The Story of Phosphorus: missing global governance of a critical resource

Preliminary findings from 2 years of doctoral research

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Abstract

Phosphorus is a critical resource for food production in the form of fertilizers, yet current global phosphate reserves could be depleted this century. More concerning is a global peak in phosphorus production – peak phosphorus – based on current official estimates of world resources, is estimated to occur around 2030, only decades after the likely peak in oil production. The situation for phosphorus is worse than for oil however, as there is no substitute for phosphorus in food production. Demand for phosphorus will increase over the next 50 years as the world population is projected to increase by 50% and with changing diets. While the exact timing of peak production might be disputed, it is widely known within the industry that the quality of remaining phosphate rock is decreasing, and costs are increasing. The price of phosphate rock has increased 700% in 14 months alone. Yet unlike water, energy and nitrogen, there is no international organisation which has taken on responsibility for the long-term stewardship or management of phosphorus resources for global food security. Institutional arrangements surrounding the global phosphorus cycle are fragmented and phosphorus sustainability is perceived quite differently by different stakeholders. In the absence of any deliberate international oversight, phosphorus resources are governed by the forces of the international market and national interest. Furthermore, control of phosphate commodities is in the hands of only a few producing and exporting countries. While the recent price spike in phosphate rock will trigger further innovations in and adoption of phosphorus recovery and efficiency measures, the market alone is not sufficient to manage phosphorus in a sustainable, equitable and timely manner. Significant institutional changes will be required in the future. There is no single 'quick fix' solution to solving mineral phosphorus scarcity, however substantial opportunities exist for recovering phosphorus from human excreta, food waste, manure, reducing global demand through increasing efficiency in both agricultural use of phosphorus fertilizers and reducing losses in the food commodity chain and influencing diets. This paper presents the preliminary findings from research on the physical and institutional dimensions of the sustainability of global phosphorus resources for global food security.

Keywords: phosphorus scarcity, sustainability, global food security, peak phosphorus, phosphate rock, reuse, global governance.

1 Introduction: global phosphorus supply, demand and geopolitics

All modern agriculture is today dependent on continual inputs of phosphate fertilizer from mined rock to replenish the soil with what is taken away by harvested crops. Yet phosphate rock is a non-renewable resource and we have approximately 50-100 years left of current known reserves (Steen, 1998; Smil, 2000b; Gunther, 2005). The reserves that do exist, are under the control of a handful of countries, including China, US and Morocco. While China has the largest reported reserves, it has recently imposed a 135% export tariff on phosphate, effectively banning any exports in order to secure domestic supply. US, historically the world's largest producer, consumer, importer and exporter of phosphate rock and phosphate fertilizers, has approximately 25 years left of domestic reserves (Stewart et al., 2005; Jasinski, 2008). US companies import significant quantities of phosphate rock from Morocco to feed their phosphate fertilizer plants (Jasinski, 2008). This is geopolitically sensitive as Morocco currently occupies Western Sahara and its massive phosphate rock reserves, contrary to international law. Trading with Morocco for Western Sahara's phosphate rock is highly condemned by the UN and importing rock via Morocco has been boycotted by several Scandinavian firms (The Norwegian Support Committee for Western Sahara, 2007; Corell, 2002).

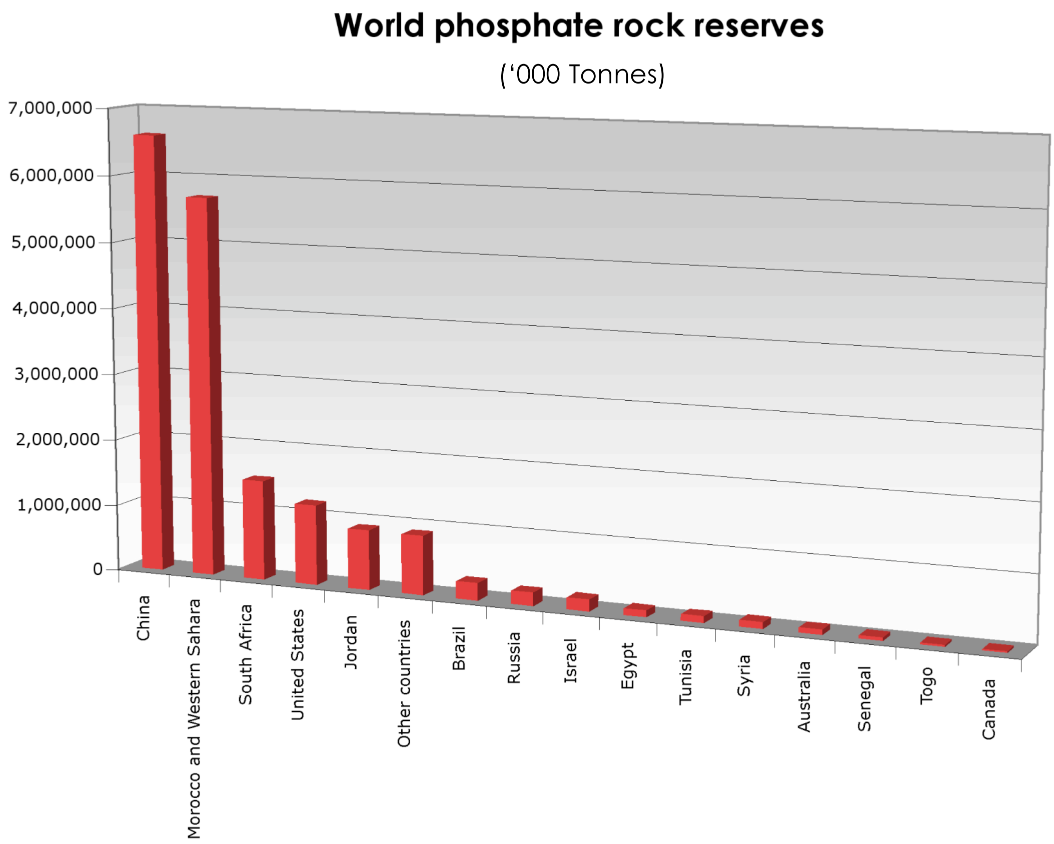

Figure 1: Global phosphorus reserves are highly geographically concentrated and are under the control of only a handful of countries. (data: Jasinski, 2008)

Historically, crop production relied on natural levels of soil phosphorus with the addition of organic matter like manure and in parts of Asia human excreta (Mårald, 1998). To keep up with rapid population growth and food demand in the 20th Century, concentrated mineral sources of phosphorus were discovered in guano and phosphate rock and applied extensively (Brink, 1977; Smil, 2000b). Today, we are effectively addicted to phosphorus from mined phosphate rock. Without continual inputs we could not produce food at current global yields[1]. Following more than half a century of generous application of phosphorus and nitrogen, agricultural soils in Europe and Northern America are now said to have reached 'critical' phosphorus levels, and thus only require application to replace what is lost in harvest (FAO, 2006; European Fertilizer Manufacturers Association, 2000). However in developing countries and emerging economies the situation is quite different. In Sub-Saharan Africa for example, where at least 30% of the population is undernourished, fertilizer application rates are extremely low and 75% of agricultural soils are nutrient deficient[2] thus yields are falling (IFDC, 2006; Smaling et al., 2006). While UN's Humanitarian Officials have called for a new

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[1] The Green Revolution (including the production and application of mineral fertilizers) in the mid 20th Century is said to be responsible for increasing per capita nutritional intake and doubling crop yields IFPRI (2002).

[2] Soil nutrient deficiency is due to both naturally low phosphate soils and anthropogenic influences like soil mining and low application rates which have resulted in net negative phosphorus budgets in many parts of Sub Saharan Africa (Smaling et al, 2006).

Green Revolution in Sub-Saharan Africa, including increased access to fertilizers, to mitigate further ramifications of the global food crisis (Blair, 2008), there is little discussion on the finiteness of those phosphate fertilizers in the future[3]. Global demand is forecasted to increase by around 3% until 2010/11, with around 2/3 of this demand coming from Asia (FAO, 2007a).

