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The story of phosphorus: Global food security and food for thought

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ABSTRACT

Food production requires application of fertilizers containing phosphorus, nitrogen and potassium on agricultural fields in order to sustain crop yields. However modern agriculture is dependent on phosphorus derived from phosphate rock, which is a non-renewable resource and current global reserves may be depleted in 50–100 years. While phosphorus demand is projected to increase, the expected global peak in phosphorus production is predicted to occur around 2030. The exact timing of peak phosphorus production might be disputed, however it is widely acknowledged within the fertilizer industry that the quality of remaining phosphate rock is decreasing and production costs are increasing. Yet future access to phosphorus receives little or no international attention. This paper puts forward the case for including long-term phosphorus scarcity on the priority agenda for global food security. Opportunities for recovering phosphorus and reducing demand are also addressed together with institutional challenges.

1. Introduction

Food production is fundamental to our existence, yet we are using up the world's supply of phosphorus, a critical ingredient in growing food. Today, phosphorus is mostly obtained from mined rock phosphate and is often combined in mineral fertilizers with sulphuric acid, nitrogen, and potassium. Existing rock phosphate reserves could be exhausted in the next 50–100 years (Steen, 1998; Smil, 2000b; Gunther, 2005). The fertilizer industry recognises that the quality of reserves is declining and the cost of extraction, processing and shipping is increasing (Runge-Metzger, 1995; Driver, 1998; Smil, 2000b; EcoSanRes, 2003). Box 1 outlines the key issues.

Common responses to resource scarcity problems include higher prices, more efficient resource use, the introduction of alternatives, and the recovery of the resource after use. The use of phosphorus is becoming more efficient, especially in Europe. Farmers in Europe and North America are increasingly avoiding over fertilization, and are ploughing straw and animal manure into agricultural soils, partly to recycle phosphorus (European Fertilizer Manufacturers Association, 2000). However, most of the discussion about efficient phosphorus use, and most of the measures to achieve this, have been motivated by concerns about toxic algal blooms caused by the leakage of phosphorus (and nitrogen) from agricultural land (Sharpley et al., 2005). While such measures are essential, they will not by themselves be sufficient to achieve phosphorus sustainability. A more integrated and effective approach to the management of the phosphorus cycle is needed—an approach which addresses future phosphorus scarcity and hence explores synergies that reduce leakage and recover and reuse phosphorus.

The following sections of this paper assess the historical, current and future availability of phosphorus in the context of global food security. Possible options for meeting the world's future phosphorus demand are outlined and institutional opportunities and obstacles are discussed.

2. Humanity's addiction to phosphate rock

Historically, crop production relied on natural levels of soil phosphorus and the addition of locally available organic matter like manure and human excreta (Mårald, 1998). To keep up with increased food demand due to rapid population growth in the 20th century, guano and later rock phosphate were applied extensively to food crops (Brink, 1977; Smil, 2000b). Fig. 1 gives a broad outline of the evolution of phosphorus fertilizer use for food production.

The Chinese used human excreta ('night soil') as a fertilizer from the very early stages of their civilization, as did the Japanese from the 12th century onwards (Matsui, 1997). In Europe, soil degradation and recurring famines during the 17th and 18th

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Box 1. Phosphorus (P): A closer look at an emerging crisis.

- Plants require phosphorus to grow. Phosphorus is an element on the periodic table that cannot be substituted and is therefore vital for producing the food we eat (Steen, 1998).
- 90% of global demand for phosphorus is for food production, currently around 148 million tonnes of phosphate rock per year (Smil, 2000a,b; Gunther, 2005).
- The demand for phosphorus is predicted to increase by 50–100% by 2050 with increased global demand for food and changing diets (EFMA, 2000; Steen, 1998).
- Phosphorus is a non-renewable resource, like oil. Studies claim at current rates of extraction, global commercial phosphate reserves will be depleted in 50–100 years (Runge-Metzger, 1995; EcoSanRes, 2003; Steen, 1998). The remaining potential reserves are of lower quality or more costly to extract.
- Phosphate rock reserves are in the control of only a handful of countries (mainly Morocco, China and the US), and thus subject to international political influence. Morocco has a near monopoly on Western Sahara's reserves, China is drastically reducing exports to secure domestic supply, US has less than 30 years left of supplies, while Western Europe and India are totally dependent on imports (Jasinski, 2006; Rosmarin, 2004).

