Preferred future phosphorus scenarios: A framework for meeting long-term phosphorus needs for global food demand

Dana Cordell*,[a,b], Dr Tina Schmid-Neset[a], Dr Stuart White[b] and Dr Jan-Olof Drangert[a]

[a]Department of Water and Environmental Studies, Linköping University, Sweden
[b]Institute for Sustainable Futures, University of Technology, Sydney, Australia

*Corresponding author: Dana.Cordell@uts.edu.au

Abstract This paper puts phosphorus recovery in a global sustainability context, with particular reference to future phosphate rock scarcity and global food security. While phosphorus fertilizers are essential for sustaining high crop yields, all modern agricultural systems currently rely on constant input of mined phosphate rock. However, phosphate rock, like oil, is a finite resource, and global production of high quality phosphate rock is estimated to peak by 2033, after which demand for phosphorus fertilizers will increasingly exceed supply. Phosphorus cannot be manufactured; though fortunately there are a number of technologies and practices that together could potentially meet long-term future phosphate fertilizer needs for global food demand. This paper develops probable, possible and preferred long-term scenarios for supply and demand-side measures. The preferred scenarios together demonstrate how substantial reduction in demand for phosphorus can be achieved, and how the remaining demand can be met through high recovery and reuse of organic sources like human and animal excreta (e.g. direct reuse, struvite crystals), crop residues, food waste and "new" sources like seaweed, ash, bonemeal and some phosphate rock.

INTRODUCTION

Phosphorus, together with nitrogen and potassium, is an essential nutrient in fertilizers. As an element, phosphorus has no substitutes for plant and animal growth. Hence there will always be a global demand for phosphorus to produce fertilizers to in turn feed a growing world population. While historically agriculture relied on organic sources of phosphorus, the past century has witnessed a dramatic increase in the dependence on phosphate rock to achieve high crop yields. Yet environmental, economic and geopolitical concerns could mean the end of an era for phosphate rock this century. The fertilizer industry acknowledges that cheap fertilizers are a thing of the past and it is widely accepted that quality of remaining reserves is decreasing

Edited by Ken Ashley, Don Mavinic and Fred Koch. ISBN: 9781843392323. Published by IWA Publishing, London, UK.

(Stewart *et al.*, 2005; IFA, 2006; Smil, 2002). This paper presents an integrated approach to how we use and source phosphorus that looks beyond the current focus on agricultural efficiency (largely driven by concern of phosphate pollution in rivers and lakes). It addresses inefficiencies in the food commodity chain, consumer demand for phosphorus-intensive diets, and reuse opportunities from organic sources.

METHODOLOGY: SCENARIO DEVELOPMENT IN THE FACE OF UNCERTAINTY

This paper presents qualitative and quantitative scenarios for meeting global phosphorus fertilizer demand, while accounting for substantial uncertainty about future food demand, lack of consensus about the key issues and limited data regarding the availability of phosphate rock. The purposes of the scenarios are, firstly, to allow consistent analysis of a disparate group of options within a single framework (there are currently numerous options under investigation by different groups). Secondly, to trigger debate among scientists and policy-makers about preferred phosphorus futures, alternative pathways and what is feasible. Finally, to support future decision-making.

Forecasting and backcasting approaches are combined to provide three scenarios of the future. While forecasting projects a present point into the future, backcasting[i] works backwards from a specified preferred future to the present (Dreborg, 1996). The preferred future in this case is based on global food security (no under- or over-nutrition), since this is considered the greatest global significance of phosphorus resources for humanity, in addition to optimal soil fertility and minimum environmental impacts (Cordell, 2008).

A ‘probable’ scenario considers ‘*where are we heading?*’ by forecasting business-as-usual. A ‘possible’ scenario considers ‘*where could we go?*’ by backcasting from a maximum achievable scenario while a ‘preferred’ scenario considers ‘*where do we want to go?*’ (Gidley *et al.*, 2004) by backcasting from a desired future situation taking into consideration what is possible and the criteria in box 1.

Best available data[ii] and knowledge are used to determine future supply and demand side measures for meeting phosphorus needs, presented in million tonnes of phosphorus in 2005, 2050 and 2100 and supported by a qualitative ‘storyline’. Demand-side measures include changing diets, food chain efficiency and agricultural efficiency, while the supply-side measures consider sourcing phosphorus from mined rock, manure, human excreta, food waste and crop residues. All scenarios use UN medium world population estimates of 6.1 billion in 2005, 9.19 billion in 2050 and 9.1 billion in 2100 (UN, 2007; UN, 2003). Combining qualitative and quantitative scenarios has been used extensively in long-term global studies on energy, climate, water and global change (Royal Dutch Shell, 2008; Mitchell and White, 2003; Netherlands Environmental Assessment Agency, 2006; Pacala and Socolow, 2004).

The preferred scenarios are aggregated together in an iterative manner, taking into account potential physical quantities of phosphorus and other important environmental, economic, institutional and social criteria (Box 1).

Box 1: 10 *PROVISIONAL* 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 (i.e. Not just from a single stakeholder perspective).
4. Sufficient quantity and quality (i.e. Future **demand** can be met by **supply**).
5. **Minimises adverse environment impacts**, including at all key life-cycle phases (e.g. 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 (e.g. Water, energy, sanitation, poverty reduction, environmental health).
9. Independent **monitoring** of phosphorous 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.

The data points for the present (2005) are sourced from the authors' flows analysis of phosphorus through the global food production and consumption system (Cordell *et al.*, in press), with estimates of the major flows in mining, fertilizer application, harvest, food processing, consumption and excretion (and phosphorus losses and recovery from the chain at each of these stages).

AN INTEGRATED FRAMEWORK FOR ANALYSING FUTURE SUPPLY AND DEMAND OPTIONS

There are few integrated analyses or frameworks covering the spectrum of options available to meet future global phosphorus demand in a sustainable way[iii]. Figures 1 and 2 provide an integrated classification of supply and demand-side measures which are then analysed in the subsequent sections.

Supply measures range from *used* sources to *new* sources and vary in terms of the *process* by which they are sourced, treated and applied in agriculture.