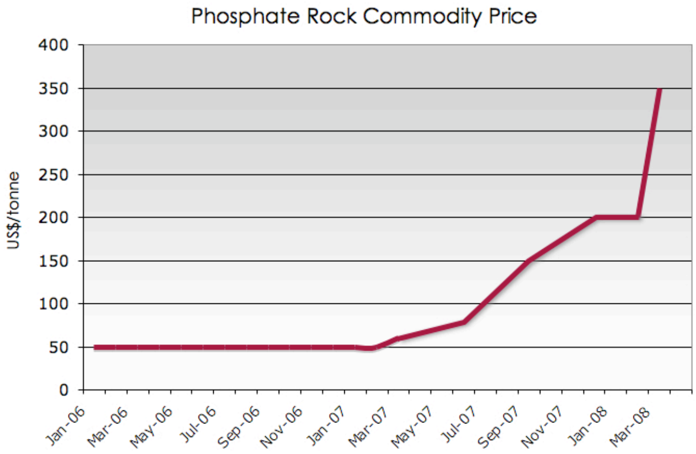

Figure 2: Phosphate rock commodity price (Morocco) increased 700% between January 07 and March 08 *(data: Minemakers, 2008)*

In 2007/8, the same pressures that have caused the recent global food crisis has resulted in a demand for phosphate rock and fertilizers exceeding supply and a price increase of 700% (figure 2). Increasing meat and dairy-based diets, especially in growing economies like China and India, require significantly more phosphorus fertilizer per capita (Cordell et al., submitted). Phosphate rock production and especially trade is linked to the price of oil. The recent sharp increase in biofuel production is not only competing for grains and productive land for food, but also for phosphorus fertilizers. The International Fertilizer Industry Association expect the fertilizer market to remain tight for at least the next few years (IFA, 2008). It is therefore anticipated that the price of phosphate rock and related fertilizers will continue to rise in the near future, until new mining projects such as in Saudi Arabia are commissioned (Heffer and Prud'homme, 2007). It can also be expected that the increased price of fertilizers has not yet impacted the current price of food and agricultural commodities. This may be felt following harvest and sale of this year's fertilized crops. Most farmers were completely unaware of the spike in price of fertilizers. In India, which is totally depended on phosphate imports, there have been instances of farmer riots and deaths due to the severe national shortage of fertilizers (Bombay News, 2008).

Despite increasing global demand for non-renewable phosphate rock both in the short and longer term, and its critical role in food production, global phosphate scarcity is missing from the dominant debates on global food security and global environmental change. For example, phosphorus scarcity has not received explicit mention within the Food and Agricultural Organisation of the UN (FAO, 2007a; FAO, 2006; FAO, 2005), International Food Policy Research Institute (IFPRI, 2005; IFPRI, 2002), the Global Environmental Change and Food Systems programme (GECAFS, 2006), International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD, 2008) and the recent High-level Conference on World Food Security hosted by FAO (FAO, 2008). The widening gap between supply and demand still remains in marginal discussions by few concerned scientists.

2 Methodology

Like other emerging challenges of global environmental change, the phosphorus situation itself crosses disciplinary boundaries, from physical to social and institutional sciences and hence demands a transdisciplinary research framework.

The analysis is framed by systems thinking, in that physical and social spheres are viewed each as systems and together as interlinked systems (figure 3). They are systems within systems. The physical systems analysis uses quantitative methods drawn from industrial

[3] A recently published paper on "Long-term global availability of food: continued abundance or new scarcity?" (Koning et al, 2008) does address phosphorus scarcity as a key factor likely to limit future food availability.

ecology (Brunner and Rechberge, 2004; Graedel, 1996) and the physical sciences to better understand the nature of the physical limits of phosphate rock in the context of food security ('what' and 'by how much'), and the potential for other phosphorus supply- or demand- side options. The institutional systems analysis uses more qualitative methods including stakeholder and institutional analyses (drawing from Glaser, 1998; Vatn, 2005; Young, 2002; Biermann et al., 2007) exploring 'how' phosphorus is perceived and 'why' it is not currently viewed as critical among the appropriate stakeholders, to gain insights into the institutional arrangements and power relationships that influence the issue, and to identify what would be required to move towards a more sustainable future. Checkland's Soft Systems Methodology (Checkland and Scholes, 1999) is used to frame the entire analysis[4].

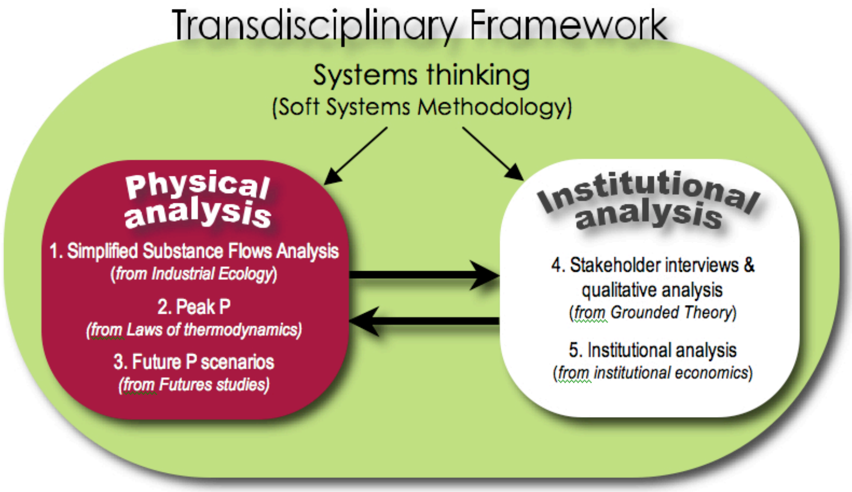

Figure 3: Transdisciplinary research framework, framed by systems thinking and incorporating both physical and institutional analyses.

Qualitative and quantitative data have been sourced from multiple sources, including the literature, in-depth international and Australian stakeholder interviews and unpublished 'oral' material via experts.

3 Physical dimensions of an unsustainable global phosphorus cycle

Analysing physical dimensions of the phosphorus situation involved an analysis of historical, current and future global flows of phosphorus for food production, including a peak phosphorus curve. It is important to note that available robust data to support such an analysis is scant, hence the analysis and findings are more indicative than conclusive. These findings also point to a immediate need for a more complete and transparent data set on global phosphorus resources and demand.

3.1 Phosphorus flows through the food system

The systems approach to understanding the phosphorus cycle, particularly through the global food production and consumption system, can aid identification of the magnitude and location of losses or inefficiencies in the system and thus to potential recovery points. A modification of the Substance Flows Analysis (SFA) tool from Industrial Ecology has been applied to track phosphorus within a defined boundary[5]. This simplified SFA tracks the major flows of P through society in relation to food production and consumption, as 90% of societies use of P

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[4] The application of Soft Systems Methodology is not included in this paper, however it is covered in detail in Cordell (2008).

[5] SFA quantifies the material inputs and outputs from processes and stocks within a system of concern (typically expressed in kg or tonnes/year) to better understand pollution loads on a given environment, and determine places to intervene in a system to increase its efficiency, or reduce wastage/pollution for example Brunner & Rechberge (2004).

is for food production.

The findings are summarised in figure 4. The inner white area defines the system boundary (food related human activity), while the outer area is the 'natural' phosphorus biogeochemical system (in which the human activity system is embedded). The arrows indicate the rough quantities of phosphorus processed between each key stage (the boxes) in food production and consumption process, beginning with mining, fertilizer production, application to agricultural soil, harvesting of crops, food and feed processing, consumption by animals and humans, excretion and the final fate of phosphorus in the anthropogenic or natural environment or its recirculation.