centuries created the need to supplement animal and human excreta with other sources of phosphorus (Mårald, 1998). In the early 19th century, for instance, England imported large quantities of bones from other European countries. In addition to the application of phosphorus from new sources, improved agricultural techniques enabled European agriculture to recover from the famines of the 18th century (Mårald, 1998). These improvements included crop rotation, improved handling of manure, and in particular, the introduction of new crops such as clover which could fix nitrogen from the atmosphere.

Liebig formulated his 'mineral theory' in 1840, which replaced the 'humus theory' that plants and animals were given life in a mysterious way from dead or decomposing plants and animals (Liebig, 1840; Mårald, 1998). Liebig provided a scientific explanation: nutrients such as nitrogen, phosphorus and potassium were elements circulating between dead and living material (Mårald, 1998). This discovery occurred during a period of rapid urbanization in Europe, when fertilizer factories were being established around growing cities. Food production was local and the factories manufactured phosphorus fertilizers from locally available organic waste products, such as human excreta, industrial organic waste by-products, animal dung, fish, ash, bones, and other slaughterhouse by-products (Mårald, 1998; Neset et al., 2008).

However, around the mid-to-late 19th century, the use of local organic matter was replaced by phosphorus material from distant sources. The mining of guano (bird droppings deposited over previous millennia) and phosphate-rich rock had begun (Brink, 1977; Smil, 2000b). Guano was discovered on islands off the Peruvian coast and later on islands in the South Pacific. World trade in guano grew rapidly, but it relied on a limited resource which declined by the end of the 19th century (Stewart et al., 2005). Phosphate rock was seen as an unlimited source of concentrated phosphorus and the market for mineral fertilizers developed rapidly. At the same time, the introduction of flush toilets in towns meant that human waste was discharged into water bodies instead of being returned to the soil. There were protests among intellectuals that farmers were being robbed of human manure. Among them was Victor Hugo who wrote in *Les Miserables*:

> Science, after having long groped about, now knows that the most fecundating and the most efficacious of fertilizers is human manure. The Chinese, let us confess it to our shame, knew it before us. Not a Chinese peasant – it is Eckberg who says this – goes to town without bringing back with him, at the two extremities of his bamboo pole, two full buckets of what we designate as filth. Thanks to human dung, the earth in China is