SOURCE:		PROCESS: *i.* source separation, composting & reuse	*ii.* wastewater mixing & reuse	*iii.* recovery & reuse of byproducts/ residuals	*iv.* struvite generation & reuse	*v.* virgin extraction, processing & use	*vi.* incineration/ burning & reuse
type A: USED SOURCES	A1. Human excreta	*e.g. urine (storage and direct reuse), composted dry faeces*	*e.g. direct use of diluted wastewater; use of treated effluent as irrigation water*	*e.g. activated sewage sludge from wasterwater treatment plant; sludge from biogas/biofuel digester; composted filter cake from sugar factories*	*e.g. from mixed wastewater at the treatment plant*		*e.g. incinerating toilet*
	A2. Greywater	*e.g. minimum treatment and non-portable reuse*					
	A3. Animal manure	*e.g. direct application of manure*			*e.g. from dairy waste*		
	A4. Other industrial waste						
	A5. Animal meal	*e.g. ground bonemeal, meatmeal, bloodmeal*		*e.g. ground bonemeal, meatmeal, bloodmeal*			
	A6. Food waste	*e.g. composted food waste*	*e.g. ground in-sink-orator*	*e.g. composted residues from food processing.*			
	A7. Crop residues	*e.g. crop residues ploughed back in to field*		*e.g. oil cakes and press mud from oil and sugar industry.*			
type B: NEW SOURCES	A8. Crops	*e.g. Green manure*		*e.g. sludge from anaerobic digestion of virgin crops*			*e.g. slash and burn*
	A9. Phosphate rock			*e.g. extracting P from phosphogypsum stockpiles*		*e.g. mining existing and potential reserves; seabed phosphate*	
	A10. Aquatic vegetation, sediments and seawater					*e.g. seaweeds as liquid fertilizer, algae, seawater*	

Figure 1. A classification matrix of supply-side measures to meet future global phosphorus needs for food security.

DEMAND MEASURES:	STAGE IN FOOD PRODUCTION & CONSUMPTION PROCESS:			
	i. Extracting and processing raw fertilizer materials	*ii*. agricultural fertilizer use and crop growth	*iii*. food processing and retailing	*iv*. food consumption
A1. Minimising P losses	*e.g. reducing storage and distribution losses of phosphate rock and other sources*	*e.g. reducing erosion and runoff*	*e.g. minimise crop and food losses from food processing, storage and transport; minimise losses from retailers (e.g. supermarket dumping of expired, excess or unpresentable food)*	*e.g. Minimising household food waste*
A2. Reducing P demand		*e.g. Soil testing, precision agriculture (e.g. using remote sensing)*		*e.g. Reducing demand for P-intensive diets like meat and dairy; reducing over-eating*
A3. Increasing P uptake	*e.g. Breading, selection and manipulation of seeds and livestock to improve P uptake*	*e.g. Biostimulants (inoculants) at root zone to increase soil P availability; optimising soil biochemistry (pH, carbon, moisture); organic farming techniques, permaculture*		*e.g. Ensuring consumers have healthy bodies (e.g. free of diseases like diarrhoea) to maximise P uptake*

Figure 2. A classification matrix of demand-side measures to meet future global phosphorus needs for food security.

Demand measures include minimising phosphorus losses in each stage of the food production and consumption process, reducing the overall demand for phosphorus, and increasing phosphorus uptake by plants, humans and animals.

FUTURE GLOBAL PHOSPHORUS DEMAND: A MOVING TARGET

There are many interlinked and dynamic variables affecting the overall demand for phosphorus, making informed long-term forecasts challenging (FAO, 2000). Phosphorus fertilizer demand is strongly linked with population and crop demand, in addition to price of food and non-food commodities, consumer preferences for meat and dairy diets, farmer' soil knowledge, price of phosphate fertilizer commodities, farmer purchasing power and demand for alternative sources of phosphorus (Cordell, forthcoming). Approximately 90% of the global demand for phosphorus is for fertilizers, animal feed and food additives (Smil, 2000). However the future fraction of fertilizers that is for food versus non-food crops is difficult to estimate, given the recent dramatic increase in biofuel crop production.

Steen's (1998) 'most likely' 2% annual growth estimate for phosphate consumption (estimated a decade ago) did not foresee the increased demand for biofuel crops that require fertilizer application or growing demand for meat and dairy foods. The most recent official forecasts suggest a growing annual demand at around 3% until 2010–12 (FAO, 2007a; Heffer and Prud'homme, 2008). In the short-term, biofuel demand, lack of investment and possible investor speculation, resulted in the price of phosphate rock increasing 700% within a 14-month period (IFA, 2008).

While fertilizer demand has stabilised or is decreasing in the developed world because of previous overfertilisation (FAO, 2006; European Fertilizer Manufacturers Association, 2000), demand continues to increase sharply in developing and emerging economies (especially China and India), and Africa in particular will need decades of high application before its agricultural soils reach the so-called critical soil P point. Koning *et al.* (2008) suggest approximately 13 times current global P consumption would be required to reach the critical soil P point in the world's phosphorus-poor agricultural soils.

If demand for meat/dairy and biofuels continues to increase, along with population growth, total phosphorus demand could grow annually by 3% until 2050 (99 MT P) and by 4% until 2100 (707 MT P). However, if every person in the world received precisely the required amount of nutrients, i.e. the Recommended Daily Intake (RDI) of 1.2g P/person/day (European Fertilizer Manufacturers Association, 2000) and system losses are minimised to 20%, this would equate to a demand of just 4.79 MT P in 2050 and 4.78 MT P in 2100.

Our 'probable' scenario estimates demand will rise by 2% annually until 2050 (64 MT P) due to increases in population, meat and dairy demand, biofuel crops, fertilizer application on P-deficient soils to attain critical P levels (and a modest level of agricultural efficiency). It is probable that the annual growth rate will reduce to 0.5% until 2100 (82 MT P) due to a stabilisation of world population, soils reaching critical P levels (hence only what is lost in harvest needs replacing) while increased per capita demand remains due to demand for biofuel crops and meat and dairy demand. This probable scenario provides the baseline demand in Figure 11.

FUTURE PHOSPHORUS DEMAND REDUCTION MEASURES

The current food production and consumption system is extremely inefficient: while globally we mine 15 million tonnes of P annually for food production, 80% of this never reaches the food on our dinner table (Cordell *et al.*, in press). Much of the lost phosphorus can be physically recovered and reused, however preventing losses first is typically more energy and economically efficient.

Substantial opportunities exist for not only increasing the efficiency of the food production and consumption system, but to also rethink the way we use of phosphorus to achieve nutritional security for the global population. This broader view (conceptualised in the demand matrix in Figure 2) facilitates the exploration of options that reduce the overall demand for phosphorus.