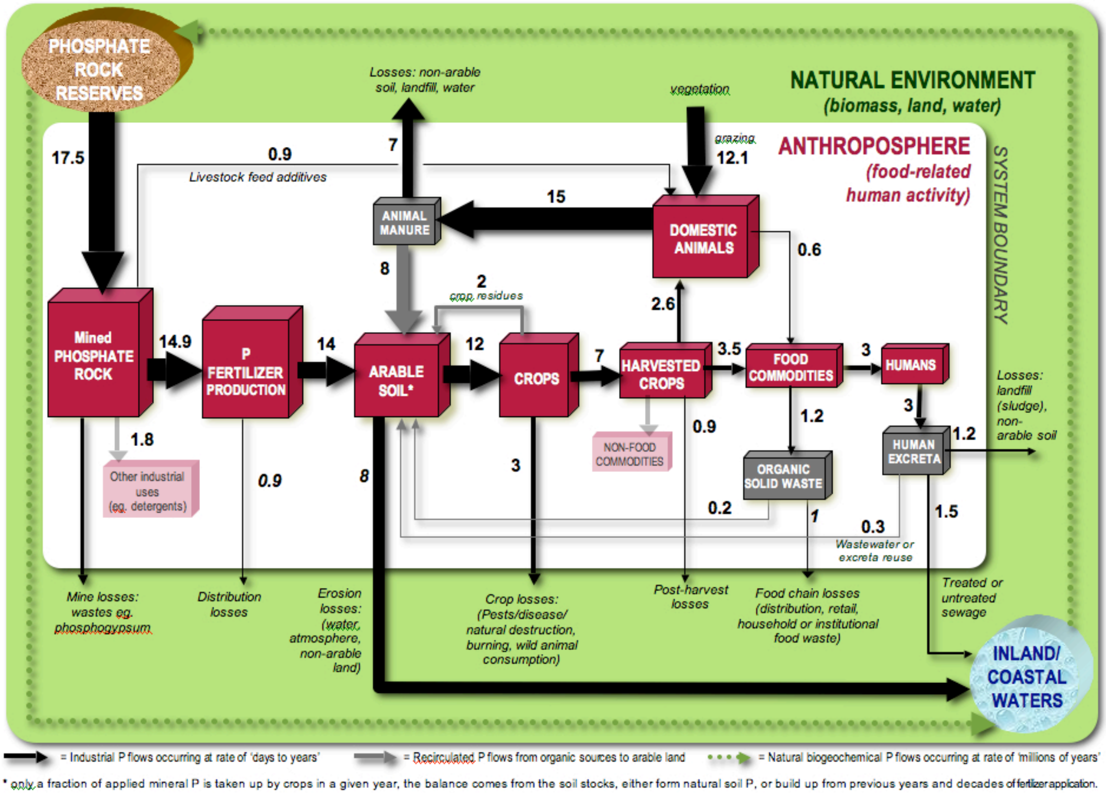

Figure 4: Major global phosphorus flows through the food production consumption system. Width of arrows indicates size of flux. Units are in million (metric) tonnes of phosphorus per year. (*source: Cordell, Drangert and White, submitted*).

From the figure, we can determine that while humans are only consuming around 3 MT P per year, we are mining 5 fold this amount (14.9 MT P) for food production[6] (Cordell et al., submitted). Significant losses occur throughout the system – from mine to field to fork. Calculations based on Smil (2000a; Smil, 2002) suggest total phosphorus in global harvests is approximately 12 MT P of which 7 is processed for feed and food and fibre, while around 40% of the crop residues remaining are returned to land[7].

Once crops take up phosphorus and are harvested for use in feed and food production, it is estimated that 55% of P is then lost in the commodity chain between 'farm and fork'. Smil (2000a) estimates that around 50% of the P consumed and hence excreted by livestock is returned to agriculture globally. However there are significant regional imbalances, such as

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[6] Our bodies only require roughly 1.2 g/person/day for healthy functions, which equates to approximately 3 MT P globally.

[7] This is relatively consistent with estimates by Liu et al (2008), published after this analysis. Both analyses have drawn heavily from Smil, so this is not exceedingly surprising. The actual amount lost from agricultural fields that is directly attributed to applied phosphate fertilizer is very difficult to calculate, as soil phosphate chemistry is complex and available phosphorus can move to unavailable forms and back again.

an oversupply of manure in regions where a critical soil P has already been reached (such as The Netherlands or North America), and a lack of manure in regions where soils are most phosphorus-deficient (such as Sub-Saharan Africa or Australia) (Runge-Metzger, 1995; Smaling, 2005).

Every year, the global population excretes around 3 million tonnes of P in the form of urine and faeces. Given more than half the world's population are now living in urban centres, and the urbanisation trend is set to increase (FAO, 2007b), cities will become P sinks and P 'hotspots' of human excreta and organic 'waste' (Cordell et al., submitted). Indeed, urine is the largest single source of phosphorus emerging from cities. While most excreta ends up in water bodies or non-arable land, It is estimated that on average, around 10% is currently recirculated back to agriculture or aquaculture either intentionally or unintentionally, such as poor urban farmers in Pakistan diverting the city's untreated wastewater to irrigate and fertilize the crops (Ensink et al., 2004), or pit or composting toilets in rural China, Africa and other parts of the world (Esrey et al., 2001). Recirculating urban nutrients such as urine back to agriculture therefore presents an enormous opportunity for the future[8].

Finally, it is estimated that meat based diets can result in the depletion of up to twice the phosphorus compared to a vegetarian diet (Schmid-Neset et al., 2005; Tangsubkul et al., 2005; Cordell et al., submitted).

This sSFA analysis tells us that in addition to minimising P losses from the farm (losses estimated at around 8 MT P) to reduce algal blooms in receiving waterways, we must simultaneously address the P scarcity issue and hence also minimise losses in the food commodity chain (losses estimated at 2 MT P) and look for alternative renewable P sources, like manure (around 15 MT P), human excreta (3 MT P) and food residues (1.2 MT P) and other important mechanisms to reduce demand (such as optimising soil carbon to improve phosphate availability or influencing diets). This analysis also identifies where data is available and accurate, and where there are research gaps in our knowledge of P in the global food system.

3.2 Peak Phosphorus

In a similar way to oil and other non-renewable resources, the rate of global production of phosphate rock will eventually reach a maximum or peak, after which production will drop year upon year, seeing a widening gap between demand and supply (Hubbert, 1949). A conservative analysis using industry data suggests global peak phosphorus could occur by 2034 (figure 5)(Cordell et al., submitted), within decades of peak oil (estimated this decade). While small-scale trials of phosphorus recovery from excreta and other waste streams exist (CEEP, 2008), there are no alternatives on the market today that could possibly replace phosphate rock in any significant way. Significant physical and institutional infrastructure that could take decades to implement will be required.

[8] Human excreta (urine and faeces) are renewable and readily available sources of phosphorus. Urine is essentially sterile and contains plant-available nutrients (P,N,K) in the correct ratio. Treatment and reuse is very simple and the World Health Organisation has published 'guidelines for the safe use of wastewater, excreta and greywater in agriculture' (WHO, 2006; Esrey, et al., 2001; Drangert, 1998).

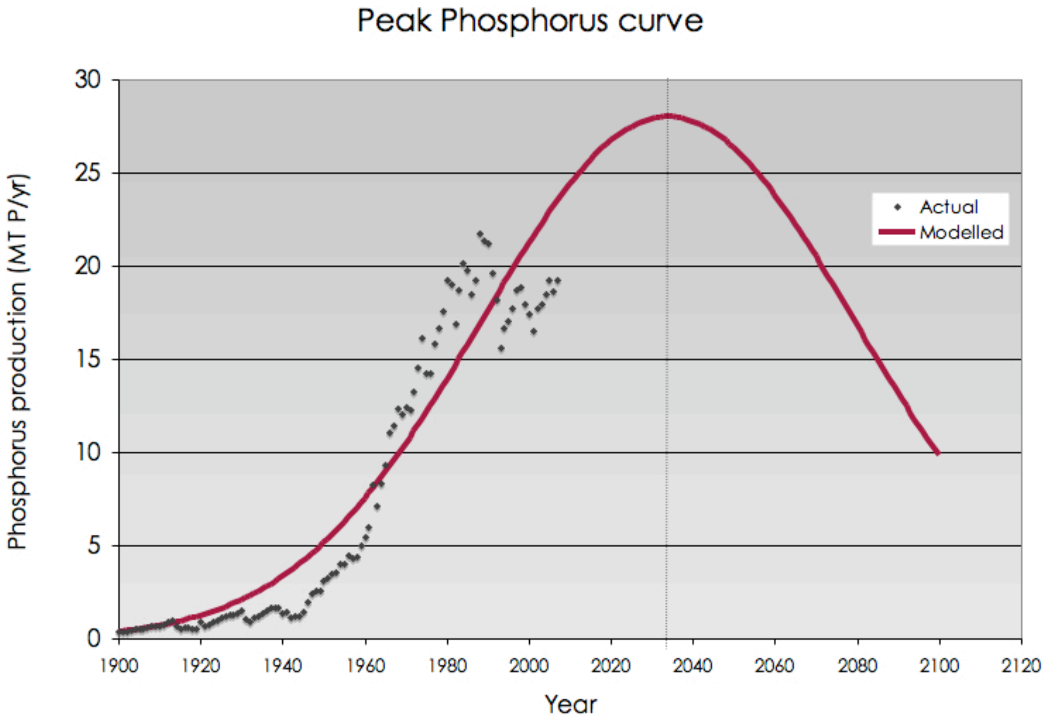

Figure 5: Peak phosphorus curve, illustrating that, in a similar way to oil, global phosphorus production is also likely to peak. (see: http://phosphorusfutures.net/index.php?option=com_content&task=view&id=16&Itemid=30, *adapted from Cordell, Drangert and White, submitted*).

