or are irrigated (Commonwealth of Australia, 2001). FIFA (in Commonwealth of Australia, 2001), estimate nearly half of the total value of fertilisers applied to pastures in Australia are now applied on dairy farms. Phosphate fertiliser application rates vary predominately across climatic zones; dryland pastures typically receive <5 kg P/ha whereas irrigated and high rainfall pastures receive more (10-15 kg P/ha) (Commonwealth of Australia, 2001).

Australian livestock phosphorus intake occurs from three major routes: feed (grains, hay) (containing approximately 52 kt/a of P), grazing (estimated at 164 000 t/a of P in fertilized pastures[16]) and supplements (estimated at 15 kt/a of P). Average phosphorus intake from feed varies for different animals, as indicated in table 3.

Table 3. Phosphorus intensity of Australian grain-fed livestock: phosphorus consumed in feed annually by different livestock animals (Source: own calculations from ABARE, 2007).

Livestock animal	Feed (kg/a of P per animal)
Cattle - Feedlot meat	4.53
Cattle - Dairy	4.40
Pigs	2.63
Poultry - Layers	0.16
Poultry - Broilers	0.15
Sheep for live export	0.07
Grazing ruminants	0.02

Almost all the phosphorus consumed in grains and via grazing is excreted in manure and this makes up the largest output from the livestock sector. The amount and concentration of phosphorus in manure varies from animal to animal, meat cattle contributing by far the most phosphorus in manure (table 4). Collectively, this results in a massive 500 (±100) kt/a of P generated from livestock manure each year[17]. While this figure is comparable to the total amount of phosphorus applied in mineral fertilisers each year (455 kt/a of P), most of this is recirculated to soils directly on grazelands and pastures (hence not figured outside the 'Livestock' box in figure 6). Some manure from feedlots is reused as fertiliser in cropping systems.

[16] The phosphorus content of unfertilized grazeland consumption has not been quantified here.

[17] Calculations from ABS sources (ABS, 1996) based on European data, also suggests the *total* nutrient content (not the fraction reused in agriculture) of Australian livestock excreta could be in the order of 514 kt/a of P.

Table 4. Breakdown of livestock animals in Australia by number, manure generation and phosphorus contained in manure (Source: various sources).

Livestock animal	Number of animals[a]	Manure generated per animal[b] (kg/a)	Phosphorus generated per animal (kg/a)[b]	Phosphorus concentration of manure[c] (%P)	Total phosphorus generated in manure[d] (kt/a of P)
Cattle - dairy	2,700,000	22,706	26.8	0.12%	72
Cattle - grazing meat	21,866,609	13,444	21.3	0.16%	466
Cattle - feedlot meat	3,533,391	13,444	21.3	0.16%	75
Sheep & lambs	85,700,000	662	1.4	0.21%	120
Pigs	2,600,000	1,287	3.2	0.25%	8
Broilers	82,100,000	28	0.1	0.32%	7
Layers	15,300,000	42	0.2	0.45%	3
Horses & ponies	257,123	8,377	11.7	0.14%	3
Goats	517,649	958	2.6	0.27%	1
Turkeys	1,166,000	117	0.6	0.49%	1

a. ABS, 7121.0 - Agricultural Commodities, Australia, 2006-07
b. 'Table A1: Livestock manure coefficients' in Hofmann, N & Beaulieu, MS, A Geographical Profile of Manure Production in Canada, 2001
c. calculated from b and c.
d. these figures may be slightly lower due to variation between different estimates of P concentration of manures (eg. between FAO (2006), Hofmann & Beaulieu (2001) and others. Variances may be due to some figures referring to 'fresh' wet-weight animal excreta, while others may be referring to semi-dried manures.

The smaller fraction that is taken up by the animal's body ends up in animal products (meat, milk, carcases, eggs) estimated to be around 82 kt/a of P - most of which is exported and hence consumed overseas. Some is also lost as offal, fat, blood, and other parts such as hooves, which have not been included in the above estimate. The 82 kt/a of P in animal products is based on carcass weight figures and therefore does not demonstrate the amount of P in edible animal products. The United States Department of Agriculture (USDS, 1992) suggests 1/3 of carcass weight is bone, while the remaining 2/3 of the carcass is used for meat production and has an average %P concentration of 0.2% (McLaughlin et al., 1992), inferring that nearly 15 kt P is available annually for consumption in animal products.

Live export of sheep, cattle and goats result in a permanent export of approximately 19 kt/a of P from the Australian food system (since non-meat parts of the carcass - such as offal, blood, fat, bones - cannot be reused within the Australian food system, nor can the P in meat food waste and human excreta be recovered domestically). Demand for live animals from various markets due to cultural, religious and practical reasons, and the positive economical impact of the live export trade is a reason why Australia continues to meet the request of high P-laden stock (ACIL Tasman, 2009).

5.4 Phosphorus in food: imports, exports, production & consumption

Nearly two thirds of Australian food is exported, much of which are high phosphorus concentration food products – meat, fish, diary, grains[18] (DAFF, 2008). For this reason it is estimated that approximately 75% of the phosphorus in food and fibre produced in Australia

[18] For example, cereals contain around 3.3 mg/g phosphorus, meat contains around 1.8 mg/g phosphorus, while fruit and vegetables contain around 0.2-0.4 mg/g phosphorus (Gumbo, 2005 – FAO ???).

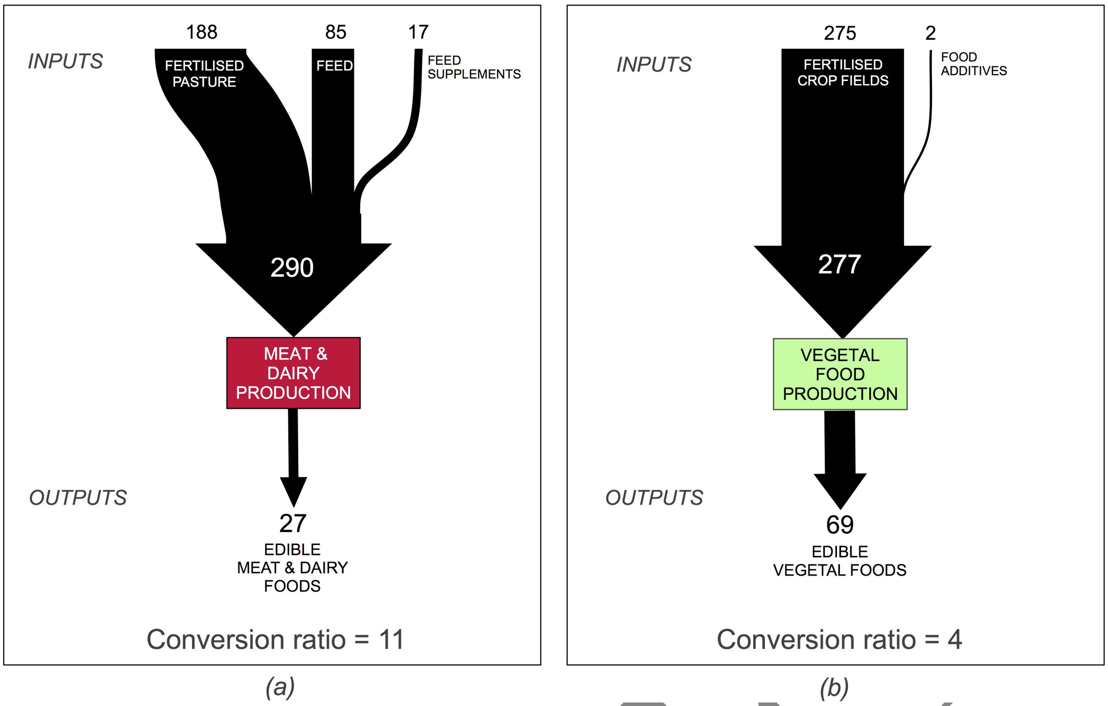
is exported off Australian shores (approximately 85 kt/a of P). However, most of the 'embodied' phosphate in these commodities, which is a much larger number, is locked up temporarily in Australia's agricultural soils, washed off to waterways, or stockpiled in landfills[19]. Imports, on the other hand, make up a relatively small percentage of the total P flow within the Australian system. Limited available public data suggests P import in food imports are in the order of 1 kt of P annually. Overseas food products equate to a small percentage of Australia's consumption, and hence P, due to Australia producing near sufficient amounts of food products for total domestic supply, and also those products that are imported contain relatively low phosphorus concentration levels. Total annual consumption of domestic and imported phosphorus equates to around 12 kt/a of P.