Changing diets

Changing diets in this context refers to influencing consumer preferences away from phosphorus-intensive diets or overeating (there are currently more overweight people than undernourished in the world (Lundqvist *et al.*, 2008; WHO, 2006b)). Meat and dairy-based diets require up to three times as much phosphorus as a vegetarian diet, in addition to requiring substantially more water, energy and nitrogen (Fraiture, 2007; Cordell *et al.*, in press). FAO predicts a doubling of global meat, dairy and fish consumption by 2050 (particularly in the rapidly developing world) (WWF, 2004). A deliberate reversal of the current trend (in addition to a reduction of the already high meat demand in the developed world) could therefore drastically reduce the global demand for phosphorus in addition to other environmental impacts. Smil (2007) calls for a ‘smart vegetarian’ diet that prioritises lower P-intensive foods, while the Food Ethics Council is encouraging supermarkets to reduce consumer choice and availability of environmentally damaging goods (including meat products) (Food Ethics Council, 2008). Figure 3 provides 3 scenarios.

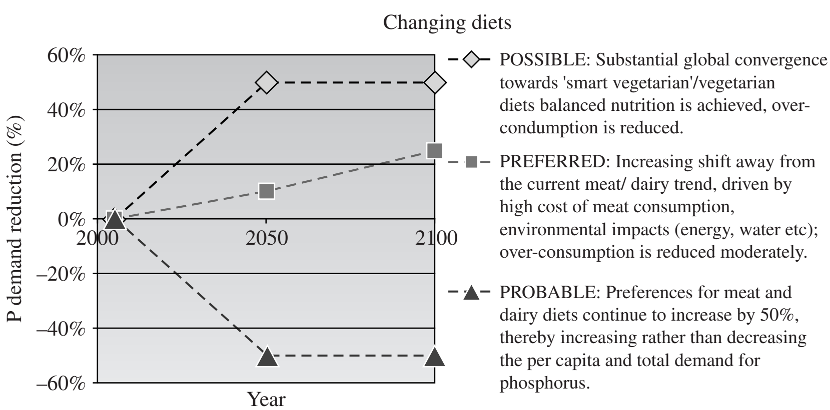

Figure 3. Scenarios for reducing phosphorus demand through changing diets.

Food chain efficiency

Food chain efficiency involves reducing food losses throughout the food chain, indicated in the scenarios in Figure 4. The globalised food commodity chain has resulted in more players, more processes, further distances and increased trade of commodities. Longer production chains contribute to more food losses in transport, production, storage and retail (Lundqvist *et al.*, 2008). In developed countries, the percentage of food lost from farm to fork can be as much as 50%, while in developing countries this is significantly less (IWMI, 2006). In Britain alone, householders throw out £10 billion worth of food (equal to a third of the food that is purchased). Approximately 60% of this is unused edible food and hence avoidable waste (WRAP, 2008).

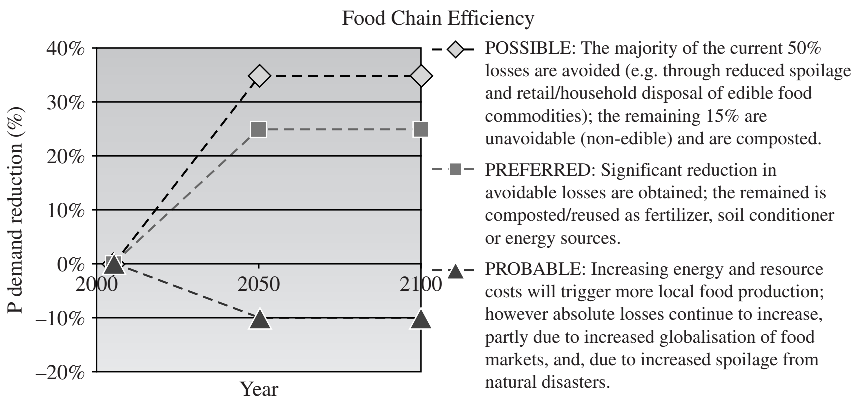

Figure 4. Scenarios for reducing phosphorus demand through increasing food chain efficiency.

Producing food closer to the point of demand – mostly from cities – would reduce food waste as well as energy, water and other resources. Ongoing urban and peri-urban agriculture (e.g. growing food on roofs, gardens, public spaces, agroparks) (FAO, 1999) are examples of more sustainable food chains.

Agricultural efficiency

Agricultural efficiency in this paper refers to increasing crop yields per unit input of phosphorus. The current level of efficiency varies widely between regions, and typically only 15–30% of the applied fertilizer P reaches the crop[iv] (FAO, 2006), hence there is still potential for new innovations to increase crop phosphorus use efficiency. For over a decade, the FAO and fertilizer industry have called for more integrated nutrient management (INM), that ensures crop productivity through optimising soil fertility and meeting nutrient needs from a range of organic and inorganic sources (FAO, 2006; FAO, 2008; IFA, 2007). Efficiency measures include: appropriate timing and application rate of fertilizers (e.g. precision agriculture); improving chemical and physical properties of soil (e.g. pH, moisture, aeration, root-penetrability); and addition of microbial inoculants (e.g. Mycorrhizae fungi) to the root zone to increase the uptake of nutrients (FAO, 2006). Organic farming, permaculture and conservation farming all aim to minimise nutrient losses and to close on-farm nutrient cycles, thereby requiring zero or minimal external fertilizer inputs (FAO, 2007b; Holmgren, 2003; García-Torres *et al.*, 2003). Figure 5 provides 3 scenarios.

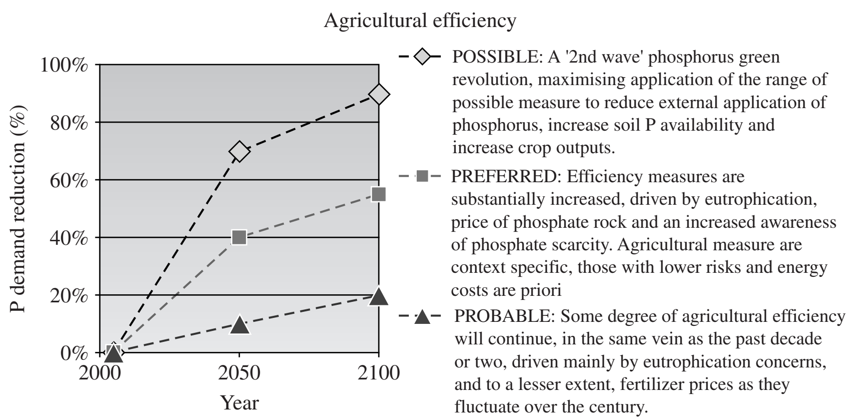

Figure 5. Scenarios for reducing phosphorus demand through increasing agricultural efficiency.