While the timing of the production peak may be uncertain, and contested[9], the fertilizer industry does not deny that the quality of existing phosphate rock is declining, and cheap fertilizers will become a thing of the past. Processing and transporting phosphate fertilizers from the mine to the farm gate bears an ever increasing energy cost, which up to now relies on cheap fossil fuel energy. Phosphate rock is today one of the most highly traded commodities in the world (pers comm., Michel Prud'Homme 5/10/07). Figure 6 shows the longest conveyor belt in the world, transporting phosphate rock from Western Sahara's Bou Kra deposits.

[9] Some scientists (Pazik, 1976; Michael Lardelli pers comm 9/8/08) suggest USGS phosphate rock reserve data (on which this peak P estimate is based) is likely to represent an over-estimate, hence the real peak is likely to occur much sooner than the date predicted in this analysis). If production has been assumed to be at maximum capacity in the period to about 1990, this would suggest that peak production would have occurred at about that time (Dery and Anderson, 2007), but that reserves are approximately half of the amount estimated by the USGS.

Figure 6: Aerial Google map of Western Sahara, indicating the world's longest conveyor belt carrying phosphate rock 150 km from the inland Bou Kra mine to the port for collection by freight ships. The diagonal white line (starting from bottom right) is the Saharan desert sand blown up against the side of the conveyor belt. (*source*: Google maps, 2007)

With growing concern about peak oil and climate change, the current pattern cannot continue in the long term. Each tonne of phosphate also generates 5 tonnes of phosphogypsum with radium levels too high for reuse (USGS, 1999; Wissa, 2003) and are being stockpiled. Similarly, cadmium and other heavy metals which are increasingly present in high quantities must be removed from phosphate prior to use (Steen, 1998; Driver, 1998). Finally, the average grade of phosphate rock has been declining, and remaining reserves are less than 13% P, compared to 15% P in 1970s (IFA; 2006; Smil, 2002).

3.3 *The Australian case*

Analyses and solutions at one geographical scale are not necessarily transferable to other scales (Young 2002; Zurek and Henrichs, 2006, 2008). For this reason, a regional analysis was undertaken using the Australian continent as a case study[10]. Australia has a unique situation and the findings are by no means transferable to other regions, nor the global scale. However the methods used to assess the situation are transferable. This is what Zurek and Henrichs (2007) refer to as soft links that are 'coherent' across scales, that is, the same scenario logics apply, however the drivers are different, and the links are only 'soft', preventing full downscaling.

Prior to the arrival of European settlers, the most significant human induced flux of phosphorus by Aboriginal people was due to fire. They manipulated the environment through 'firestick farming' to reduce the build up of fuel in vegetation and increase the productivity of edible plants and animals. This mobilised significant quantities of P into the environment via smoke and ash, converting organic P in flammable vegetation into readily available inorganic P sources (Cordell, 2001). Since European settlement, Australia's economy is said to have been built 'on the sheep's back', in that agricultural and livestock exports have always represented a significant share of the Australian GDP (Commonwealth of Australia, 2001; Cordell and White, forthcoming). Australia's agricultural productivity was 'revolutionised' in the 20th century by the discovery and importation of cheap, high-grade, and highly available

[10] For a more complete discussion, see Cordell & White (*forthcoming*).

Nauruan phosphate: guano[11] (Garrett, 1996).

Figure 7 presents a simplified SFA of the major phosphorus flows through the Australian food production and consumption system. Organic sources such as manure have been excluded due to substantial lack of data or estimates (pers comm., Andre Leu, 12/03/08). While Australia has some of the most naturally phosphorus-deficient soils in the world, we have simultaneously invested in phosphorus intensive export industries, like wheat, beef and wool (Cordell and White, forthcoming). Australia has a net deficit of phosphorus in the food production and consumption system. Around 80% of the phosphorus in food and fibre produced in Australia is exported off Australian shores. However most of the depleted phosphate embodied in those commodities actually ends up unavailable in soils or washed off to waterways, where it is causing eutrophication of waterways and even causing damage to the Great Barrier Reef (Commonwealth of Australia, 2001).

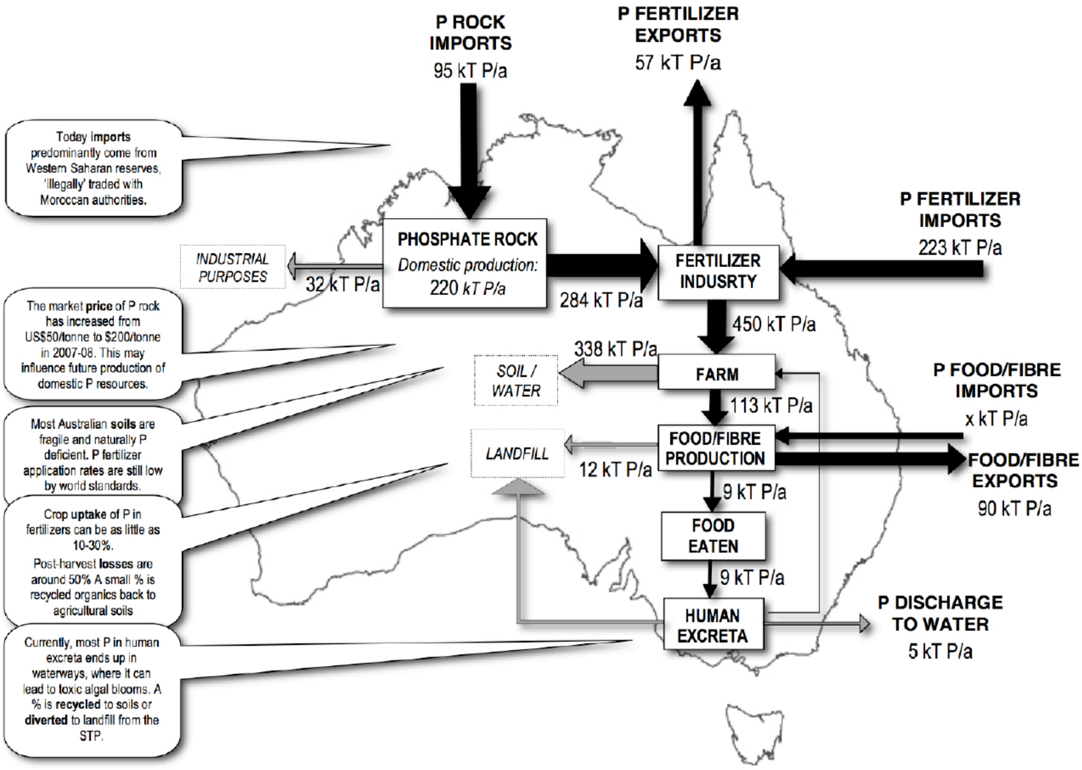

Figure 7: Major phosphorus flows in the production, consumption and trade of P commodities in Australia *(Cordell and White, forthcoming).*

The analysis indicates that only 2% of phosphorus in applied fertilizers ends up in the food Australians eat. Close to 100% of the P consumed in food is excreted from the human body. This means that while human excreta represents a significant fraction of phosphorus fertilizer needs globally (20% of current mineral fertilizer use), it presents a very small fraction (2%) of P demand in Australian agriculture. This means even if 100% human excreta were recirculated, Australia would still have a phosphorus deficit. While Australia does not have a food security problem per se, there is still a need to secure sustainable sources of phosphorus for food production in the future. A sustainable phosphorus future in Australia would still need to address the rising cost of fertilizers, the energy intensity of mineral fertilizer production and trade and the current support for an illegal occupation of Western Sahara by importing rock from Moroccan authorities or phosphate fertilizer from US companies. Similar

[11] Guano is bird and bat droppings that have been deposited over thousands of years. The guano deposits in Nauru were discovered by New Zealander Albert Ellis around 1906 (and around the same time in other South Pacific Islands, notably, Christmas Island, Banaban Islands, Kiribati), and subsequently claimed by the British Phosphate Commission – a joint venture between New Zealand, Australia and Britain. This led not only to exploitation of 80% of Nauru's non-renewable guano deposits, yet also resulted in the displacement of local populations and the Nauruan economy became entirely dependent on royalties from P mining (Garrett, 1996; Carty, 2007).

to the global situation, there is no obvious institutional home for the long-term sustainable management of Australia's phosphate resources for food production[12].

4 Institutional dimensions of phosphorus scarcity

This section synthesizes the preliminary findings from an institutional and stakeholder analysis. The soft systems methodology was used to frame the entire analysis, with inputs from the qualitative analysis of stakeholder interviews and an institutional analysis. Further, comparisons were drawn between water and phosphorus scarcity, and peak phosphorus and peak oil.