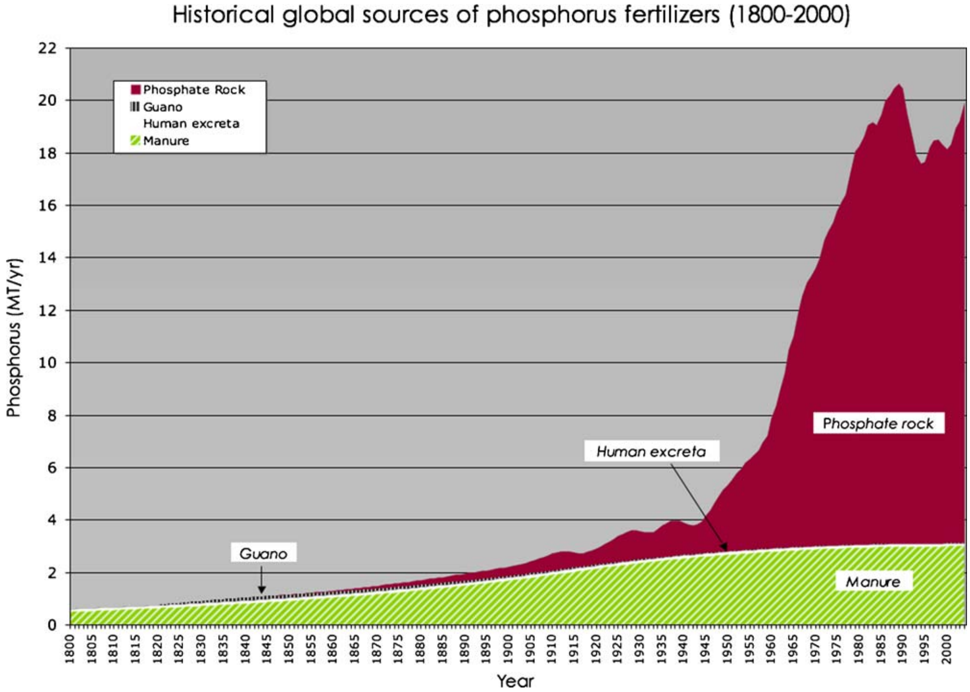

Fig. 1. Historical sources of phosphorus for use as fertilizers, including manure, human excreta, guano and phosphate rock (1800–2000) (Reliability of data sources vary, hence data points for human excreta, guano and manure should be interpreted as indicative rather than precise.). Calculations based on data in Brink (1977), Buckingham and Jasinski (2004), IFA (2006) and Smil (2000b).

> still as young as in the days of Abraham. Chinese wheat yields a hundredfold of the seed. There is no guano comparable in fertility with the detritus of a capital. A great city is the most mighty of dung-makers. Certain success would attend the experiment of employing the city to manure the plain. If our gold is manure, our manure, on the other hand, is gold (Hugo, 1862).

Trade in food grew steadily with urbanization and colonization, but insufficient amounts of nutrients were returned to the areas of food production to balance off-takes. By the late 19th century, processed mineral phosphorus fertilizer was routinely used in Europe and its use grew substantially in the 20th century (International Fertilizer Industry Association, 2006; Buckingham and Jasinski, 2004). Processed mineral fertilizers such as ordinary superphosphate (OSP) typically contained an order of magnitude greater concentration of phosphorus than did manures (Smil, 2000b). Application of such highly concentrated fertilizers helped rectify the phosphorus deficiency of soils. In the mid-20th century the Green Revolution improved agricultural output in many countries. As well as introducing new crop varieties, the Green Revolution involved the application of chemical fertilizers.[1] This new approach saved millions from starvation and the proportion of the world's population that was undernourished declined despite rapid population growth (IFPRI, 2002a). Today, food could not be produced at current global levels without the use of processed mineral fertilizers. We are effectively addicted to phosphate rock.

3. The current situation

3.1. Demand for food, demand for fertilizers

Following more than half a century of generous application of inorganic high-grade phosphorus and nitrogen fertilizers, agricultural soils in Europe and North America are now said to have surpassed 'critical' phosphorus levels, and thus only require light applications to replace what is lost in harvest (FAO, 2006; European Fertilizer Manufacturers Association, 2000). Consequently, demand for phosphorus in these regions has stabilized or is decreasing.

However in developing and emerging economies the situation is different. Global demand for phosphorus is forecast to increase by around by 3–4% annually until 2010/11 (Maene, 2007; FAO, 2007a), with around two-thirds of this demand coming from Asia (FAO, 2007a), where both absolute and per capita demand for phosphate fertilizers is increasing. There will be an estimated 2–2.5 billion new mouths to feed by 2050 (IWMI, 2006), mainly in urban slums in the developing world. Meat and dairy products, which require higher phosphorus inputs than other foods, are becoming more popular in China and India. According to the International Water Management Institute (Fraiture, 2007) global food production will need to increase by about 70% by 2050 to meet global demand. Under these circumstances, acquiring enough phosphorus to grow food will be a significant challenge for humanity in the future.