FUTURE PHOSPHORUS SUPPLY OPTIONS

This section introduces a range of organic and inorganic sources that can be used as phosphorus fertilizers. These include recovering organic phosphorus from the food production and consumption chain (manure, crop residues, food waste, human excreta), and virgin sources (such as seaweed, algae, phosphate rock). These vary widely in terms of phosphorus concentration, chemical form, and state (solid, liquid or sludge). Our preferred scenarios build on important sustainability criteria such as total energy consumption of sourcing and using phosphorus, level of contaminants, phosphorus concentration, chemical use, long-term availability and accessibility to farmers, and reliability of quality and quantity.

Phosphate rock

Phosphate rock has been the dominant source of phosphorus fertilizers for the past century (Buckingham and Jasinski, 2004). While initially perceived as an abundant source of highly concentrated and easily accessible phosphorus, numerous environmental, economic, geopolitical and social concerns about remaining phosphate rock reserves could mean the end of the phosphate rock era this century (Cordell *et al.*, in press).

US Geological Survey data (the most comprehensive publicly available data sets on global phosphate reserves) suggest remaining economically and technically feasible global reserves are around 18,000 million tonnes of phosphate rock (Jasinski, 2008). At the present rate of consumption, these reserves will be depleted within 50–100 years (Steen, 1998; Smil, 2000; Gunther, 2005), leaving behind lower quality and less accessible rock. More concerning however is that a peak phosphorus analysis based on industry data suggests a peak in maximum production could occur within 30 years (Cordell *et al.*, in press). While the timeline of the peak may be disputed[v], the fertilizer industry recognises that the quality of remaining reserves are decreasing and cheap phosphate rock is a thing of the past (Stewart *et al.*, 2005; IFA, 2006; Smil, 2002).

Remaining phosphate rock reserves are under the control of only a handful of countries, mainly China, the US and Morocco (which occupies Western Sahara and it's reserves) (WSRW, 2007). The US, historically the world's largest producer and exporter of phosphate rock, now has 25 years remaining of their reserves (Stewart *et al.*, 2005; Jasinski, 2008). China has recently imposed an export tariff that effectively bans phosphate exports[vi].

Each tonne of processed phosphate also generates five tonnes of phosphogypsum with radium levels too high for reuse (Wissa, 2003). Cadmium and other heavy metals are increasingly present in low-grade phosphate rock (even 'cadmium-free' phosphorus contains cadmium hundredfold the level of excreta) (Steen, 1998; Driver, 1998; Jönsson *et al.*, 2004). Processing and transporting phosphate fertilizers from the mine to the farm gate bears an increasingly significant energy cost, which currently relies on cheap fossil fuel energy.

For the reasons outlined above, it is probable that phosphate rock will constitute an even smaller proportion of global phosphate demand in the first half of this century (see scenarios in Figure 6).

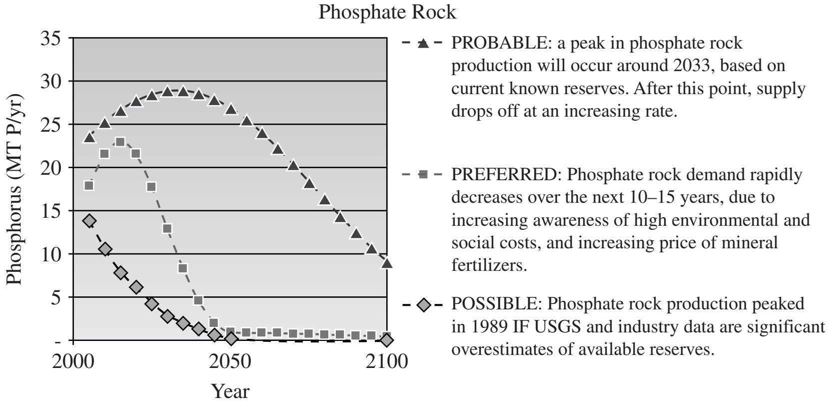

Figure 6. Scenarios for the contribution of phosphate rock to meeting future phosphorus demand.

Manure

Animal manure has always been widely used as a source of fertilizer in most regions of the world. Its phosphorus content is easily available for plants, however the concentration varies from 2.9% P_2O_5 in poultry manure, to 0.1% P_2O_5 in cattle dung (FAO, 2006). Livestock manures can also be mixed and composted with other solid farm organic matter such as bedding (known as Farm Yard Manure), food waste and human excreta. The resultant compost also has good soil conditioning properties that does not occur with direct application of organic wastes. While composted urban material can contain as much as 1% P_2O_5 (compared to 0.2% P_2O_5 in rural organic matter), it is more likely to contain heavy metals if industrial wastes and sewage sludge are mixed in (FAO, 2006). Another common source is sludge from biogas digesters[vii] (1.1–1.7% P_2O_5) designed to convert organic wastes into methane and hydrogen for cooking and lighting. Over 21 million small-scale biogas digesters are already in use in China and other regions (UNDP, 2007).

Smil estimates 40–50% of the annual 15MT of phosphorus generated in manure is recirculated to agriculture (Smil, 2000). It would be difficult to recirculate 100% of manure if the livestock industry remains geographically separate from crop production. Further, in some parts of the world manure supply exceeds demand (e.g. North America, The Netherlands), while in other regions demand exceeds supply (e.g. Australia, Africa). Future scenarios are presented in Figure 7.