4.1 Stakeholder perceptions of phosphorus

The in-depth, face-to-face international stakeholder interviews[13] were undertaken in September 2007, prior to the recent oil and phosphate price shocks and the global food crisis. In these semi-structured interviews, respondents were asked a range of open-ended questions followed by probing follow-up questions. The purpose of the interviews was to explore how key international stakeholders perceived the sustainability of phosphorus in the context of global food security and what it would take to ensure all farmers have access to phosphorus in the long term, to meet global food demand, in a sustainable way, including roles and responsibilities.

International stakeholders positioned in the nexus between global phosphorus resources and food security are concerned about the sustainability of phosphorus, however there is no consensus the way the situation is perceived. Several respondents felt there was ample phosphate rock reserves to meet growing future demand for at least a few hundreds of years, and as phosphate rock becomes more scarce, the price will increase, which will in turn trigger new investments in mines and associated infrastructure and fuel technological innovation. These respondents rather though the more significant sustainability issues related to environmental pollution of surrounding land and water from phosphate rock mining, or phosphate runoff from agricultural fields or livestock production. Others felt a phosphate shortage was more imminent, and one respondent was also very concerned about the geopolitical tensions surrounding Morocco's occupation of Western Sahara and control of its' phosphate reserves, and US support for Morocco. Others did not believe the situation between Morocco and Western Sahara was or would present a significant problem for phosphate supplies in the future. At the time of the interviews, only one respondent had heard of the concept of 'peak phosphorus'. However several thought it was feasible, though not likely to be of immediate concern. Two of these thought *demand* for P would likely peak (due to population peak and nutrient-deficient soils reaching their critical point) before any P production peak would constrain supply. When probed, there was some concern among respondents regarding farmers access to fertilizer markets and the unsustainable situation of Sub-Saharan Africa's nutrient-deficient soils, however views on the key barriers that would need to be overcome and who's responsibility this is were widely divergent.

Whilst some of these stakeholder perceptions were complementary, others were conflicting (figure 8) and a possible cause for the lack of effective governance of P. This relates to Biermann *et al*'s (2007) notion of 'conflictive' institutional fragmentation (see discussion in section 4.2.1).

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[12] This ongoing participant-observation research will therefore include a one-day National Phosphorus Workshop to bring together key Australian stakeholders to discuss implications of global phosphate scarcity (and related sustainability and ethical issues) for Australia's food production and consumption system and vision possible future scenarios (see workshop details at the Global Phosphorus Research Initiative (2008) website: http://phosphorusfutures.net/index.php?option=com_content&task=view&id=23&Itemid=36)

[13] These included international representatives of global food security, the environment, the fertilizer industry, geological mineral reserves, sustainable sanitation and public health. The respondents organisational identity has been kept confidential in this paper until the research ethics process is complete. However it is anticipated that organisational identity attributed to specific quotes and perspectives will be included in more detail in Cordell, *forthcoming*.

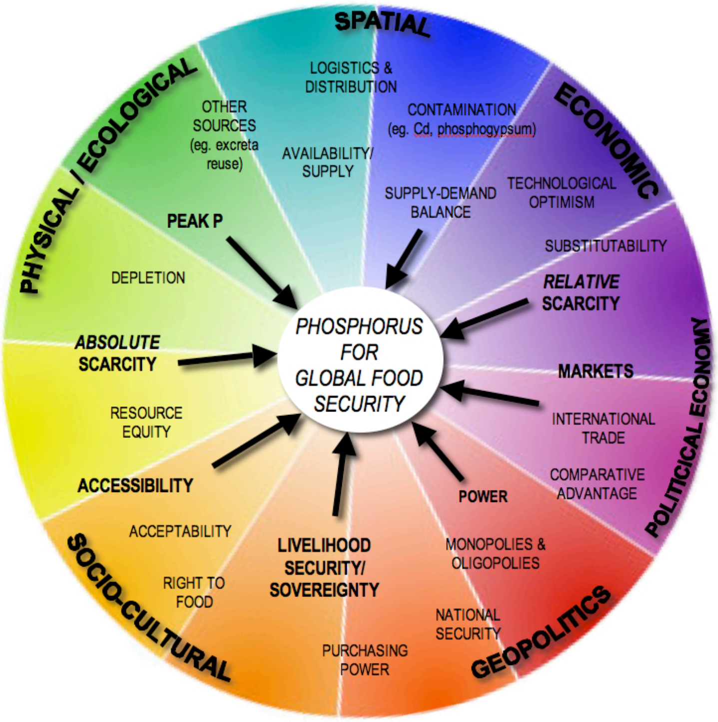

Figure 8: Multiple stakeholder perspectives on phosphorus sustainability in the context of global food security. While adjacent perspectives are not incompatible, perspectives on opposites sides can be conflicting and a source of ineffective governance (Cordell, *forthcoming*)

While no respondent claimed to be against the use of organic sources of phosphate fertilizers (such as manure, crop residues, human excreta), many respondents suggested phosphate rock was currently favoured due to its efficiency of use, the possibility to convert to higher analysis fertilizer, its ample supply to meet demand, the easiest to process, a quick fix to achieve high yields, the ability to apply it when needed (rather than requiring costly storage of say manure). Probing revealed that respondent views on the use of human excreta as a fertilizer ranged widely from active proponents of using human urine and faeces in food production, to sceptics who thought there was too much stigma and heavy metal contamination for widespread use, with a few in between who were not opposed to the idea, but hadn't thought about it ever playing a role.

Regarding governance of global phosphorus resources, respondents suggested there were no international policies, protocols, guidelines or organisations actively responsible for the management of phosphorus, that it was simply left the market forces of supply and demand. Two respondents also added the importance of subsidies and taxes as a significant influence on the trade of phosphorus. No respondent could say with confidence who might be responsible for long-term management of global phosphorus resources to meet the world's future food needs, however some suggested a UN body would be appropriate, or a 'non-partisan', while others suggested large companies would invest in new resources, with the help of the World Bank. Two respondents believed the market would take care of ensuring demand is met, though one of these respondents felt national institutions are responsible for fertilizer security in addition to the international industry body and the FAO. One respondent noted phosphorus doesn't really have a proper home, although ideally it should sit between the FAO and UNEP with input from WHO.

Respondents predicted a range of possible future trends based on a broad range of certainties, from analysis based on empirical data to speculation. Possible medium term trade-related trends (suggested with a greater sense of certainty) included: a shift in trade patterns (such as who are the major producing and consuming countries, importers and exporters, however Morocco is likely to remain the greatest exporter), more joint ventures and increased vertical integration of mining and fertilizer production. One respondent suggested the likelihood of a phosphate 'OPEC', while another respondent commented that Morocco tried forming a phosphate OPEC in the 1970's and it failed. Respondents suggested changes in production are likely to include: increasing efficiency of mining and processing, extracting P from mining waste, increasing P from sewage and other sources, an increase in input costs due to increased prices of raw materials like oil, thereby increasing the cost of mining and the price of the fertilizer commodities. Poor farmers unable to access the fertilizer markets will slash and burn to release phosphate. A suggested long term trend is that agricultural soils in phosphate-deficient agricultural regions will eventually reach a critical phosphate point after which time only sufficient P to replace harvested P would be required (in the same way that European and Northern American soils have). One respondent discussed with confidence the sustained 'tightness' between supply and demand in the short-term. However none mentioned the imminent short-term price increase of phosphate rock that occurred following the interviews. This could be due in part to a lack of awareness and monitoring of the situation, in addition to commercial confidence of industry data. For example, the industry respondent was repeatedly unable to comment on issues related to price or cost.

In relation to what might need to happen to move towards a more sustainable situation in the future, some respondents refused to 'speculate', while others imaged it would take 'more dead bodies', national involvement to ensure a constant supply and consider recycling and increased efficiency, a special focus on African farmers and investment in African phosphate deposits, data transparency, incentives to 'close the loop', urban agriculture recycling urban nutrients (such as rooftop gardens, edible parks). Interestingly, several stakeholders suggested the price of phosphate would need to rise before phosphorus could be put on the global agenda. Given the price of phosphate rock has indeed risen 700% in 14 months, it remains to be seen whether this will actually be the case.

4.2 Institutional analysis

An institutional analysis of the dominant institutions and actors[14] governing phosphorus (described in Cordell and Kerschner, forthcoming) found that there is no single international organisation or regime responsible for long-term management of global phosphorus resources for food production. Without such an organisation or regime, there is also no monitoring of the long-term situation, nor feedback. Additionally, there is no comprehensive sustainability quality control and associated feedback loops systems regarding the ecological, ethical and economic impacts of P fertilizers. Such negative feedback loops are essential for any operating system to function efficiently and effectively. As noted by Brown: "Any system in a state of positive feedback will destroy itself unless a limit is placed on the flow of energy through that system" (Brown, 2003).