Significant losses of phosphorus occur between harvesting and food consumption. While some of these losses are unavoidable (such as crop residues and other inedible fractions), other losses are due to inefficient or improper management, leading to spillages, spoilage and hence discarding edible food from food processing, supermarket retailing and household consumption. The Australia Institute estimates that around $5.2 billion worth of food is wasted each year by Australian households alone (Baker et al., 2009). Smil (2000) estimates that approximately 55% of food is lost between 'farm and fork' globally (estimated at approximately 16 kt/a of P for Australia via mass balances). These losses either end up buried in landfill, lost to water bodies or reused. The food that is consumed contains relatively high levels of phosphorus. Australian diets vary between age groups and geographic regions, but phosphorus rich foods such as cereals, meats and dairy products make up a large proportion of most diets (McLennan and Podger, 1995).

The following analyses in figure 7 indicates the embodied phosphorus[20] in meat and vegetal foods produced in Australia indicates that while meat production requires approximately 11 times the phosphorus to produce, vegetal products require 4 times the phosphorus to produce. This indicates the higher phosphorus intensity of meat-based diets compared to vegetable-based diets. Similar results were found on the global scale (Cordell et al., 2009a).

[19] This figure is reasonably consistent with Gumbo's calculations that over 120 kt/a of P exported from Oceania in food and fibre products (Gumbo, 2005)

[20] The amount of phosphate rock depleted to produce a food commodity.



Notes:

a. ‘Input’ refers to P contained in phosphate rock mined to produce fertilisers, feed or supplements (not the farm gate P).
b. ‘Output’ refers to ‘edible’ products (food ready for retail/wholesale), not output from farm or actual food consumed. There is substantial food wastage between production of edible foods and final consumption (as noted in section 5.5).
c. 'Edible meat and dairy foods, including meat, eggs, milk or other animal-based food product sold for retail. Carcasses, offal, blood etc, are excluded, unless they are part of the food item. Pet food is not included.
d. ‘Edible vegetal foods’ includes fresh fruit and vegetables and all edible
e. Edible products include all foods *produced* in Australia, regardless of whether they are *consumed* domestically or overseas. This includes the edible meat fraction of live exports. A substantial fraction of the final products (or their intermediates, such as live sheep, or wheat) are exported.

Figure 7: Embodied phosphorus in a) meat & dairy foods and b) vegetal foods produced in the Australian food system. Units are in kt/a of P. Conversion ratios indicate the P in phosphate rock (input) used to produce edible foods (output). See Appendix B for data and assumptions.

5.5 *Phosphorus in organic waste: generation, recovery and losses*

Australia generated an estimated 43.8 Mt of waste in 2006-07. Phosphorus is present in all organic waste fractions. It is estimated that organic waste makes up 72% of municipal solid waste, 62.5% of commercial and industrial waste and 11% of construction and demolition waste (Commonwealth of Australia, 2010). This results in approximately 20 Mt of organic waste generation, of which 13.6 Mt were landfilled and 6.4 Mt were recovered for reuse on arable or non-arable land (Commonwealth of Australia, 2010) (containing approximately 11 kt/a of P and 5 kt/a of P respectively). Zero Waste Australia estimate approximately 1 Mt of composted organic material from food and garden waste (containing approximately 4-8 kt/a of P[21]) are made available for reuse in agriculture in Australia each year (Zero Waste Australia, 2008).

In relation to organic waste in Australian agriculture, current farming practice is typically for crop residues to be plough back into the soil, burnt, left to decompose, or grazed by stock, which ultimately creates an internal phosphorus recovery cycle. However, there are views that deem it may be appropriate to remove and utilise a portion of this organic waste for energy

[21] This assumes compost contains approximately 1-2% P_20_5, however phosphorus content will vary depending on type of organic matter. It is unclear what fraction originates from food waste versus garden waste.

production (Commonwealth of Australia, 2010), which could ultimately remove a potentially significant source of phosphorus recovery for the agricultural sector (Andrews, 2006).

5.6 Phosphorus in human excreta: generation, recovery and losses

Close to 100% of the phosphorus consumed in food is excreted from the human body (Jönsson et al., 2004), which is equivalent to about 12 kt of P in Australia[22]. Most of the Australian population live in urban areas (approximately 85% ref), serviced by centralised wastewater treatment systems. This means that most of the phosphorus in excreta ends up in effluent discharged to oceans and rivers, unless recovered. It is estimated that currently 40-50% of the phosphorus reaching our wastewater treatments plants is applied to soils in the form of treated effluent or biosolids[23] (Michael Warne, 2008, CSIRO Land and Water, pers. comm. 19th February). However it is unclear what fraction is used productively on agricultural soils to replace mineral fertilisers, verses applied to soils where the nutrients are not actually needed. Urine and faeces, in addition to detergents and other industrial uses of phosphorus, are the sources of the phosphorus in these biosolids (Tangsubkul et al., 2005). The remainder of biosolids not reused are stockpiled, sent to landfill, leached to soils from septic tanks in rural/remote areas, or blended with compost and used as a soil conditioner. In Warne et al.'s (2008) draft position paper on biosolids, the recommended guidelines suggest that while biosolids application should continue, caution needs be taken when considering soil types to ensure levels of cadmium, zinc and copper are kept below accepted levels.

5.7 Summary

The phosphorus balance indicates that overall, the Australian food system is far from 'close-looped' or sustainable from a phosphorus perspective. While Australia does meet half its mineral phosphate needs through domestic sources, a substantial amount of phosphorus is imported into the Australian food system (315 kt of P as phosphate rock and fertilisers). Only a very small fraction of the fertiliser applied to Australian fields ends up in the food consumed by the nation (2-3%). This is because a large amount of phosphorus is permanently exported (105 kt of P in food and livestock exports) or via erosion (110 kt of P) and other permanent losses. There is also a substantial amount of phosphorus accumulating within the system (largely in soils).

6 LONG-TERM FUTURE P SCENARIOS FOR AUSTRALIA

What will Australia's food system look like in a phosphorus scarce future? Will phosphorus demand rise significantly as agricultural production expands to meet to food needs of a growing world population and to support the biofuels market? Will phosphorus demand stabilise or reduce due to reduced exports, less meat-based diets? Concerning, there are very few studies into either business-as-usual or sustainable scenarios for phosphorus. A workshop on the Future of Phosphorus in 2008 brought key stakeholders together to share knowledge and initiate a debate on where we might be heading if no changes are made, and, what we want a phosphorus secure phosphorus to look like in Australia (ref Synthesis).

Projecting business-as-usual into the future (through forecasting) has traditionally been the

[22] Assuming average phosphorus content of consumed food and hence excreta is 1.2g of P per person per day (ref) and a population of xxx million (ref).

[23] Biosolids reuse varies dramatically from state to state, from close to 100% in South Australia to negligible rates in Victoria (Michael Warne, 2008, CSIRO Land and Water, pers. comm. 19th February).

most common form of future analysis to determine where we are likely to be heading. Scenarios, on the other hand, provide images of possible futures situations, rather than an expected or probable future. Scenarios "aim to stimulate creative ways of thinking that help people break out of established ways of looking at situations and planning their actions. Scenarios are useful tools where complexity and uncertainty are high" (Wollenberg et al., 2000) and have been used extensively in long-term global studies on energy, climate, water and global change (Mitchell and White, 2003; Pacala and Socolow, 2004; Netherlands Environmental Assessment Agency, 2006; Royal Dutch Shell, 2008).

To further trigger debate among scientists and policy-makers about preferred phosphorus futures, alternative pathways, what is feasible and to support future decision-making, this section provides very preliminary picture of a 'probable' scenario (where are we heading?), if no changes to the current phosphorus use trajectory are made, followed by a conceptual integrated framework for considering preferred sustainable scenarios. No quantifications are made at this stage due to the substantial lack of data and analysis. However, clear recommendations for such future analysis is outlined in the recommendations.