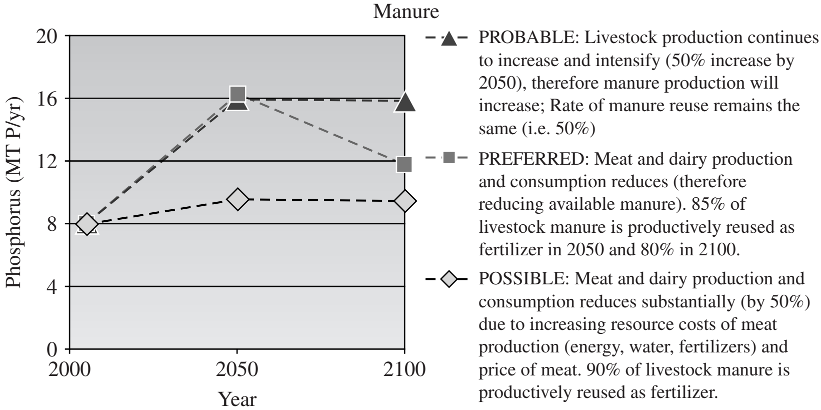

Figure 7. Scenarios for the contribution of manure to meeting future phosphorus demand.

Human excreta

Reusing phosphorus in human excreta as a fertilizer can occur through direct use (e.g. of urine), following composting, mixing with municipal wastwater, incineration, struvite crystallisation and sludge reuse, with phosphorus concentrations ranging from 0.16% (urine) to 3.2% P_2O_5 (activated sewage sludge) (Kvarnström *et al.*, 2006; FAO, 2006; Raschid-Sally and Jayakody, 2008; Reindl, 2007; SCOPE, 2004).

Human excreta has been reused as fertilizer by the Chinese for the past 5,000 years. Because urine is essentially sterile and contains plant available nutrients (N,P,K), it can be used directly as a fertilizer in a safe way if it is not mixed with faeces in toilets and by taking simple precautions. Urine from one person alone provides more than half the per capita phosphorus required to fertilize cereal crops, yet its potential as a fertilizer is often overlooked (Drangert, 1998) and should be considered along side other phosphorus recovery options.

Some 200 million (mostly poor) farmers today divert wastewater from cities to agricultural fields because it is a cheap and reliable source of water and nutrients (Raschid-Sally and Jayakody, 2008). In aquaculture, two thirds of farmed fish globally are fertilized by wastewater (World Bank, 2005). However it is essential that minimum precautionary measures are adhered to in order to avert serious health risks. Indeed, the World Health Organisation has now published extensive risk-based guidelines on the safe reuse of human excreta in agriculture and aquaculture (WHO, 2006a).

Water bodies are often polluted by high anthropogenic nutrient loads. Capturing urine at source (at the toilet) can be much more energy efficient and cost-effective than removing high levels of phosphorus at the wastewater treatment plant. At the same time this avoids heavy metal contamination (like Cadmium) from the mixed wastewater. Struvite recovery can also be more cost effective than chemical and biological removal (Shua *et al.*, 2005).

Humans produce 1–1.5 g P/person/day in human excreta[viii]. This means globally, we produce around 3 million tonnes of P in our excreta each year. Approximately 10% is currently returned to agriculture as sludge or direct wastewater reuse (Cordell *et al.*, in press). Future scenarios are presented in Figure 8.

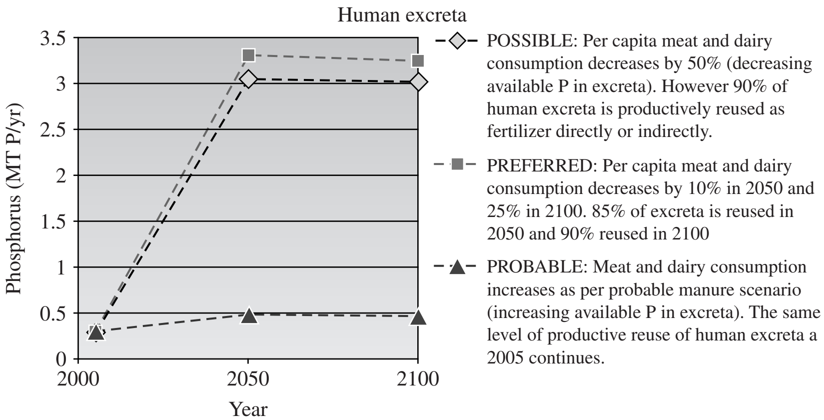

Figure 8. Scenarios for the contribution of human excreta to meeting future phosphorus demand.

Food Waste

For the purpose of this analysis, food waste constitutes all organic matter byproducts from post-harvest food processing through to consumption waste. For example, the residual byproduct ‘oil cakes’ following oil extraction from oilseeds contain at least 0.9–2.9% P_2O_5 which is significantly higher than crop residues (FAO, 2006). Approximately 2 million tonnes of phosphorus in post-harvest and food waste is currently lost and not recirculated (Cordell *et al.*, in press). While food chain efficiency could reduce avoidable losses substantially, the remainder can be composted or digested and reused. Figure 9 provides three scenarios.

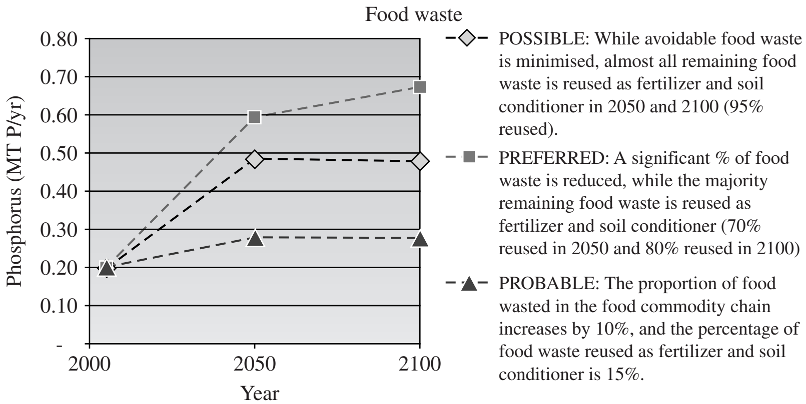

Figure 9. Scenarios for the contribution of food waste to meeting future phosphorus demand.

Crop Residues

Crop residues such as straw, husks, and stalks can be ploughed back into the soils after harvest, for their soil conditioning and fertilizer value (0.05–0.75% P_2O_5) (FAO, 2006). Around 40% of the 5 MT P in crop residues generated annually are currently reused as fertilizers (Smil, 2002). The remainder are used for feed, fuel, roofing bedding, sold or disposed of through burning or other means. Figure 10 presents future scenarios.