4.2.1 Institutional lack of fit and fragmentation of the phosphorus cycle

Mapping the different stakeholder perspectives, the institutional paradigms that inform them (touched upon in section 4.1) and their relative power, against the physical phosphorus cycle, highlighted a 'lack of fit' (Young, 2002) between P cycle and institutional arrangements. Young here refers to the mismatch between a biogeochemical cycle and the institutional arrangements governing it. This lack of fit is evident in both spatial and temporal terms.

Firstly, there is no intentional environmental regime or institution created to deal with the sustainability of the global phosphorus cycle through the food production and consumption system. In the absence of this, it is by default governed by the forces of the international market and its actors. While the recent price spike in phosphate rock is likely to trigger further innovations in and adoption of phosphorus recovery and efficiency measures, the market alone is not sufficient to manage phosphorus in a sustainable, equitable and timely manner.

[14] Institutions here includes norms, conventions and rules (Vatn, 2005) - essentially what Biermann et al (2007) refer to as 'institutional architecture'.

This form of 'regime' is partial, only sufficient to govern part of the system (such as efficiency of trade), and ignores many fundamental relationships and functions of the whole system (see bullet points 1,2,4,5 and 7 below). Young warns that "*faulty models or misleading discourses can go far toward producing mismatches between ecosystems and the attributes of regimes humans create to govern their interactions with these systems"* (p17, 2005).

Secondly, the typical rate of change of global biophysical systems (here phosphorus cycle) is too slow to be picked up by the current institutional arrangements – the international market. There is a temporal mismatch of at least an order of magnitude (see bullet point 3). The consequences of this are serious, as the system will eventually reach a tipping point (see bullet point 7), where the biophysical change is too fast for the 'sluggish' (Cordell and Kerschner, forthcoming) institutional change to keep up with in a timely manner. Young notes that "*Institutional arrangements...often change or evolve at a much slower pace [than biophysical and technological changes]; major adjustments in many – though by no means all - resource regimes can take years to decades*" (p.22, ibid). While the current institutional arrangements pertaining to global phosphorus resources, has little adaptive capacity (See bullet point 9), there is a growing interest generally in "*devising more flexible institutions, capable of monitoring and adjusting quickly to changing ecological conditions* (p.23, ibid). Indeed, the recent establishment of the Stockholm Resilience Centre[15] is an indication of this emerging awareness.

In summary, the current market system fails to 'govern' or manage global phosphorus resources because it does not address:

1. **Accessibility by all farmers**. Many poor farmers around the world cannot access the phosphate fertilizer market due to low purchasing power or access to credit (IFPRI, 2003; IATP, 2006). Further, in Sub-Saharan Africa, where fertilizers are most needed, phosphate fertilizers can cost farmers 2-6 times more at the farm gate than European farmers (Runge-Metzger, 1995; Fresco, 2003). The recent price spike and anticipated high prices for the foreseeable future further reduces the purchasing power of poor farmers.

2. **Physical resource scarcity**. The basis of the market system does not acknowledge the finite nature of non-renewable resources like phosphate rock (or oil) (Cordell and Kerschner, forthcoming). Rather, it is based on the assumption that as a non-renewable resource commodity becomes more scarce, the price will increase, which will in turn trigger new investments and fuel technological innovation (Ayres, 2007). This is consistent with the principles of neoclassical economics which suggests that phosphate scarcity is only relative, not absolute in a physical sense, because one scarce resource can merely be replaced by another resource indefinitely. This represents a technological optimism – that new technology will always facilitate this substitution. Neoclassical economics in this instance clashes with the laws of thermodynamics, that suggest low entropy matter are scarce in an absolute sense. This in turn means the market does not accept the concept of peak phosphorus, as the latter is based on the notion of resource scarcity in an absolute or physical sense.

3. **Long-term time frames**. We are entering a new and unprecedented era of global environmental change this century (Biermann, 2006). As we are learning from climate change, global water scarcity, a long-term time frame is essential for understanding, managing and adapting our current system in a timely way. The same applies to global food security and phosphorus resources. Current global phosphate reserves might be depleted in the next 50-100 years, which is very significant for humanity, yet the market system and its actors are structured to operate on short-term timelines of 5-10 years at most. This change in the global phosphorus cycle is also below the radar or early warning system of most political decision makers as their timelines are

[15] www.stockholmresilience.org

similarly short-term[16].

4. **Resource distribution**. Geologically, phosphate rock is unevenly distributed and highly concentrated in only a handful of countries (Jasinski, 2008). Under the market system, countries and their firms are entitled to own the resources within their political boundaries. Despite phosphate being critical to food production in every country and every modern farming system, the overwhelming majority of phosphate rock reserves are currently controlled by just three countries – China, Morocco and the US. The market currently has no mechanisms for equitable distribution of such essential resources (Daly, 1992). Those with purchasing (or military) power have the most access (Cordell and Kerschner, forthcoming).

5. **Energy intensity and environmental impact**. Phosphate rock is one of the most highly traded commodities on the international market. Each year around 30 million tonnes of phosphate rock is traded across the globe (IFA, 2006). Global trade of phosphate commodities is extremely energy intensive and currently relies on cheap fossil fuel energy for mining, processing and particularly freight. With growing concern about fossil fuel scarcity, and the price of oil rising, this current energy intensive process may not be desirable or possible in the future. Mining lower grade rock decreases the energy profit ratio.

6. **Investor speculation**. Due to a growing awareness of the global food crisis, and a future tightness between supply and demand, investors are increasingly investing in scarce agricultural resources – both food and raw materials (IATP, 2008). This is likely to be the same for phosphate rock and fertilizer commodities due to the recent price rise and increasing awareness of scarcity. Investor speculation causes significant increases in commodity prices, yet here are currently no mechanisms to prevent such investor speculation of vital commodities (Murphy, 2008).

7. **Irreversibility and tipping points**. Continual anthropogenic pressure on a resource or ecological system can push the system past a ‘tipping point’ to a new, irreversible state. This is the great concern with climate change or loss of biodiversity (Stockholm Resilience Centre, 2007). In the case of phosphorus, the tipping point is peak phosphorus, after which supply will be increasingly unable to meet demand. Food riots and farmer suicides are examples of social consequences of the short-term imbalance between in supply and demand for food and fertilizers. Dead zones are an ecological example[17] (World Resources Institute, 2008).

8. **Information and data transparency**. There is very little data or analysis regarding supply and demand of phosphorus resources for future food production[18]. Data which does exist, is typically generated and owned by the mining and fertilizer industry[19]. While some basic data is publicly available, such as US Geological Survey data on global phosphate reserves, most data is held by industry and considered ‘commercial in confidence’. Knowledge production itself is also not independent (often undertaken by mining industry) and assumptions can influence findings, such as how long current global phosphate reserves will last. Similarly, there is no publicly available times series commodity price data for phosphate rock or phosphate fertilizers. Some commercial data exists, at very high cost[20]. The market does not ensure knowledge production is

[16] Although increasingly parties may have long-term goals with respect to the environment. A rare example in the case of phosphorus is the Swedish National Environmental Goal of recirculating 60% of P in sewage back to arable land by 2015 (Swedish Environmental Objectives Council, 2007).

[17] Where excess nutrient runoff (phosphorus and nitrogen) from agriculture and sewage effluent result in the death of entire aquatic ecosystems which can be irrecoverable.

[18] Liu et al (2008) recently published a paper on Global Phosphorus Flows.

[19] In Australia, for example, the national government’s geological centre, GeoScience Australia, does not have a complete account of Australia’s phosphate rock reserves and annual phosphate production because mining and fertilizer firms are not obliged to disclose such information (GeoScience staff, pers comm. 30/01/08).

[20] for example, a subscription to the comprehensive Fertilizer Week statistics costs 2850 Euros (http://www.cruonline.crugroup.com/FertilizersChemicals/FertilizerWeek/tabid/177/Default.aspx)

participatory, equitable, transparent or sufficient.