6.1 Business-as-usual future scenario

6.1.1 Phosphorus demand

Global phosphorus demand is expected to increase at around 2-3% p.a. in the medium term according to industry projections (FAO, 2007; Heffer and Prud'homme, 2008), and meeting the world's long-term food needs is estimated to increase phosphorus demand 2% p.a. and 0.5% p.a. to 2050 and 2100 in a Business-as-usual scenario (Cordell et al., 2009b). While much of the global growth is anticipated to come from developing and emerging economies (as noted in section 2.6). The demand for phosphorus in Australia is likely to increase over the next 40 years (i.e. to 2050), due to a number of economic, social and ecological factors, including: population growth, changing diets, changes in export market, soil fertility status (phosphorus required for Australian agricultural soils to reach critical phosphorus levels) and other drivers.

1. Australian population. The Australian population is expected to increase from 21 million in 2007 to 27 million in 2025 (a 30% increase) and 35 million in 2050 (a 67 % from 2007) according to ABS Series B (ABS, 2008) (figure 8). This will increase domestic food demand and hence fertiliser requirements for domestically produced crops and food.

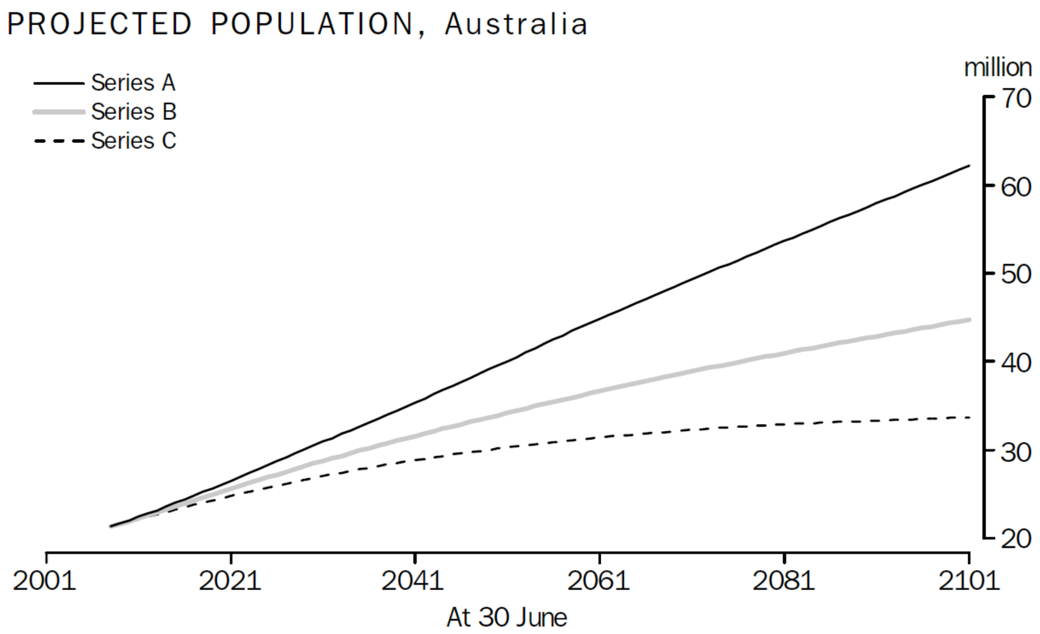


Figure 8. Australian population projections. Series B represents medium scenario. Source: (ABS, 2008)

2. Average diet. There is a global trend towards more meat- and dairy-based diets (particularly as affluence increases in China and India) FAO ref). Research indicates that type of diet can have a significant impact on resource demand and pollution. For example, supporting a meat-based diet compared to a vegetal-based diet demands more energy, water and fertilisers to produce, and leads to increased greenhouse gas generation due to the conversion losses associated with feeding livestock and producing meat (Smil, 2007; Lundqvist et al., 2008). In the global food system, 2.6 Mt/a of P in grains is fed to livestock, while 0.6 Mt/a of P is returned to the food system as meat[24] (Cordell et al., 2009a). An average meat-based diet results in the depletion of approximately 2-3 times more phosphorus than as a vegetarian diet (Cordell et al., 2009a; Cordell et al., 2009b), which is comparable to the analysis presented in figure 7 which indicates that producing animal-based foods in the Australian food system is approximately 2.6 times more phosphorus demanding than producing vegetable-based foods. This means, if Australia (and global diets) continue to trend towards more meat and dairy, phosphorus demand in Australia will increase accordingly.

3. Agricultural, food & fibre exports. Australian agriculture, and in turn Australian phosphorus demand, is highly dependent on the export market, as established earlier. Increasing global demand for agricultural and food commodities (for example in Asia) will consequently increase the fertiliser demand in Australia to keep up with production of such export commodities (assuming Australia remains at the same market share).

4. Soil fertility – many of Australia's agricultural soils are currently phosphorus deficient (Commonwealth of Australia, 2001), and thus would require increased application rates of phosphorus to reach optimal or 'critical' phosphorus levels. Indeed, the NLWRA (Commonwealth of Australia, 2010) estimates that 1.4 million hectares of Australian soils are P deficient for most rural land uses and ~24.6 million hectares are classified as marginal P status for most systems of land use. These soils would require substantial additions of

[24] While such conversion losses are permanent with respect to water, and semi-permanent with respect to energy, most phosphorus conversion losses end up in manure, meaning there is a potential to recover the phosphorus for reuse. However the location of the manure many not always been close to arable land that requires fertilisers.

phosphorus to reach critical soil levels, after which only marginally more phosphorus that is taken away in harvest need be replaced in fertiliser additions (assuming business-as-usual application techniques and management).

5. Other drivers – other drivers, such as climate change, peak oil, water scarcity, pollution, farm economics, technological advances may increase the efficient use of phosphorus to a degree (regardless of the phosphorus situation), and hence reduce the overall phosphorus demand. For example, ongoing concerns about phosphorus pollution due to soil erosion from farms and other landscapes may continue to improve farm phosphorus use efficiency which simultaneously reduces demand for external phosphorus fertilisers. However it is likely that these business-as-usual efficiency gains will be outweighed by increased demand due to the above factors.

6.1.2 Phosphorus supply from mineral sources

As discussed earlier, almost all Australia's phosphorus demand is met from mineral fertilisers processed from phosphate rock. Unlike Europe and India, which are totally dependent on phosphate imports, Australia has domestic mineral resources. Estimating Australia's mineral phosphate resources is however fraught with difficultly due to errors and uncertainties associated with reporting, exploration and assumptions. The best available figures indicate an Economic Demonstrated Resource (EDR)[25] of 81.6 Mt phosphate rock (table 4) (containing 8.6 Mt of P) (Geoscience Australia, 2009). All EDR is from Phosphate Hill in Queensland and has an average grade of about 24% P_2O_5[26].

The estimation of Inferred Resources in Australia has recently increased to 1,574 Mt phosphate rock (Geoscience Australia, 2009). This increase is largely the result of several mining companies investing or developing phosphate operations, mostly within the Georgina Basin, which spans Queensland and Northern Territory boundaries, following the 2008 phosphate price spike. Whilst the Inferred Resources are substantial in apparent magnitude, several important factors mean these resources are limited and hence not ultimately a sustainable source for the future. Firstly, the grade (P_2O_5) of Inferred Resources is markedly lower (16-20% and some resources as low as 4-7% P_2O_5) (Leesa Carson, 2010, Geoscience Australia, pers. comm., 14th May). The higher the grade of phosphate rock, the better the project (and hence likelihood of becoming part of EDR). Therefore the lower grade deposits will require more beneficiation (upgrading the ore to the grade the client wants). Some of these Inferred Resources are also more difficult to access, contain higher amount of contaminants. Therefore these resources will require more energy and input costs to produce.

Further, a large share of the commodities and intermediates from these new operations are assumed destined for overseas markets, and therefore not available for domestic use. Legend Holdings International Inc. for example has an agreement with the Indian Farmers Fertiliser Co-operative for the purchase of up to 5 Mt/a Direct Shipping Ore grading 30-34 % phosphate, which Legend hopes to meet by 2013 (Geoscience Australia, 2009). This prospective export (containing approximately 700 kt/a of P) is alone greater than Australia's current total domestic consumption of mineral phosphate fertilisers (455 kt/a of P). Minemakers is also aiming to be producing 3 Mt/a of Direct Shipping Ore phosphate by 2011 (Geoscience Australia, 2009).