In Sub-Saharan Africa, where at least 30% of the population is undernourished, fertilizer application rates are extremely low and 75% of agricultural soils are nutrient deficient,[2] leading to declining yields (IFDC, 2006; Smaling et al., 2006). The UN and the Alliance for a Green Revolution in Africa has called for a new Green Revolution in Sub-Saharan Africa, including increased access to fertilizers (Blair, 2008; AGRA, 2008) but there has been little discussion of the finiteness of phosphate fertilizer reserves.

In 2007–2008, the same pressures that caused the recent global food crisis led to phosphate rock and fertilizer demand exceeding supply and prices increased by 700% in a 14-month period (Minemakers Limited, 2008). Two significant contributors to the increased demand for phosphorus have been the increasing popularity of meat- and dairy-based diets, especially in growing economies like China and India, and the expansion of the biofuel industry. Increasing concern about oil scarcity and climate change led to the recent sharp increase in biofuel production. The biofuel industry competes with food production for grains and productive land and also for phosphorus fertilizers. The year 2007 was the first year a clear rise in phosphate rock demand could be attributed to ethanol production (USGS 2007, pers. comm., 5th September).

The International Fertilizer Industry Association expects 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 remain high in the near future, until new mining projects such as those planned in Saudi Arabia are commissioned (Heffer and Prud'homme, 2007). The sudden spike in the price of fertilizers in 2007–2008 took most of the world's farmers completely by surprise. In India, which is totally dependent on phosphate imports, there have been instances of farmer riots and deaths due to the severe national shortage of fertilizers (Bombay News, 2008). While this short-term crisis is not a direct consequence of the long-term scarcity issues outlined in this paper, the short-term situation can be seen as an indication of what is to come.

3.2. Global food security and resource scarcity

The UN's Food and Agricultural Organization (FAO) states that food security "exists when all people, at all times, have access to sufficient, safe and nutritious food to meet their dietary needs for an active and healthy life" (FAO, 2005b, p1). Securing future food security is now considered a global priority (UN, 2000; IFPRI, 2002b). At the turn of the Millennium, 191 nations formalised their commitment to the eight Millennium Development Goals (MDGs), one of which is to decrease poverty and hunger by 50% by 2015 (UN, 2000). Currently, there are over 800 million people without sufficient access to food (SOFI, 2005; UN, 2005). While over 40% of Africans today cannot secure adequate food on a day-to-day basis, many people in both the developed and developing world are suffering from obesity[3] (UN Millennium Project, 2005; SIWI-IWMI, 2004; Gardner and Halweil, 2000). Food security is a challenge that can only be met by addressing a number of relevant issues. The FAO's annual State of Food Insecurity (SOFI) reports, the International Food Policy Research Institute's (IFPRI) reports and the UN Millennium Development Project all stress that food insecurity is a consequence of numerous linked factors, including frequent illness, poor sanitation, limited access to safe water and lack of purchasing power (FAO, 2004a; Braun et al., 2004; UN Millennium Project, 2005).

Today it is acknowledged that addressing energy and water issues will be critical for meeting the future nutritional demands of a growing population (Smil, 2000a; Pfeiffer, 2006) but the need to address the issue of limited phosphorus availability has not been widely recognized. Approximately 70% of the world's demand for

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[1] The Green Revolution in the early 1960s was enabled by the invention of the Haber-Bosch process decades earlier, which allowed the production of high volumes of artificial nitrogenous fertilizers (Brink, 1977).

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

[3] For example, a recent FAO study found that in Egypt, there are currently more overweight than underweight children (see FAO, 2006, Fighting hunger – and obesity, Spotlight 2006, Agriculture 21, FAO, [Online], available: http://www.fao.org/ag/magazine/0602sp1.htm [accessed 4/6/06]).

fresh water is for agriculture (SIWI-IWMI, 2004) and about 90% of worldwide demand for rock phosphate is for food production (Rosmarin, 2004; Smil, 2002). It is predicted that demand for both resources will outstrip supply in the coming decades. Experts suggest that a radical shift in the way we think about and manage water is required (Falkenmark and Rockström, 2002), to deal with the 'hydroclimatic realities' of water availability (SIWI-IWMI, 2004). In a similar way, food security faces the 'geochemical realities' of limited phosphate reserves.