9. **Adaptive capacity**. While commodity price rises tend to trigger new exploration, alternatives and technological advances in the short term, the market is not responsive enough to changes in the longer term, such as global environmental change. This is partly attributed to the ‘short-termness’ of industry and the market and a lack of independent early warning systems that monitor the phosphorus for food situation with subsequent feedback mechanisms to the system to adapt in a timely way. The recent fertilizer price and supply crisis was not foreseen by most of the world’s farmers nor policy makers. Most national and international governmental organisations have not monitored phosphate rock often because it is not seen as a commodity of significance (GeoScience staff, pers comm. 30/1/08; ABARE staff, pers comm. 10/1/07). World Bank commodity price data (both ‘real’ and projected) for phosphate rock completely missed the recent price spike[21] (World Bank, 2008). There is currently no institutional diversity that could allow the system to adapt as the market is the only institution governing phosphorus resources.

A third case of mismatch that emerges when the institutional arrangements are mapped against the phosphorus cycle through the global food system are the signs of *conflictive* institutional fragmentation (p4. Biermann et al, 2007). That is, institutionally, there is a noticeable fragmentation between the different sectors that P flows through in the global food production and consumption system (as shown in figure 9), some of which are incompatible or inconsistent (as discussed in section 4.1). For example, the P we eat, comes out in our urine and faeces[22], yet institutionally, there is little if no link between stakeholders (and institutional arrangements) around food consumption and sanitation. Young warns “*a regime that ignores what turn out to be significant elements of an ecosystem cannot produce sustainable results”* (p12. Young, 2002). At the international level, while the WHO has recently published comprehensive guidelines on the safe reuse of human excreta (such as urine) in agriculture (WHO, 2006), the sole actor responsible for fertilizer demand strategies for farmers at the FAO headquarters, only focuses on phosphate rock and not organic sources of P, and does not foresee a phosphate rock supply problem in the future. Additionally, at the time of the stakeholder interviews, there was no staff responsible for organic fertilizers at the FAO headquarters. The cycle has been fragmented and divided between several different sectors and their associated paradigms. As suggested in section 4.1, phosphorus is perceived and conceptualised by stakeholders in many different ways depending in part on the context, sector and individual stakeholders disciplinary background. Figure 9 shows phosphorus is perceived as an ‘environmental pollutant’ by the freshwater ecologist, or an ‘agricultural commodity’ by the resource economist, and so on. Further, within each of these disciplines, P is often not perceived as a priority area, hence it has no institutional home. It is only when the cycle is perceived as a whole system, that its importance becomes obvious (Cordell, forthcoming; Cordell, 2008)[23].

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[21] The forecasts have since been updated online.

[22] This is the case regardless of whether we are looking at the ‘natural’ phosphorus cycle, or the ‘anthropogenic’ (human designed) phosphorus cycle.

[23] This fragmentation was also observed in a study of the barriers and opportunities to the reuse of urine in Australia (Cordell, 2006).

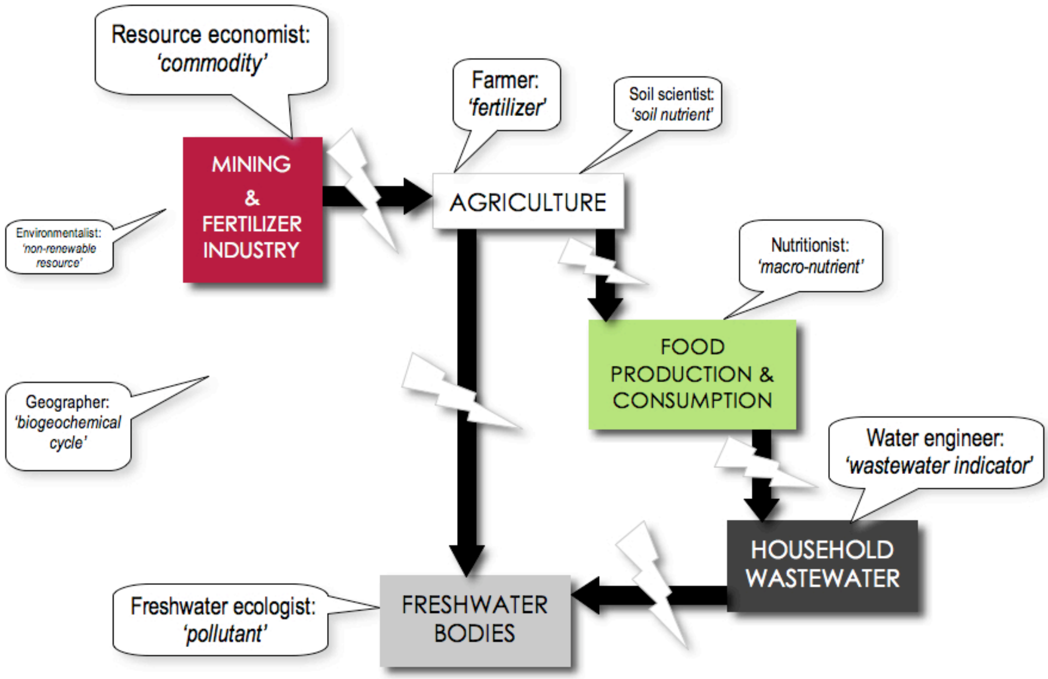

Figure 9: Institutional fragmentation of the phosphorus cycle through the global food production and consumption system. The speech bubbles indicate different stakeholder perspectives and the size of the speech bubbles are indicative of the relative power or popularity currently attributed to that perception of phosphorus (Cordell, 2008).

4.2.2 Power dynamics

A stakeholder analysis of power versus interest revealed that the most powerful stakeholders have the least interest in acknowledging phosphate scarcity, peak phosphorus and the long-term equitable access to phosphorus resources by the world's farmers (figure 10). They are contributing to the continuation of the market as the dominant institution governing phosphorus. Figure 10 also indicates the power and interest of nations that are key actors at the international level. In this figure, 'interest' refers to the nature (+ = positive interest, - = negative interest or 0 = neutral), of a stakeholders likely interest (i.e. in favour or opposed) in seeing more attention given to phosphate scarcity and subsequent institutional change required for more sustainable governance. 'Power' refers to the stakeholders influence over the outcomes for governing phosphorus (eg. decision-making power, political power) and the degree to which they can help achieve or block the institutional change (0= negligible power, + = some power, ++ = very powerful).

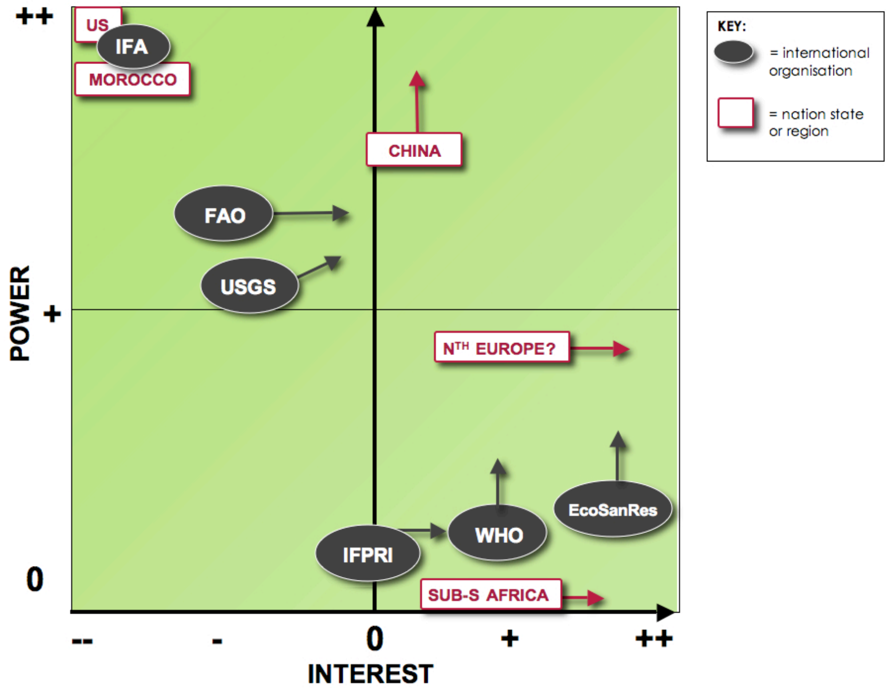

Figure 10: Illustrative representation of perceived stakeholders power versus interest in supporting awareness of global phosphate scarcity, farmer accessibility to phosphate and subsequent institutional change required for improved governance of global phosphorus reserves. The arrows indicate the anticipated direction some stakeholders would move to, if any. (source: Cordell and Kerschner, forthcoming); *IFA = International Fertilizer Industry Association; FAO = Food and Agricultural Organisation of the UN; USGS = US Geological Survey; IFPRI = International Food Policy and Research Institute; WHO = World Health Organisation; EcoSanRes = the Ecological Sanitation Research programme of the Stockholm Environment Institute.*

Power dynamics exist not just between international stakeholders and nations, but also between commodities and institutional norms and conventions (Bowker and Star, 1996; Vatn, 2005). Some of these are highlighted in Table 1[24]. Although in a physical sense, phosphorus can be sourced from multiple organic and inorganic sources, phosphate fertilizer commodities based on phosphate rock are viewed as the superior source in modern agriculture. Least powerful commodities include those derived from human excreta, such as urine as a ready liquid fertilizer. Whilst human excreta presents a significant source of plant available P, a 'urine blindness' (Drangert, 1998) and general aversion to human excreta prevents policy makers and professionals from seeing the value in this resource.