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[25] JORC Code definitions and categories (including EDR and Inferred Resources) are described in Appendix C..

[26] This excludes Christmas Island figures, due to lack of publically available data. However a recent motion by the Environment Minister will result in the closure of all Christmas Island phosphate operations due to environmental damage (ref).

Table 4. Breakdown of Australia's and the World's demonstrated phosphate rock resources and annual mine production (1998-2008). Units are in million tonnes of phosphate rock, not P, hence actual P content will vary substantially. Data sources: various (see table notes).

Phosphate rock	AUSTRALIA					WORLD	
	Demonstrated Resources[a] (Mt)			Inferred Resources[a,b] (Mt)	Mine Production[c] (Mt/a)	Reserves[d] (Mt)	Mine production[d] (Mt/a) (d)
	Economic (EDR)	Subeconomic					
		Para-marginal	Sub-marginal				
1998	88	981	-	3 739	-	12 000	141
1999	107	981	-	3 739	-	12 000	138
2000	77	981	-	1 155	0.806	12 000	139
2001	91	981	-	1 151	2.300	12 000	128
2002	91	981	-	1 126	2.000	17 000	133
2003	91	981	-	1 126	0.922	18 000	138
2004	86	981	-	1 125	0.884	18 000	138
2005	85	980	-	1 085	0.884	18 000	145
2006	85	980	-	1 085	2.154	18 000	145
2007	82	912	-	1 150	2.129	18 000	147
2008	82	997	-	1 574	2.154	15 000	167

a. Source: Geoscience Australia (1999, 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008, 2009)
b. Total inferred resources in economic, sub-economic and undifferentiated categories.
c. Source: Australian Bureau of Agricultural and Resource Economics (ABARE, year??)
d. Source: USGS Mineral Commodities Summaries (1999-2009)

Despite recent exploration in Australia, continuing to use phosphate rock in the long-term will be constrained not by the quantity, but by other key factors, such as accessibility, quality, economics, embodied environmental impacts, security/reliability of supply, and associated geopolitics. Important future challenges (exogenous or endogenous factors) that will contribute to an unsustainable scenario if not actively addressed include:

- The average grade (percentage P_2O_5) of phosphate rock (reserves and inferred) is declining globally due to the non-homogeneity and finiteness of phosphate rock (Cordell, 2010; Prud'Homme, 2010);
- The physical accessibility of potential (inferred) reserves is more difficult;
- The lower grade of remaining reserves means increased energy use and the greenhouse gas emissions associated with mining, processing and in particular transporting phosphate rock and fertilisers around the world (Cordell et al., 2009a);
- Costs will increase as a consequence, thus cheap fertilisers will become a thing of the past;
- The natural presence of uranium, thorium and cadmium in phosphate rock, which must be removed and managed to avoid downstream ecological and societal health risks when phosphorus is handled and used (the by-product currently stockpiled as radioactive phosphogypsum stacks) (Cordell et al., 2009a);
- Global environmental challenges, including oil scarcity, water scarcity, climate change, eutrophication. For example, future societies and systems will need to use water and energy more efficiently. However in some cases these sustainable systems have adverse impacts on phosphorus, such as alternative fuels (e.g. biofuel crops that require fertilisers to grow, or some electric vehicle batteries that contain 60 kg of phosphate in every battery pack – both which will increase demand for P and speed up the rate of depletion) (Cordell, 2010; Renard, 2010);

- Rising fossil fuel costs directly impact farm-gate phosphate fertiliser prices (due to sea freight costs) (FIFA, 2010);
- Environmental costs associated with landfills (e.g. landfill gas) and rising landfill costs in and around Australia's urban areas puts pressure on reducing waste to landfill (including the large phosphorus-rich organic waste fraction) (Commonwealth of Australia 2010);
- Australia's naturally P-deficient soils, which means building soil fertility (and avoiding depletion) is key to ensuring productivity; and
- Spatial spread of cities (and potentially habitable land) and fertile land. Distances are often large, which can be a barrier to returning urban nutrients back to agricultural systems.

Further, the "weights" of the past may also compound a hard-landing situation if not addressed. These include:

- Due to globalized trade, sea freight costs associated with shipping phosphorus commodities will affect both imported and domestic phosphate prices (FIFA, 2010), leading to fertiliser farm gate price volatility (as demonstrated in 2008);
- While all Australian farmers need access to phosphorus fertilisers, there are very few phosphate producers in the current market structure (Incitec Pivot Limited control 70 per cent market share at the wholesale level in eastern Australia and CSBP control approximately 65 per cent of the market share in Western Australia) (Commonwealth of Australia 2009). The major phosphate rock producers and importers in Australia at present represent an oligopoly (Commonwealth of Australia, 2008), and hence farmers accessibility to fertilisers is compromised;
- Lag times (averaging 3 months) between fertiliser orders and farm gate arrival can contribute to short-term scarcity (FIFA, 2010);
- Inefficiencies in the current food production and consumption system resulting in substantial phosphorus losses (permanent or accumulation);
- The Australian economy is dependent on agricultural exports, and is a net food producer. Many of these export commodities are phosphorus-intensive to produce.
- The geopolitics of phosphate resources, future usage trends and the uncertainty associated with global reserves, which all impact on the accuracy of reserve estimates and hence the timeline of peak phosphorus (Cordell et al., 2009a); and
- Lack of adequate accounting for the continuous generation of a phosphorus 'waste' stream that can pollute water bodies (Neset and Andersson, 2008).
- A significant share of imported phosphate rock and fertilisers are sourced from phosphate rock mined in Western Sahara by Morocco, which is supporting a UN-condemned occupation. Wesfarmers recently committed to reducing imports of Western Saharan rock via Moroccan authorities, in line with Scandinavian firms that have also boycotted trade with Morocco (Hagen, 2008).
- General mainstream perception that use of human excreta as a fertiliser is bad or a health risk (Cordell, 2006).
- The existing phosphate rock knowledge-base (or 'know how') creates a perceived barrier to changing to other forms of phosphorus (such as excreta etc).
- There are no clear institutional roles and responsibilities regarding securing a sustainable phosphorus future. Current institutional arrangements are fragmented (Cordell, 2010).

Whilst difficult to quantify, the business-as-usual situation is likely to result in a growing gap between phosphorus demand and supply in Australia. This could lead to a 'hard landing' for Australian agriculture and the Australian community in response to phosphorus scarcity, with escalating and volatile prices, increased energy consumption and waste generation. However, this situation is neither desirable nor inevitable. A soft-landing is possible, which takes in account a wide range of integrated sustainability measures, long-term time frames, and seeks synergies with solutions to other pertinent challenges such as climate change and water scarcity.

With more than half of Australia's phosphorus originating from overseas, and from areas of potential volatility, there is need to secure sustainable sources of phosphorus for food production in the future. Recent domestic phosphate rock exploration could potentially diminish risks (further discussed in section 5), but with key issues such as low quality grade phosphate rock, high energy inputs, high costs, difficulty to access, and overseas export agreements, these new developments should not be seen as a primary solution. In 2008, a Senate Inquiry into Food Production was established with an objective to address the question of how to produce food with a sustainable impact on the environment (Senate Select Committee on Agricultural and Related Industries, 2008). In order to construct a sustainable phosphorus future in Australia, issues such as the rising cost of fertilisers, the energy intensity of mineral fertiliser production and ethical concerns regarding the trade and current indirect support for an illegal occupation of Western Sahara by importing rock from Moroccan authorities or phosphate fertiliser from US companies must be addressed.

6.2 Preferred sustainable future scenario

A preferred scenario to ensure long-term phosphorus security must explicitly identify key aspirations of a future sustainable vision, in addition to future global challenges and weights of the past (figure 9). Backcasting was used in a participatory high-level stakeholder workshop on the future of phosphorus (Cordell and White, 2009) to facilitate the co-generation of a preferred phosphorus future for Australia, and to help identify key policy, infrastructure and social changes that would be required to reach the future vision. Key objectives of future phosphorus security for Australia include [27]:

- Reduce Australia's *dependence* on increasingly scarce mineral phosphate sources (imported and domestic);
- Maintain or improve Australia's *agricultural and food productivity* in the long-term, including investing in *healthy soils*;
- Ensure *farmer needs* are met;
- Maximise the *efficient use* and *recovery* of phosphorus throughout the food production and consumption system;
- Minimise the deleterious environmental impacts of phosphorus use, particularly related to *eutrophication*, energy consumption and mobilising heavy metals into the environment.