Global food production is also highly dependent on cheap energy, particularly from fossil fuels like oil. Transporting food all over the world in addition to mining and manufacturing fertilizers is only possible while cheap oil exists. However a peak in global oil production is imminent (Royal Dutch Shell, 2008) and alternatives to fossil-fuel-dependent agricultural systems will be required in the future (Pfeiffer, 2006).

3.3. *Global phosphate rock reserves and geopolitics*

All modern agriculture is today dependent on regular inputs of phosphate fertilizer derived from mined rock to replenish the phosphorus removed from the soil by the growing and harvesting of crops. However, phosphate rock is a non-renewable resource and approximately 50–100 years remain of current known reserves (Steen, 1998; Smil, 2000b; Gunther, 2005). The world's remaining phosphate rock reserves are under the control of a handful of countries, including China, the US and Morocco. While China has the largest reported reserves, it has recently imposed a 135% export tariff on phosphate, effectively preventing any exports in order to secure domestic supply (Fertilizer Week, 2008). The 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 factories (Jasinski, 2008). This is geopolitically sensitive as Morocco currently occupies Western Sahara and controls its phosphate rock reserves. The Western Sahara Resource Watch claims that "*extracting and trading with phosphates from Western Sahara are contrary to international law*" (WSRW, 2007) and such trade is highly condemned by the UN (Corell, 2002). Several Scandinavian firms have boycotted this trade in recent years (The Norwegian Support Committee for Western Sahara, 2007).

Together, Moroccan and Western Saharan reserves represent more than a third of the world's supply of high-quality phosphate rock (IFA, 2006). Ironically, the African continent is simultaneously the world's largest exporter of phosphate rock and the continent with the largest food shortage (FAO, 2006; Jasinski, 2006) (see Fig. 2).

This highlights the importance of phosphorus *accessibility*, in addition to physical (and political) scarcity. Indeed, the average sub-Saharan farmer has less purchasing power to access fertilizer markets, yet phosphate fertilizers can cost an African farmer 2–6 times more than they cost a European farmer due to higher transport and storage costs (Runge-Metzger, 1995; Fresco, 2003).

3.4. *Quantifying today's phosphorus flows through the food system*

A systems approach to understanding the phosphorus cycle, particularly in global food production and consumption, can help in locating and quantifying losses and inefficiencies and thus assist in identifying potential recovery points. A modification of the Substance Flows Analysis (SFA) tool from Industrial Ecology has been applied to track global phosphorus flows. SFA quantifies the material inputs and outputs from processes and stocks within a system to better understand pollution loads on a given environment, and determine places to intervene in a system to increase its efficiency, or reduce wastage and pollution (Brunner and Rechberge, 2004). The simplified SFA in Fig. 3 traces phosphorus through the global food production and consumption system, from the mine through to consumption, and identifies losses throughout the system. Unlike water (SIWI-IWMI, 2004; Lundqvist et al., 2007), carbon (GCP, 2008) and nitrogen (UNEP, 2007), there are no comprehensive studies analysing anthropogenic global flows of phosphorus.[4]

The inner white area termed the 'Anthroposphere' defines the human-activity system (in this case, food-related human activity), while the outer area termed 'Natural Environment' represents the 'natural' phosphorus biogeochemical system (in which the human activity system is embedded). The dotted arrows in the natural biogeochemical system occur at a rate of millions of years (for example, natural weathering and erosion of phosphate-bearing rock). The solid arrows within the human activity system indicate the approximate quantities of phosphorus (in millions of metric tonnes of phosphorus per year, MT P per year) in each key stage (the boxes) in the food production and consumption process. These stages are: mining, fertilizer production, the application of fertilizers to agricultural soils, the harvesting of crops, food and feed processing, consumption of food by animals and humans, excretion and leakage from the system to either the natural environment or recirculation back to the food system.