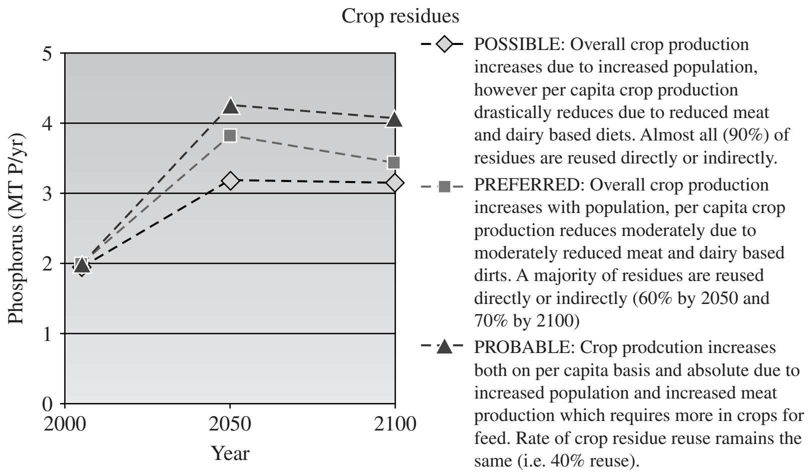

Figure 10. Scenarios for the contribution of crop residues to meeting future phosphorus demand.

Other sources

Other concentrated sources of phosphorus include: commercial organic fertilizers (processed to ensure consistent characteristics) (FAO, 2006); ash (e.g. from slash-and-burn techniques); animal meal (ground bone, meat and blood) (Mårald, 1998); guano (bat and bird droppings) (Cordell *et al.*, in press); aquatic vegetation and sediments, (Koning *et al.*, 2008, p.34).

It is assumed that these sources together could provide the remaining 1–1.2 MT P required in 2050 and 2100 to meet the new phosphorus demand following implementation of preferred demand measures outlined in section 1.5.

A LONG-TERM PERSPECTIVE: HISTORICAL AND FUTURE SCENARIOS

A synthesis of the *preferred* future supply and demand scenarios together with historical sources of phosphorus fertilizers (Cordell *et al.*, in press) are provided in Figure 11.

Figure 11 illustrates how if unchecked, demand for phosphorus will continue to rise over the remainder of the 21st century, reaching 83 MT P in 2100. The figure also demonstrates how this demand can be substantially reduced through measures such as changing diets, food chain efficiency, and most substantially through improved agricultural efficiency. However there will likely be lag time of at least a decade (i.e. until 2020) before significant results from these policy and technical measures are realised. After 2020, total demand decreases and can be met through multiple sources of phosphorus, shifting away from relying on phosphate rock by around 2015–2020 (assuming a lag time for the shift). In this case, the majority (∼65–90%) of human excreta, manure, crop residues and remaining food waste will need to be recovered and reused in an efficient and ethical manner in order to meet future food needs. The remaining gap between demand and supply can be supplemented through new sources such as seaweed, algae and ash.

INSTITUTIONAL CHALLENGES AND POLICY IMPLICATIONS

Phosphorus recovery and demand management are more than just technical solutions. Significant institutional changes will also be required at the

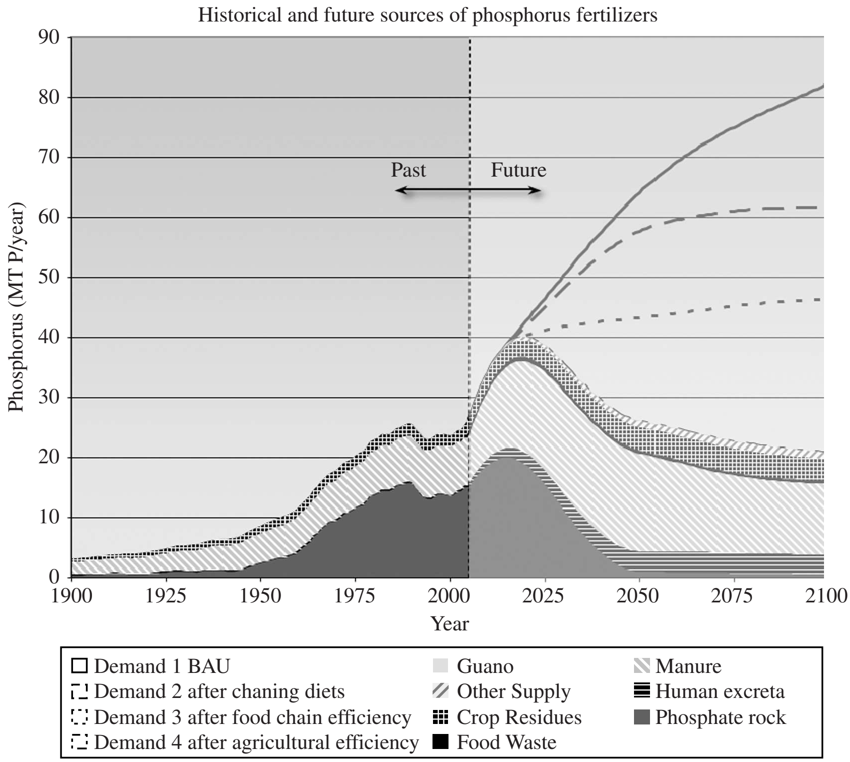

Figure 11. Long-term historical and future sources of phosphorus fertilizers for global food demand, based on aggregated preferred future scenarios.

international and national level in order to achieve the preferred scenarios in Figure 11. At minimum, this will require:

- Global governance that considers: roles and responsibilities for managing phosphorus use; integrating the phosphorus issue into global food security policies; independent and transparent monitoring and analysis of phosphorus source and use data; and, a deliberate paradigm shift to decouple sanitation's current association with water (e.g. 'WatSan' programs) towards an institutional link with food programs (e.g. 'FoodSan').
- Local and regional physical infrastructure to collect, treat and use phosphorus effectively and efficiently from multiple sources (food waste, excreta etc).

- National and local institutions and markets to manage and finance the new systems of reuse (e.g. new entrepreneurs).
- New national and local dialogues on community preferences and perceptions on phosphorus and food (from global scarcity to excreta reuse) and preferred pathways to achieving a sustainable situation.

CONCLUSIONS

The scenarios developed in this paper are designed to facilitate discussions among international and national policy makers, scientists, industry and community groups, aiming for a common framework for future phosphate recovery, demand management and governance structures to meet future global food demand.