[27] The factors have been drawn in part from the national phosphorus stakeholder workshop and other recent research on global phosphorus scarcity and implications for Australia (Cordell 2010).

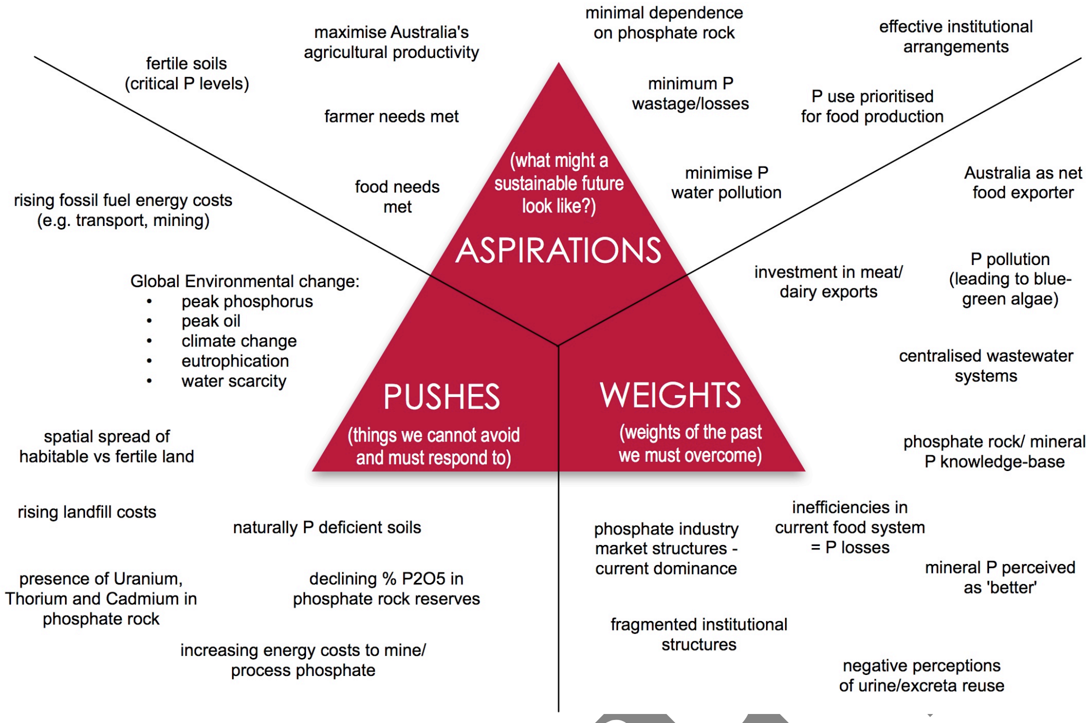

Figure 9: Sustainable phosphorus future must respond to 1. Weights (i.e. inertia of existing physical and institutional infrastructure and other systems); 2. Pushes (i.e. important factors that cannot be avoided, and must be responded to, such as Climate Change); and 3. Aspirations (i.e. future visions or goals).[28]

Taking into account the current phosphorus balance, future challenges and objectives of a sustainable phosphorus future, Figure 10 below indicates conceptually how the gap between demand and supply could be met through a range of measures. While there are substantial uncertainties regarding demand and supply trends and timing of peak phosphorus, there will be a growing gap that will need to be addressed. To ensure Australia's growing long-term future demand for phosphorus is met, without compromising soil fertility, economic sustainability, the environment and farmer livelihoods, a range of options will be required. It is unlikely that any single measure could secure a sustainable phosphorus future, and hence measures that seek to increase efficiency in the entire food production and consumption chain will play an important role, as will sourcing phosphorus from other, more local and renewable sources. Further, it is important that the demand management strategy considers not only increasing efficiency (i.e. optimizing the existing system), but also how the overall demand for phosphorus can be reduced in the first place. Demand-side measures are described in further detail (including assumptions and drivers) in tables 5, and supply-side measures in table 6.

In this sustainable scenario, the substantial dependence on imported phosphate rock has been reduced, due to geopolitical, economic and environmental factors (see table 6). Domestic supply of phosphate rock will likely play a role, however following an eventual peak[29] of current EDR, it is unclear how much will available from Inferred Resources for productive use due to quality concerns, economics, environmental and social impacts, and the need to diversify sources to better buffer against short-term price and availability fluctuations.

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[28] see the futures studies work of Sohail Inayatullah for explanation of 'Weights', 'pushes' and 'aspirations' www.metafuture.org.

[29] The area under the 'Domestic Phosphate Rock Reserves' curve in figure 10 is equal the current EDR of Australian phosphate rock.

Further, much of Australian Inferred Resources are assumed to be mainly intended for export and hence unavailable for domestic use (as noted earlier).

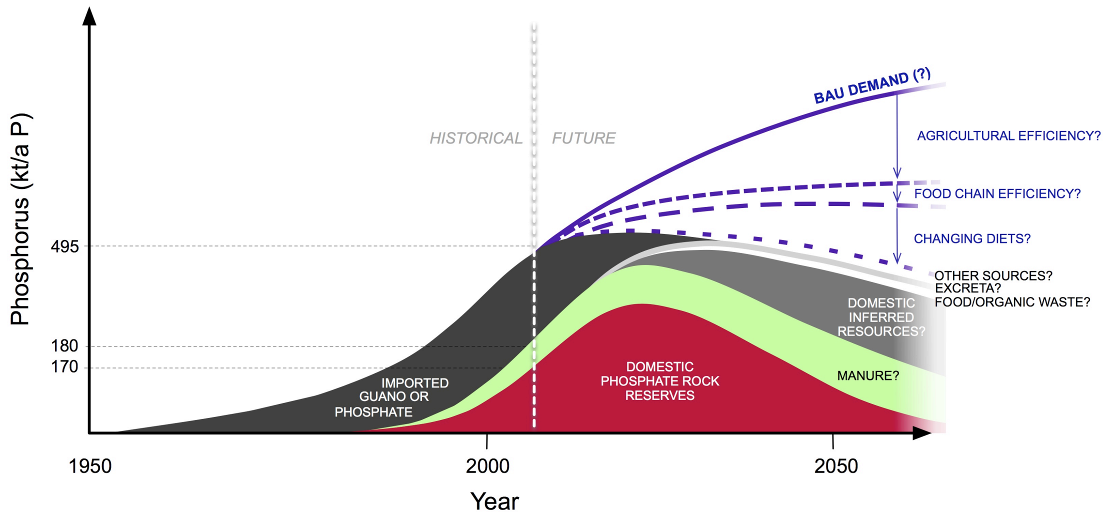

Figure 10. Filling the gap: a sustainable phosphorus scenario for meeting Australia's long-term phosphorus needs.

The remaining gap (between business-as-usual demand and supply from phosphate rock sources) can be largely met largely through efficiency gains and renewable phosphorus sources. In order to achieve the preferred scenario, a number of measures could be implemented by different stakeholders and sectors. Whilst substantial opportunities exist in the agricultural sector (see Reviews II - IV), it will be essential that sustainability initiatives take place in other sectors, including the mining and fertiliser sector, food sector, sanitation and waste sector and environmental management sectors. Addressing these other sectors will be essential to both securing a sustainable phosphorus future for Australia, and, for understanding the implications for agriculture.

In the agricultural and livestock sectors, sustainable phosphorus use measures can substantially reduce the overall demand for phosphorus, while maintaining Australia's productivity, reducing deleterious environmental impacts and supporting farmer livelihoods. Measures include soil testing and fertiliser selection placement and timing to ensure local soil fertility needs are met (without under or over-fertilising); soil improvement to reduce erosion losses and increase availability of existing soil phosphorus to plant roots, and plant selection and optimisation (IFA, 2009). Figure 11 conceptualises these interventions and Reviews II - IV discuss such measures at length referring to specific cropping and pasture systems within Australia. These measures can minimise the need for external phosphorus application, maximise productive uptake of phosphorus by plant roots and/or reduce losses to soil or water (Cornish, 2009; Richardson et al., 2009). Phosphorus demand could also be reduced be reconsidering the profile of the agricultural sector, including exports. That is, optimising the agricultural sector to produce more low phosphorus-demanding commodities.