Mineral phosphorus in rock phosphate was formed 10–15 million years ago (White, 2000). Since the end of World War II, global extraction of phosphate rock has tripled to meet industrial agriculture's demand for NPK fertilizers (UNEP, 2005). Approximately 90% of society's use of phosphorus is for food production (including fertilizers, feed and food additives) (Smil, 2000b; European Fertilizer Manufacturers Association, 2000). Currently, phosphorus fertilizers sourced from mined phosphate rock accounts for around 15 MT P per year (Jasinski, 2006; Gumbo and Savenije, 2001; Rosmarin, 2004; Gumbo, 2005). Modern agricultural systems require annual applications of phosphorus-rich fertilizer. However, unlike the natural biochemical cycle, which recycles phosphorus back to the soil 'in situ' via dead plant matter, modern agriculture harvests crops prior to their decay phase, transporting them all over the world to food manufacturers and to consumers.

Because phosphate rock and phosphate fertilizers are both commodities on the international market, international data exists for mining, fertilizer production and application. However after fertilizer application, there is very little accurate data available for use in a global analysis. This is particularly true of sources of organic phosphorus, such as manure, crop residues and household organic waste, which are re-circulated or lost from the food system (FAO, 2006). These organic phosphorus sources are typically not commodities, but are applied informally and on an ad hoc basis, and so there is no formal tracking of their use and losses. Data that does exist is typically compiled at a farm or local level. The use of organic phosphorus sources is often not quantified in investigations of phosphorus flows in the food production and consumption process as researchers are presently more interested in losses to water bodies causing eutrophication. Calculations based on Smil (2000a, 2002) suggest the total phosphorus content in annual global agricultural harvests is approximately 12 MT P, of which 7 MT P is processed for feed and food and fibre, while 40% of the remaining 5 MT P of crop residues is returned to the land.[5]

Studies on post-harvest losses of food and embodied water from the global food production and consumption chain (Smil,

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[4] A recently published paper by Liu et al. (2008) does provide an analysis of global anthropogenic phosphorus flows based on existing data.

[5] This is fairly consistent with estimates by Liu et al. (2008), published after this analysis. Both analyses have drawn heavily from Smil, so this is not 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.