Four key messages can be inferred from this analysis. Firstly, achieving food security in a sustainable way will likely mean the end of an era of agriculture's dependence on phosphate rock. Secondly, while there is no single quick fix solution to replacing the dependence on phosphate rock, a number of different supply and demand-side measures can together meet the growing demand for phosphorus in the long-term. Thirdly, in order to reach a desired pathway that is equitable and sustainable, significant changes will be required to both physical and institutional infrastructure. Finally, due to the serious lack of data, analysis and discussions at the international and national level regarding policies to achieve phosphorus security for food production, there is a significant and pressing need to act now, in order to avert a potentially serious shortage of phosphorus for food production.

ACKNOWLEDGEMENTS

The authors would like to thank Tom Lindström for his modelling and graphical assistance in the iterative aggregation of the preferred scenarios in Figure 11.

REFERENCES

Buckingham, D. and Jasinski, S. (2004). *Phosphate Rock Statistics 1900–2002*, US Geological Survey.

Cordell, D. (2008). *Phosphorus, food and 'messy' problems: A systemic inquiring into the management of a critical global resource*, paper submitted to the Australia New Zealand Systems Conference (ANZSYS), December 1st–3rd 2008, Perth.

Cordell, D. (forthcoming) *Phosphorus: A nutrient with no home – Multiple stakeholder perspectives on a critical global resource*, Institute for Sustainable Futures, University of Technology, Sydney (UTS) Sydney.

Cordell, D., Drangert, J.-O. and White, S. The Story of Phosphorus: Global food security and food for thought. *Global Environmental Change,* in press.

Drangert, J.-O. (1998). Fighting the urine blindness to provide more sanitation options. *Water SA,* **24**.

Dreborg, K. (1996). Essense of Backcasting. *Futures,* **28,** 813–828.

Driver, J. (1998). Phosphates recovery for recycling from sewage and animal waste. *Phosphorus and Potassium,* **216,** 17–21.

European Fertilizer Manufacturers Association (2000). *Phosphorus: Essential Element for Food Production*, European Fertilizer Manufacturers Association (EFMA) Brussels.

FAO (1999). *Urban and peri-urban agriculture*, Food and Agriculture Organisation of the United Nations, Rome.

FAO (2000). *Fertilizer Requirements in 2015 and 2030*, Food and Agriculture Organisation of the United Nations Rome.

FAO (2006). *Plant nutrition for food security: A guide for integrated nutrient management, FAO Fertilizer And Plant Nutrition Bulletin 16*, Food And Agriculture Organization Of The United Nations Rome.

FAO (2007a). *Current world fertilizer trends and outlook to 2010/11*, Food and Agriculture Organisation of the United Nations Rome.

FAO (2007b). *Organic agriculture and food availability*, International Conference on organic agriculture and food security, 3–5th May, 2007, Food and Agriculture Organisation of the United Nations Rome.

FAO (2008). *Efficiency of soil and fertilizer phosphorus use: Reconciling changing concepts of soils phosphorus behaviour with agronomic information*, FAO Fertilizer and Plant Nutrition Bulletin 18, Food and Agriculture Organization of the United Nations Rome.

Food Ethics Council (2008). *Food Distribution: An ethical agenda*, Food Ethics Council, October 2008 Brighton.

Fraiture, C.d. (2007). *Future Water Requirements for Food – Three Scenarios, International Water Management Institute (IWMI)*, SIWI Seminar: Water for Food, Bio-fuels or Ecosystems? in World Water Week 2007, August 12th–18th 2007 Stockholm.

García-Torres, L., Benites, J., Martinez-Vilela, A. and Holgado-Cabrera, A. (2003). *Conservation Agriculture: Environment, Farmers Experiences, Innovations, Socio-Economy, Policy,* Springer.

Gidley, J., Batemen, d. and Smith, C. (2004). *Futures in Education: Principles, practice and potential*, Monograph Series 2004, No. 5, Australian Foresight Institute, Swinburne University, Melbourne.

Gunther, F. (2005). *A solution to the heap problem: The doubly balanced agriculture: integration with population*, Available: http://www.holon.se/folke/kurs/Distans/Ekofys/Recirk/Eng/balanced.shtml

Heffer, P. and Prud'homme, M. (2008). *Medium-Term Outlook for Global Fertilizer Demand, Supply and Trade 2008–2012, Summary Report*, International Fertilizer Industry Association (IFA), Paris.

Holmgren, D. (2003). *Permaculture: Principles and Pathways Beyond Sustainability*, Holmgren Design Services.

IFA (2006). *Production and International Trade Statistics*, International Fertilizer Industry Association Paris, available: http://www.fertilizer.org/ifa/statistics/pit_public/pit_public_statistics.asp (accessed 20/8/07).

IFA (2007). *Fertilizer Best Management Practices: General Principles, Strategy for their Adpotion and Voluntary Initatives vs Regulations*, International Fertilizer Industry Association, Paris.

IFA (2008). *Feeding the Earth: Fertilizers and Global Food Security, Market Drivers and Fertilizer Economics* International Fertilizer Industry Association Paris.

IWMI (2006). *Comprehensive Assessment of water management in agriculture*, Co-sponsers: FAO, CGIAR, CBD, Ramsar, www.iwmi.cgiar.org/assessment

Jasinski, S.M. (2008). *Phosphate Rock, Mineral Commodity Summaries*, January 2008 <minerals.usgs.gov/minerals/pubs/commodity/phosphate_rock/>.

Jönsson, H., Stintzing, A.R., Vinnerås, B. and Salomon, E. (2004). *Guidelines on the Use of Urine and Faeces in Crop Production*, EcoSanRes, Stockholm Environment Institute Stockholm.

Koning, N.B.J., Ittersum, M.K.v., Becx, G.A., Boekel, M.A.J.S.v., Brandenburg, W.A., Broek, J.A.v.d., Goudriaan, J., Hofwegen, G.v., Jongeneel, R.A., Schiere, J.B. and Smies, M. (2008). Long-term global availability of food: continued abundance or new scarcity? . *NJAS Wageningen Journal of Life Sciences* **55,** 229–292.

Kvarnström, E., Emilsson, K., Stintzing, A.R., Johansson, M., Jönsson, H., Petersens, E.a., Schönning, C., Christensen, J., Hellström, D., Qvarnström, L., Ridderstolpe, P. and Drangert, J.-O. (2006). *Urine Diversion: One Step Towards Sustainable Sanitation*, EcoSanRes programme, Stockholm Environment Institute Stockholm.