Interventions in the livestock sector can include animal selection or breeding for minimising phosphorus requirements, feed management for maximising productive use of phosphorus in feed (e.g. through phytase enrichment), and productive use of manures and farmyard organic material as fertiliser supplements (refs).

Table 5. Supply-side measures: Key assumptions and challenges for sustainable long-term phosphorus scenarios for Australia.

Source	Goal (2025)	Goal (2050)	Assumptions	Key challenges
1. IMPORTED PHOSPHATE ROCK & GUANO	< 5% imports by 2025	Negligible % of imports by 2050	Australia needs to reduce dependency on imports due to 1. geopolitics (ethics associated with supporting Moroccan occupation of Western Sahara, and, volatility and risk of disruption of supply), 2. energy/environmental impacts associated with mining/processing & transport, 3. increasing transport (sea freight) costs, 4. Increasing price of phosphate rock and fertilisers both long-term and short-term volatility.	1. currently all phosphate producers blend domestic phosphate rock with imported rock, due to higher quality of imported rock. This may make it challenging to eliminate imports.
2. DOMESTIC PHOSPHATE ROCK	60-70 % of P demand sourced from domestic phosphate rock by 2025	Less than 50% of P demand sourced from domestic phosphate rock by 2050	Need to diversify sources of phosphorus for: 1. securing national productivity (no disruptions to P supply); 2. farmer security (reduced price volatility), 3. environmental impacts of phosphate rock mining/processing, 4. peak phosphorus.	1. current trend towards increasing investments in domestic phosphate rock deposits, despite lower quality. Could result in lock-in. 2. psychological challenge - current perception that BAU (i.e. mining phosphate rock is the right way to go in the future); 3. Need to take into account lag time (e.g. 5-10 years) due to substantial infrastructure changes required.
3. MANURE	~ 85% productive reuse on pastures or as crop fertiliser	~ 95% productive reuse on pastures or as crop fertiliser	1. Total amount of manure available depends on changing diets scenario (i.e. less meat consumption means less livestock numbers and less manure generated); 2. P recovery from manure can also reduce P pollution of water bodies (but might not be as big a problem in some Australian contexts where livestock production are not in the vicinity of water bodies); 3. Manure is also a good soil conditioner.	1. Can be challenging to physically recover and logically transport to end user, unless mixed systems with both livestock and crop production; 2. Need to take into account lag time (e.g. 5-10 years) due to substantial infrastructure changes required.

4. FOOD & ORGANIC WASTE	> 90% productive reuse as crop fertiliser	> 90% productive reuse as crop fertiliser	1. approximately half of food/organic waste can be avoided, the remainder can be recovered and reused. 2. Recovering food/organic waste can also reduce waste to landfill; 3. Composted organic waste can also be good soil conditioner (improving microbiology of soil).	1. bulky to transport for processing and reuse (if not possible to compost and reuse onsite); 2. Large distances between generation of urban organic wastes and farms (use in horticulture/landscaping may be more appropriate); 3. Quality risk if food/organic waste mixed with other wastes containing heavy metals or other toxic substances.
5. EXCRETA	> 70% productive reuse as crop fertiliser (= 8.26 kt of P)	> 95% productive reuse as crop fertiliser (= 14.6 kt of P)	1. % P in excreta depends on changing diets scenario (less meat/dairy results in lower % P in urine and faeces); 2. Recovery from excreta and other wastewater fractions can also reduce P pollution of water bodies; 3. Composted organic waste can also be good soil conditioner (improving microbiology of soil); 4. P in excreta may reduce from 1.5g/capita/day, to 1.2 g/capita/day with reduced meat intake, and reduced overeating. Total excreta production in 2025 and 2050 would therefore be 12 kt/a of P and 15 kt/a of P.	1. Possible lag-time (e.g. 5-10 years) to develop required infrastructure; 2. Psychological barrier to reusing human excreta and novel toilet systems that separate urine and faeces (e.g. urine-diverting toilets); 3. More appropriate institutional arrangements required for management and financing of phosphorus recovery from excreta, including clear roles and responsibilities for different stakeholders.
6. OTHER (CROP RESIDUES, ANIMAL MEAL, ALGAE, ETC)	> 90% productive reuse of crop residues; other sources to fill in demand	> 90% productive reuse of crop residues; other sources to fill in demand	1. Animal carcasses (especially bone) contain a substantial amount of phosphorus; 2. A large part of crop residues are (or can be) left on the field after harvest and reintegrated into the soil, where phosphorus can become mineralised and add to soil P stock; 2. Other sources from outside the food production system can be used (e.g. algae, seaweed).	2. May require sterilizing temperatures, especially regarding concerns of spread of livestock diseases (BSE, Foot and Mouth);

Table 6. Demand measures: Key assumptions and challenges for sustainable long-term phosphorus scenarios for Australia.

Demand measure	Goal (2025)	Goal (2050)	Assumptions	Key challenges
1. AGRICUTLRUAL EFFICIENCY	Reduce farm P demand by 35%	Reduce farm P demand by 50%	1. large gains in efficiency to be made here (optimising plant, soil, root phosphorus dynamics, fertilization strategies; 2. good for farm economy and 3. reduced runoff (pollution); 3. buffers etc may have greater impact on pollution prevention, but also prevents P from being lost permanently from the field. Livestock phytase - 1. reduce P demand, 2. reduces P in manure and therefore pollution risk	1. difficult to generalise across Australia and difficult to quantify soil P losses and flows; 2. GM plants involves high uncertainty/risks
2. FOOD CHAIN EFFICIENCY	<15% avoidable losses	<10% avoidable losses	1. assuming around 50% of current food waste is avoidable (e.g. edible food, or spillages due to bad management); 2. also better for household economy (saves money on wasted food); 3. Less waste to landfill	1. the food chain (from harvest to dinner table) is long and varied, therefore would need to look at opportunities for increasing efficiency in different parts of the chain and in different sectors; 2. Supermarkets are powerful stakeholders, and large wasters of food, therefore need to ensure this stakeholder is on board.
3. CHANGING DIETS	Reduce consumption of high P demanding animal products (e.g. feedlot cattle) by 25%	Reduce consumption of high P demanding animal products (e.g. feedlot cattle) by 50%	In addition to substantially reducing P demand, changing diets can also: 1. reduce climate change impacts, 2. Reduce energy consumption, 3. Reduce water consumption, 4. improve health in over-consuming cultures; 5. This measure may be the lowest hanging fruit (i.e. low cost to implement with high returns for reducing phosphorus demand).	1. may be difficult to implement politically and socially; 2. Not all animal products have the same phosphorus intensity – need to look at which contain the most embodied phosphorus.