Table 1: Powerful and least powerful influences and entities in the context of phosphorus and global food security

Entity:	Powerful	Least powerful
Commodities	Phosphate rock, mineral fertilizers	Human excreta (especially as source separated[25] urine and faeces)
Institutions*/ paradigms	International market	Right to food, laws of thermodynamics
Countries/ regions	US, Morocco, China	Western Sahara, Sub-Saharan Africa, India
Actors	OPC[a], Mosaic[b], IFA[c]	Poor farmers, hungry people

* includes norms, conventions and rules; [a] Morocco's state-owned phosphate mining company; [b] largest US private-owned mining company; [c] International Fertilizer Industry Association.

[24] For simplification to illustrate the point, 'powerful' and 'least powerful' have been used as categories, where as in reality these entities are more likely to sit on a power spectrum.

[25] Source separated in this context refers to separating human excreta fractions at the source: the toilet, such as through a urine diverting toilet (Cordell, 2006).

4.2.3 Comparing non-renewable and renewable resource attributes

To further understand how phosphorus is perceived, and why it might not be considered a priority next to water and energy in the debate on global food security or global environmental change, a comparison of attributes of oil and phosphorus (Cordell and Kerschner, forthcoming), and water and phosphorus (Cordell, 2007) was undertaken. While phosphorus scarcity has many similarities to both water scarcity and peak oil, phosphorus is a far less tangible resource. Water is highly visible and indeed utilized directly by every person on daily basis, and we pump refined oil into our cars each week, however there is no direct or visible use of phosphorus by the community. It is hidden in the embodied food we eat, and excreta we flush down the toilet. It is not surprising there is most awareness about phosphate runoff from farms and effluent causing algal blooms given the visual nature of an algal bloom and direct physical, environmental and economic impacts. Further, when the price of oil goes up, drivers feel it the next day. This is certainly not the case for phosphorus (Rosmarin, pers comm. 18/9/07).

Finally, a comparison of physical and institutional attributes of renewable versus non-renewable resources reveals that unlike renewable resources, non-renewable resources tend to have a direct attributed economic value. The irony to the resource economist, is that while they do indeed have an economic value, they are *only* valued as a commodity for a given economic service (like energy or fertilizers in the case of oil and phosphate rock respectively). This means, their other essential ecological and societal functions are not valued. Particularly, their finiteness is not valued, despite their direct threat to undermine future generations ability to produce food and other essential services. This lack of concern regarding essential non-renewable resources is in a sense a ‘Tragedy of the *non*-Commons’.

5 Recommendations and options for future phosphorus security

This section synthesizes findings from both the hard and soft analyses for securing global phosphorus resources for food production, in the form of recommendations.

The draft criteria in box 1 have been developed based on the preliminary findings from this doctoral research as a first iteration to guide what a sustainable phosphorus future might look like. It is not intended as a complete or finalised list, rather to facilitate further discussion with policy makers, scientists, industry and the community on the topic.

Box 1: 10 *DRAFT* CRITERIA FOR PHOSPHORUS SUSTAINABILITY IN THE CONTEXT OF GLOBAL FOOD SECURITY

1. Availability in the **long-term** (50-100 years);
2. **Equitably** distributed, **accessible** and **affordable** to all farmers – either fertilizer markets are accessible, or access to non-market fertilizers such as manure and excreta; more locally and renewable sources
3. **Cost-effective** from a whole-of-society perspective (ie. not just from a single stakeholder perspective);
4. Sufficient quantity and quality (ie. Future **demand** can be met by **supply**);
5. **Minimises adverse environment impacts**, including at all key life-cycle phases (eg. cadmium levels and radium-phosphogypsum management at the mine, energy intensity of production and transport, prioritise renewable rather than non-renewable sources where possible, minimises losses to waterways where eutrophication is a problem).
6. **Minimises losses** in the entire food production and consumption system;
7. **Ethical** - not supporting and trading with a country illegally occupying regions with phosphate reserves.
8. Potential synergies and/or **value-adding** to other systems (eg. water, energy, sanitation, poverty reduction, environmental health).
9. Independent **monitoring** of phosphorus resources and future trends, data and analysis **transparent** and publicly available.
10. System has **adaptive capacity** to adapt in a timely manner to changes, to ensure annual availability.

There is no single ‘quick fix’ solution to replacing current dependence on phosphate rock for phosphorus fertilizers in the long-term. However there are a number of technologies and policy options that exist today at various stages of conceptualisation - from research to demonstration and implementation - that together could potentially meet future phosphate fertilizer needs for global food demand (Cordell et al., forthcoming). This will inevitably require an integrated approach, that looks beyond the current focus on agricultural efficiency to reduce runoff to waterways. Such a combination of supply and demand side measures could include (but is not limited to): demand measures such as disincentives for P-intensive diets; increasing efficiency in agriculture; increasing efficiency in food chain; and supply from renewable sources: such as excreta, manure, food waste, other sources (such as algae, ash, bone meal).

To support the development of such feasible and desirable supply and demand options, more reliable and transparent data collection and analysis of the baseline situation (both current and business-as-usual future demand scenarios) is required from an independent body.

As the current governance of phosphorus by the international market system and its actors is partial and does not completely align with key ecological, ethical and sustainability attributes of the global phosphorus cycle through the food production and consumption system, a modified global governance structure is required[26]. This could be overseen by an independent body (either in new org or existing governmental or non-governmental programmes, such as UN bodies or ESSP) with the capacity to collect data, monitor and analyse the situation,

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[26] Söderbaum calls for ‘paradigm co-existence’ Söderbaum, P. (2006) Actors, Agendas, Arenas and Institutional Change Processes. A Social Science Approach to Sustainability, manuscript. *Journal of Interdisciplinary Economics*., where more fitting and flexible ideologies can co-exist to ensure more relevant governance for sustainable futures.

engage and inform key stakeholders, policy makers and the community in future pathways to achieving a sustainable phosphorus situation for future food security. Phosphorus needs to be placed on the global agendas for both food security and environmental change along side other essential resources. Parallels can be drawn and harnessed with both water scarcity and peak oil.

Such global governance would also need to ensure long term planning in response to most likely scenarios, and, ensure accessibility of all farmers to phosphorus (see box 1).

Further, there is a pressing need for a global paradigm shift; one that decouples phosphorus from water, where it is viewed predominantly as a 'pollutant'. Sanitation is currently physically linked to water as 'wastewater' and institutionally linked as international or regional 'WatSan' programmes for example (where sanitation management is embedded within water management). The institutional fragmentation between the food sector and sanitation sector needs to be relinked. This will facilitate future discussions on 'FoodSan' programmes rather than just 'WatSan'.

Finally, phosphorus also needs to be embedded in a wider integrated framework. That is, identifying synergies and linkages between ecological systems (eg. energy, nutrients, water) at global and national scales. For example, reducing meat consumption, in what Smil (2007) calls 'smart vegetarianism', in the future has the potential to dramatically reduce demand for water and nutrients (like phosphorus) in agriculture, in addition to reducing energy (oil) consumption and generation of greenhouse gases (Smil, 2007). Otherwise we risk the rapid development of inappropriate alternatives like first generation biofuels that not only produce significant amount of greenhouse gases, compete with food production for fertile land, but have also contributed to the recent spike in the demand for phosphorus fertilizers (IFA, 2008). Such narrow and short-term analysis is simply shifting the peak of one resource to the peak of another.

6 Conclusions

This research has highlighted a significant lack of effective, coordinated and sustainable management of the world's phosphorus resources. Given the critical role of phosphorus in sustaining global food production, phosphorus scarcity and related geopolitical and sustainability issues will need to be prioritised along side water, energy and nitrogen in the debate on global food security. Significant changes in institutional and physical arrangements are likely to be required to ensure this. In addition to introducing monitoring and feedback in the system, phosphorus efficiency and recovery options will need to be explored to ensure the long-term, equitable use and management of phosphorus resources in the global food system.

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