Lundqvist, J., Fraiture, C.d. and Molden, D. (2008). *Saving Water: From Field to Fork – Curbing Losses and Wastage in the Food Chain, SIWI Policy Brief*, Stockholm International Water Institute, Stockholm.

Mårald, E. (1998). *I mötet mellan jordbruk och kemi: agrikulturkemins framväxt på Lantbruksakademiens experimentalfält 1850–1907*, Institutionen för idéhistoria, Univ Umeå.

Mitchell, C. and White, S. (2003). Forecasting and backcasting for sustainable urban water futures. *Water Policy,* **30,** 25–28.

Netherlands Environmental Assessment Agency (2006). *Integrated modelling of global environmental change. An overview of IMAGE 2.4*, Netherlands Environmental Assessment Agency (MNP), MNP publication number 500110002/2006 October 2006 Bilthoven.

Pacala, S. and Socolow, R. (2004). Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies. *Science,* **305,** 968–972.

Raschid-Sally, L. and Jayakody, P. (2008). *Drivers and characteristics of wastewater agriculture in developing countries – results from a global assessment*, Comprehensive Assessment of water management in agriculture, International Water Management Institute.

Reindl, J. (2007). *Phosphorus Removal from Wastewater and Manure Through Struvite Formation: an annotated bibliography*, Dane County Dept of Highway, Transportation and Public Works.

Royal Dutch Shell (2008). *Shell Energy Scenarios 2050*, Shell International BV. Available: www.shell.com/scenarios

SCOPE (2004). Struvite: its role in phosphorus recovery and recycling,. *International conference 17th–18th June 2004, Cranfield University, Great Britain. Summary report in SCOPE 57*.

Shua, L., Schneidera, P., Jegatheesana, V. and Johnsonb, J. (2005). An economic evaluation of phosphorus recovery as struvite from digester supernatant. *Bioresource Technology,* **97**(17), 2211–2216.

Smil, V. (2000). Phosphorus in the Environment: Natural Flows and Human Interferences *Annual Review of Energy and the Environment,* **25,** 53–88.

Smil, V. (2002). Phosphorus: Global Transfers. IN DOUGLAS, P.I. (Ed.) *Encyclopedia of Global Environmental Change.* Chichester, John Wiley & Sons.

Smil, V. (2007). *Policy for Improved Efficiency in the Food Chain*, SIWI Seminar: Water for Food, Bio-fuels or Ecosystems? in World Water Week 2007, August 12th–18th 2007 Stockholm.

Steen, I. (1998). Phosphorus availability in the 21st Century: Management of a non-renewable resource. *Phosphorus and Potassium,* **217,** 25–31.

Stewart, W., Hammond, L. and Kauwenbergh, S.J.V. (2005). Phosphorus as a Natural Resource. *Phosphorus: Agriculture and the Environment, Agronomy Monograph No.46.* Madison, American Society of Agronomy, Crop Science Society of America, Soil Science Society of America.

UN (2003). *World Population in 2300: Highlights*, draft, United Nations Department of Economic and Social Affairs, Population Division, New York.

UN (2007). *World Population Prospects: The 2006 Revision*, United Nations Department of Economic and Social Affairs, Population Division New York.

UNDP (2007). *Overcoming vulnerability to rising oil prices: Options for Asia and the Pacific*, United Nations Development Programme (UNDP), Regional Energy Programme for Poverty Reduction, Bangkok, available: http://www.energyand environment.undp.org/undp/indexAction.cfm?module=Library&action=GetFile& DocumentAttachmentID=2327

WHO (2006a). *Guidelines for the safe use of wastewater, excreta and greywater, Vol. 4: Excreta and greywater use in agriculture*, World Health Organisation.

WHO (2006b). *Obesity and overweight, Fact sheet number 311*, World Health Organisation Global Strategy on Diet, Physical Activity and Health, Geneva, available: http://www.who.int/mediacentre/factsheets/fs311/en/index.html

Wissa, A.E.Z. (2003). *Phosphogypsum Disposal and The Environment* Ardaman & Associates, Inc. Florida, available: http://www.fipr.state.fl.us/pondwatercd/phosphogypsum_disposal.htm

World Bank (2005). *Water Resources And Environment Technical Note F.3 Wastewater Reuse* Series Editors Richard Davis, Rafik Hirji Washington, DC.

WRAP (2008). *The food we waste, Food waste report v2*, Waste & Resources Action Programme.

WSRW (2007). *The phosphate exports*, Western Sahara Resource Watch, http://www.wsrw.org/index.php?cat=117&art=521

WWF (2004). *Living Planet Report*, World Wide Fund For Nature, Cambridge. Available: http://assets.panda.org/downloads/lpr2004.pdf

Notes

[i] Backcasting is ideal to address complex, long-term, solutions-oriented future studies with a high degree of uncertainty. See Robinson (1990), Dreborg (1996), Mitchell and White (2003).

[ii] Little data is available on such sources, particularly organic phosphorus sources, due to lack of previous monitoring and research. The figures thus present best available data and should be considered for their order of magnitudes. In this way, they can be used as a framework to stimulate discussion and further data collection to increase accuracy of assumptions.

[iii] The FAO's Integrated Nutrient Management (INM) approach does provides an integrated approach to agricultural efficiency and multiple source of plant nutrients, however this does not address reducing demand beyond the field.

[iv] The rest remains chemically unavailable in the soil, or washed off to waterways.

[v] However these data sets have been heavily criticised by some scientists (Michael Lardelli pers comm 9/8/08; Ward, 2008) claiming USGS assumptions behind reserves are over-estimates and may be biased towards industry interests. On the other hand, these estimates are also viewed as under-estimates by others. Table 2 in Cordell et al (submitted) outlines factors leading to potential over- or under-estimates of phosphate rock reserves and the timeline of peak phosphorus.

[vi] Phosphate rock deposits exist in other countries and offshore on the seabed, however these are difficult to access and of lower quality and hence uneconomical to mine.

[vii] Nearly all the P in the input material is retained in the slurry, since the phosphorus cycle does not have a significant atmospheric phase.

[viii] This varies with diet, for example, excreta from a person eating meat can contain twice as much phosphorus as a vegetarian's excreta.