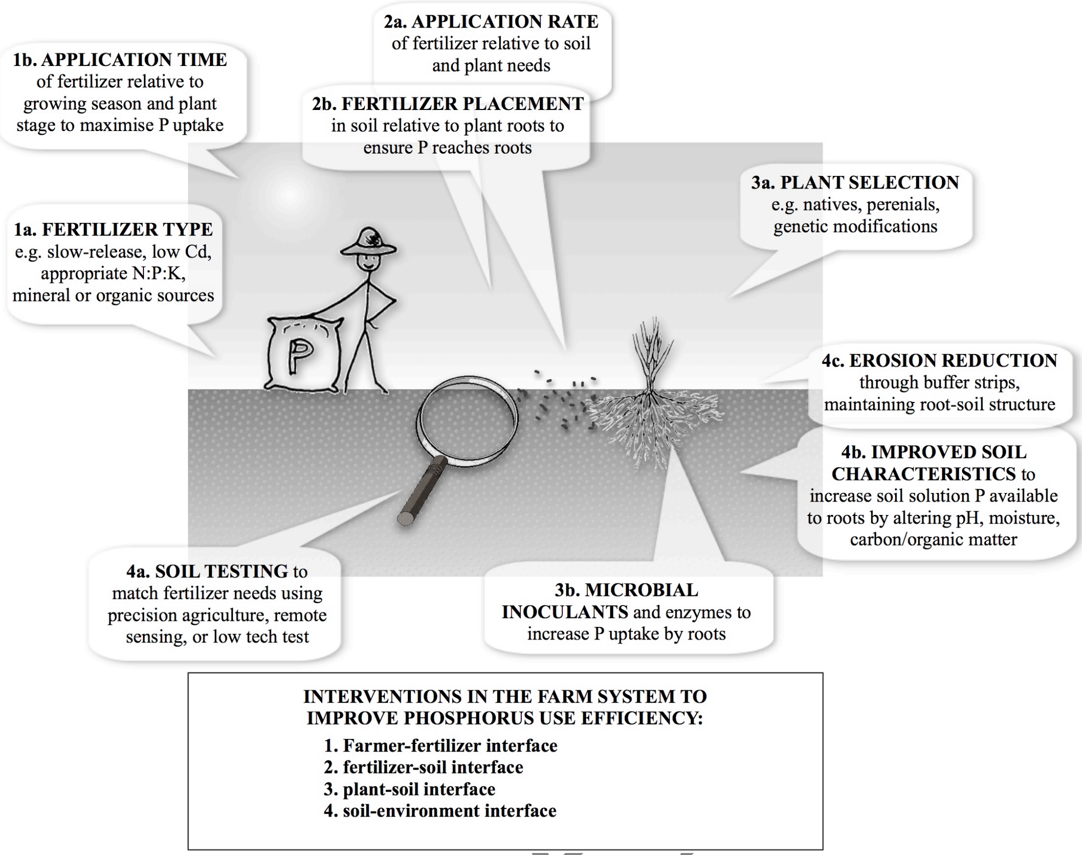

Figure 11. Measures to increase phosphorus use efficiency in agriculture – interventions in fertiliser selection and use, soil management and plant management.

Although often overlooked, there can be opportunities for efficiency gains in the mining and fertiliser sector. A recent study undertaken by the International Fertilizer Industry Association found that average losses during mining, beneficiation and fertilizer processing are in the order of x% (Prud'Homme, 2010). These losses can be reduced through improved management (such as reducing spillages). Other potential sustainable measures in the phosphate mining and fertiliser sector include (UNEP, 2001; Cordell, 2010):

- Minimising onsite environmental and social impacts (e.g. pollution/breaching of tailings dams);
- Invest in renewable sources of phosphorus that can be sold on the market;
- Invest in efficient technologies (e.g. for Cadmium removal);
- Contribute to mitigating downstream impacts, in accordance with Extended Producer Responsibility frameworks; and
- Ensure short and long-term P availability and accessibility to farmers.

Following harvest, there are numerous intervention points in the food production and consumption system to reduce the demand for phosphorus through increased efficiency. However much of the phosphorus is exported in agricultural commodities (including wheat and live sheep exports), and hence processed into food overseas. This leaves little opportunity to recover phosphorus from the resulted food waste in exported products in the Australian food system. In the domestic food production, processing and retailing sector, sustainable measures might focus on either reducing avoidable phosphorus losses in organic and food waste (e.g. reducing spillages or wastage of edible food) and seeking to compost and reuse the phosphorus in unavoidable waste (such as banana peels and oil press cake waste). This includes all food processing stages post harvest to food retailing to final consumers (Cordell et al., 2009b)(ref).

Food consumers (the final end users of most phosphorus) can collectively contribute to increased phosphorus use efficiency in the food chain, through measures such as improved food planning and shopping to reduce wastage (e.g. spoilage), use of leftovers, and avoid disposal of edible foods (even if their stated used by date has passed) (Lundqvist et al., 2008; Baker et al., 2009). Composting unavoidable waste (including both kitchen and garden and other organic matter around the house) can enable phosphorus in organic matter to be recovered for reused locally (Zero Waste Australia, 2008). Australians (and the global population) will also need to confront diets and shift towards less resource-intensive diets lower down the food chain. At the global scale, it was estimated that global phosphorus demand could be reduced by x% if x% ate less meat and dairy products (Cordell et al., 2009b). This will reduce the demand for livestock both within Australia and globally, which will in turn reduce the generation of manure.

The available manure will need to be more productively (and efficiently) recovered and reused for its phosphorus (and other nutrient) value. This means a high recovery rate, and transporting and reusing nutrients where they are needed, rather than spreading manure for disposal purposes. New technologies are emerging that extract and concentrate the phosphorus in bulky manures and other animal wastes, such as through struvite[30] precipitation or incinerator ash (refs). This can have substantial benefits in Australia where potential transport distances may be great.

Similarly, phosphorus in human excreta will need to be productively recovered for reuse as fertiliser. Human excreta currently represents a very small fraction (2-3%) of phosphorus demand in Australian agriculture - compared to the global average of 20% (Cordell et al., 2009a)) - largely because most of the phosphorus in food produced in Australia ends up in the urine and faeces of overseas food consumers. However due to the concentration of human settlements along the Australian coast, cities are essentially ‘phosphorus hotspots’ from excreta (and food waste). Indeed, urine is the largest single source of phosphorus emerging from cities (Jönsson, 2001). This presents an opportunity for phosphorus recovery from urban sanitation provision and reuse in horticultural fields in peri-urban areas. Indeed, Tangsubkul (2005) found that xxx. While there are few integrated studies analysing the most optimal means to recover and reuse phosphorus from excreta in the Australia context, water and sanitation service providers will need to treat Australia’s sewage in a way that facilitates both the efficient recovery and reuse of nutrients through energy-efficient and cost-effective means (Cordell, in press).

Policy makers at the federal, State or local government levels will play an important role in securing a sustainable phosphorus future for Australia through such measures as:

- initiating dialogue and consensus building between stakeholders;
- Facilitating or initiating a coordinated response to phosphorus scarcity, including independent research;
- Identify key policy priorities for Australia;
- Build in sustainable phosphorus knowledge into relevant educational curriculum, including practical aspects such as school garden that may be fertilized from organic waste produced from urine-diverting toilets and/or

[30] struvite is ammonium magnesium phosphate crystals high in phosphorus.

food and landscape waste compost.

Possible policy instruments to implement measures:

- *Regulatory* instruments, such as targets (e.g. recovery of P from excreta or manure etc); limits (e.g. discharge limits on P to sensitive waterways); or bans;
- *Economic* incentives such as taxes (e.g. P tax) or trading scheme (e.g. P trading scheme in a catchment)
- *Communicative*/Educational instruments such as stakeholder engagement processes and outreach (e.g. workshops, seminars); developing stakeholder-specific resource material.

7 CONCLUSIONS

7.1 Key findings

If no changes are made to the current phosphorus use trajectory, future phosphorus scarcity will likely compromise the world's ability to produce food in the long-term, including the productivity of the Australian food system. The Australian food system is far from sustainable in that it has substantial inefficiencies and is highly dependent on phosphorus imports and hence vulnerable to global changes, such as peak phosphorus and volatile markets.

Australia needs to act now to develop strategies for sustainable phosphorus use throughout its entire food production and consumption system. While further research is required to quantify measures and scenarios, securing a sustainable phosphorus future can likely be achieved through decreasing dependence on imported and domestic rock, diversifying phosphorus sources by investing in renewable phosphorus fertilisers, increasing efficient use throughout the system (not just in agriculture) and maximising recovery and reuse of phosphorus. These measures will also have positive environmental impacts by reducing water pollution, water demand, landfill waste and energy consumption.

However, achieving such a scenario will require substantial changes to the currently fragmented institutional arrangements surrounding the food system. For example, developing new partnerships and policies between the wastewater and fertiliser sector. Further science and research is urgently required due to the limited knowledge of the stocks and flows and the historical lack of attention to this crucial issue. There is a need to build capacity within government, industry and the research community to develop frameworks for dealing with the issue.

7.2 Research gaps and priorities

There are a number of key research gaps in the Australian context that will need to be addressed in order to ensure an appropriate policy response. A national dialogue – including all key stakeholders - is urgently required. Plausible and preferred phosphorus scenarios need to be developed collaboratively and implications identified. But first, new knowledge regarding baseline phosphorus flows is required upon which cost-effectiveness and energy implications of various alternatives to reduce phosphorus demand and increase recovery can be analysed, and policy mechanisms identified. Development of an integrated framework would allow consistent analysis of a disparate group of potential sustainable phosphorus measures – from analysing potential gains from investing in soil testing through to struvite precipitation from recovered excreta. More specifically, priority research needs include:

1. Improved baseline data collection to feed into future research and inform decision-making:
    a. A complete understanding of Australia's phosphate trade, including Christmas Island production and reserves;
    b. Proportion of phosphorus lost to water and non-agricultural soils, versus temporary soil stock, and, to what extent this is from fertiliser rather than soils erosion generally;
    c. Optimal mix of agricultural exports, in terms of more output per fertiliser inputs (currently the mix is weighted towards phosphorus-intensive export commodities;
    d. Organic phosphorus flows – inputs, outputs and accumulations of: manure, excreta, crop residues, food waste.

2. Business-as-usual future trends that will affect Australia's phosphorus demand or use – including changing diets, requirements for Australian agricultural soils to reach critical phosphorus levels, export trends.

3. The most appropriate means to recover and reuse phosphorus in the Australian context, taking into account recovery potential (ie. % P recoverable), logistics (e.g. location of source and end user), life-cycle energy use, life-cycle costs, effectiveness of recovered phosphorus as a fertiliser.

4. The infrastructure and socio-technical changes that would be required to recover and reuse phosphorus in the Australian context (such as urban phosphorus recovery units, household toilet use, fertiliser application technology).

5. Determining what the most effective institutional arrangements and appropriate policy options would be to achieve these goals (for example, from supporting farmers to stimulating markets for renewable phosphorus fertilizers through subsidies).

6. The costs, and marginal costs associated with supply and demand management measures.

7. The life cycle energy costs of the current system (business as usual) relative to alternative scenarios.

8. Synergies and conflicts with other sectors, including the water, sanitation, energy and food sectors (for example, from wastewater, nutrients, irrigation water and energy can be recovered, whilst providing a sanitation service).

APPENDIX A:

PHOSPHATE TRENDS: IMPORTS, EXPORTS AND PRODUCTION

A-1: Data sources for historical phosphate trade and assumptions

Figure 3 was created using data compiled from publicly available mineral statistics dating back to 1942. The British Geological Survey holds a large database on the production and trade of minerals, and within their website there is a World Mineral Statistics archive which has been utilised for phosphate rock trade data. The British Geological Survey has evolved over the years from the Colonial Geological Surveys, and has had many name changes between. More recent and reliable data has been sourced from ABARE - Australian Commodities Statistics 2009.

Assumptions:

- 1942-2003, global phosphate rock grades at 31% P_2O_5

- 2003-2008, global phosphate rock grades at 31% P_2O_5, Australian phosphate grades at 24% P_2O_5

Line graph data sources:

- 'Production' data: 1942-2007 British Geological Survey (Colonial Geological Surveys, 1950; Colonial Geological Surveys, 1956; Overseas Geological Surveys, 1962; Overseas Geological Surveys, 1964; Overseas Geological Surveys, 1966; Institute of Geological Sciences Overseas Division, 1967; Institute of Geological Sciences, 1971; Institute of Geological Sciences, 1978; Institute of Geological Sciences, 1980; British Geological Survey, 1984; British Geological Survey, 1987; British Geological Survey, 1991; British Geological Survey, 1994; British Geological Survey, 1996; British Geological Survey, 2000; British Geological Survey, 2005; British Geological Survey, 2009)

- 'Import' data: 1941-1972 British Geological Survey; 1971-2008 ABARE (Colonial Geological Surveys, 1950; Colonial Geological Surveys, 1956; Overseas Geological Surveys, 1962; Overseas Geological Surveys, 1964; Overseas Geological Surveys, 1966; Institute of Geological Sciences Overseas Division, 1967; Institute of Geological Sciences, 1971; Institute of Geological Sciences, 1978; Institute of Geological Sciences, 1980; British Geological Survey, 1984; British Geological Survey, 1987; British Geological Survey, 1991; British Geological Survey, 1994; British Geological Survey, 1996; British Geological Survey, 2000; British Geological Survey, 2005; British Geological Survey, 2009; ABARE, 2009)

- 'Export' data: 1941-1998 British Geological Survey; 1998-2008 ABARE (Colonial Geological Surveys, 1950; Colonial Geological Surveys, 1956; Overseas Geological Surveys, 1962; Overseas Geological Surveys, 1964; Overseas Geological Surveys, 1966; Institute of Geological Sciences Overseas Division, 1967; Institute of Geological Sciences, 1971; Institute of Geological Sciences, 1978; Institute of Geological Sciences, 1980; British Geological Survey, 1984; British Geological Survey, 1987; British Geological Survey, 1991; British Geological Survey, 1994; British Geological Survey, 1996; British Geological Survey, 2000; British Geological Survey, 2005; British Geological Survey, 2009; ABARE, 2009)

A-2: Data sources for historical Nauruan and Christmas Island phosphate production and Australian phosphate rock imports

Figure 4 was created using the British Geological Survey's World Mineral Statistics archives like Figure 3.

Assumptions:

- 1942-1998, global phosphate rock grades at 31% P_2O_5

Line graph data sources:

- Australian import data: 1942-1998 British Geological Survey (Colonial Geological Surveys, 1950; Colonial Geological Surveys, 1956; Overseas Geological Surveys, 1962; Overseas Geological Surveys, 1964; Overseas Geological Surveys, 1966; Institute of Geological Sciences Overseas Division, 1967; Institute of Geological Sciences, 1971; Institute of Geological Sciences, 1978; Institute of Geological Sciences, 1980; British Geological Survey, 1984; British Geological Survey, 1987; British Geological Survey, 1991; British Geological Survey, 1994; British Geological Survey, 1996; British Geological Survey, 2000)

- Nauru export data: 1941-1972 British Geological Survey; 1971-2008 ABARE (Colonial Geological Surveys, 1950; Colonial Geological Surveys, 1956; Overseas Geological Surveys, 1962; Overseas Geological Surveys, 1964; Overseas Geological Surveys, 1966; Institute of Geological Sciences Overseas Division, 1967; Institute of Geological Sciences, 1971; Institute of Geological Sciences, 1978; Institute of Geological Sciences, 1980; British Geological Survey, 1984; British Geological Survey, 1987; British Geological Survey, 1991; British Geological Survey, 1994; British Geological Survey, 1996; British Geological Survey, 2000)

- Christmas Island export data: 1941-1998 British Geological Survey; 1998-2008 ABARE (Colonial Geological Surveys, 1950; Colonial Geological Surveys, 1956; Overseas Geological Surveys, 1962; Overseas Geological Surveys, 1964; Overseas Geological Surveys, 1966; Institute of Geological Sciences Overseas Division, 1967; Institute of Geological Sciences, 1971; Institute of Geological Sciences, 1978; Institute of Geological Sciences, 1980; British Geological Survey, 1984; British Geological Survey, 1987; British Geological Survey, 1991; British Geological Survey, 1994; British Geological Survey, 1996; British Geological Survey, 2000)

APPENDIX C

AUSTRALIAN CODE FOR REPORTING OF EXPLORATION RESULTS, MINERAL RESOURCES AND ORE RESERVES (THE 'JORC CODE')

Geoscience Australia compiles data reported for individual deposits by mining companies into a national mineral resources database and this is then used to prepare an annual national assessment of Australia's mineral resources. Only mining companies listed on the Australian Securities Exchange are required to report publicly on Ore Resources and Mineral Resources under their control, using the *Australian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves* (the 'JORC Code' weblink). Foreign-listed, private and private equity companies involved in mining and mineral exploration are not required to report these figures, and therefore total mineral resource data and analysis of trends are difficult to quantify and potentially unreliable.

The national inventory system for mineral resources evolved from the McKelvey resource classification system and is compatible with the JORC code (Geoscience Australia, 2009). The system is based on two general criteria: i) the geological certainty of existence of the mineral resource, and ii) the economic feasibility of its extraction over the long term (Geoscience Australia, 2009), where Economic Demonstrated Resource (EDR) is the highest category and has a high level of confidence. EDR effectively combines JORC Code categories 'Proved Resources', 'Probable Reserves', 'Measured Resources' and 'Indicated Resources' (Geoscience Australia, 2009). Inferred Resources can be estimated with a low level of confidence, and usually lack adequate knowledge to classify the resources.

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