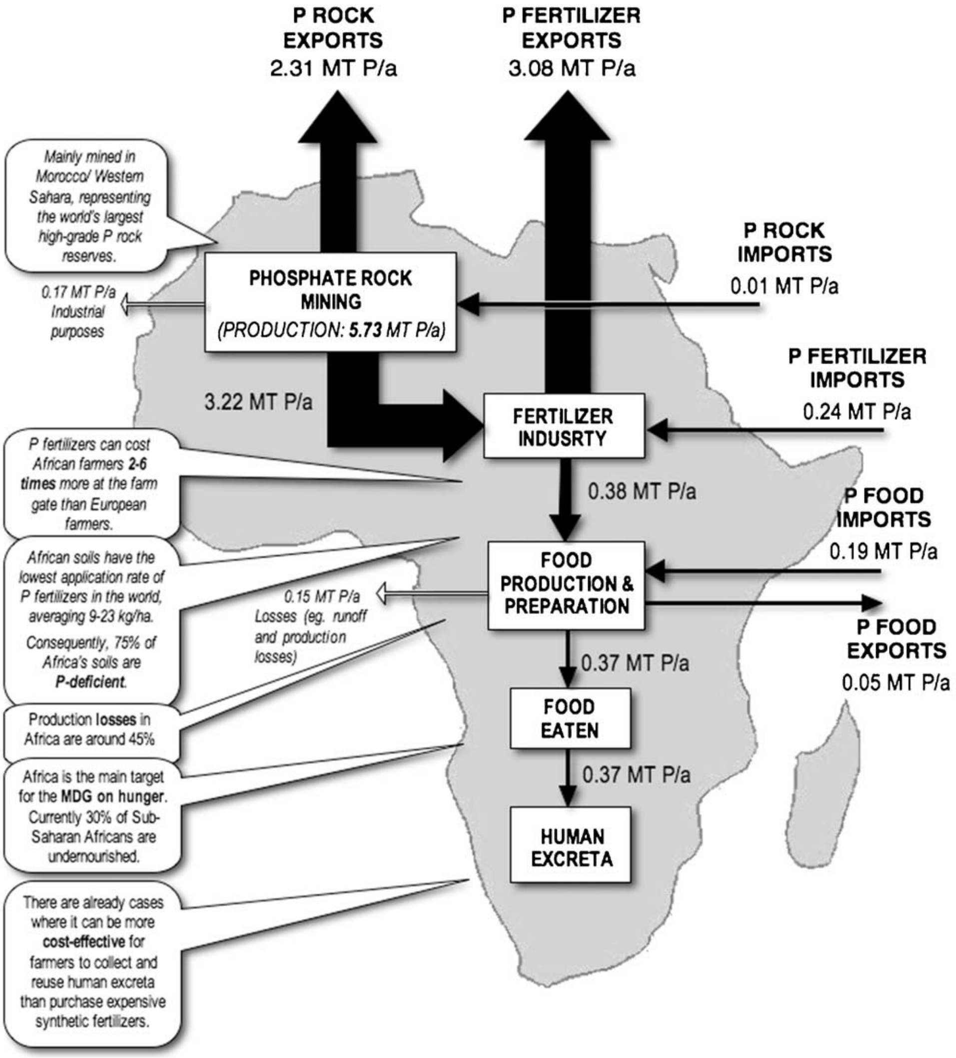

Fig. 2. Major phosphorus flows in the production and trade of phosphorus commodities in Africa, including phosphate rock, phosphorus fertilizers and food commodities. Calculations based on data in Gumbo (2005), Stockholm Environment Institute (2005), IFDC (2005) and IFA (2006) (Best available data for 2005 has been used for phosphate rock and fertilizer flows, while 2000–2003 data has been used for food flows.) (Flows are indicative and not intended to add up in all instances due lack of available data. Flows not presented in this diagram, including recirculation of organics (such as manure and crop residues) are not included due to lack of available and reliable data; a small amount of phosphate rock is used in direct application on the field; intermediate phosphate commodities, such as phosphoric acid are included as 'fertilizers' for simplicity and due to lack of complete data set. Care has been taken to avoid double counting, as phosphoric acid is used to produce most fertilizers.).

2000a; SIWI et al., 2008), can be used as a basis for estimating phosphorus losses. This suggests that approximately 55% of phosphorus in food is lost between 'farm and fork'. Smil (2000a) estimates that around 50% of the phosphorus consumed and hence excreted by livestock is returned to agriculture globally. However there are significant regional imbalances, such as an oversupply of manure in regions where a critical soil phosphorus level has already been surpassed (such as The Netherlands and parts of 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).

Close to 100% of phosphorus eaten in food is excreted (Jönsson et al., 2004). Working backwards using a mass balance, we can calculate that humans physically consume approximately 3 MT P globally.[6] Every year, the global population excretes around 3 million tonnes of phosphorus in urine and faeces. Given that more than half the world's population now lives in urban centres, and urbanization is set to increase (FAO, 2007b), cities are becoming phosphorus 'hotspots' and urine is the largest single source of phosphorus emerging from cities. While nutrient flows from food via human excreta typically found their way back to land in the past, today they more often end up in waterways via wastewater from urban centres or as sludge in landfills. Over-fertilization of agricultural soils has been a common practice in the northern hemisphere, and contributes to excess discharge into water bodies and environmental problems like eutrophication. Rosmarin (2004) estimates that close to 25% of the 1 billion tonnes of phosphorus mined since 1950 has ended up in water bodies, or is buried in landfills. It is estimated that on average, around 10% of human excreta is currently recirculated, either intentionally or unintentionally, back to agriculture or aquaculture. Examples of how this occurs include poor urban farmers in Pakistan diverting the city's untreated wastewater to irrigate and fertilize the crops (Ensink et al., 2004), and 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 (see Section 5 for examples).

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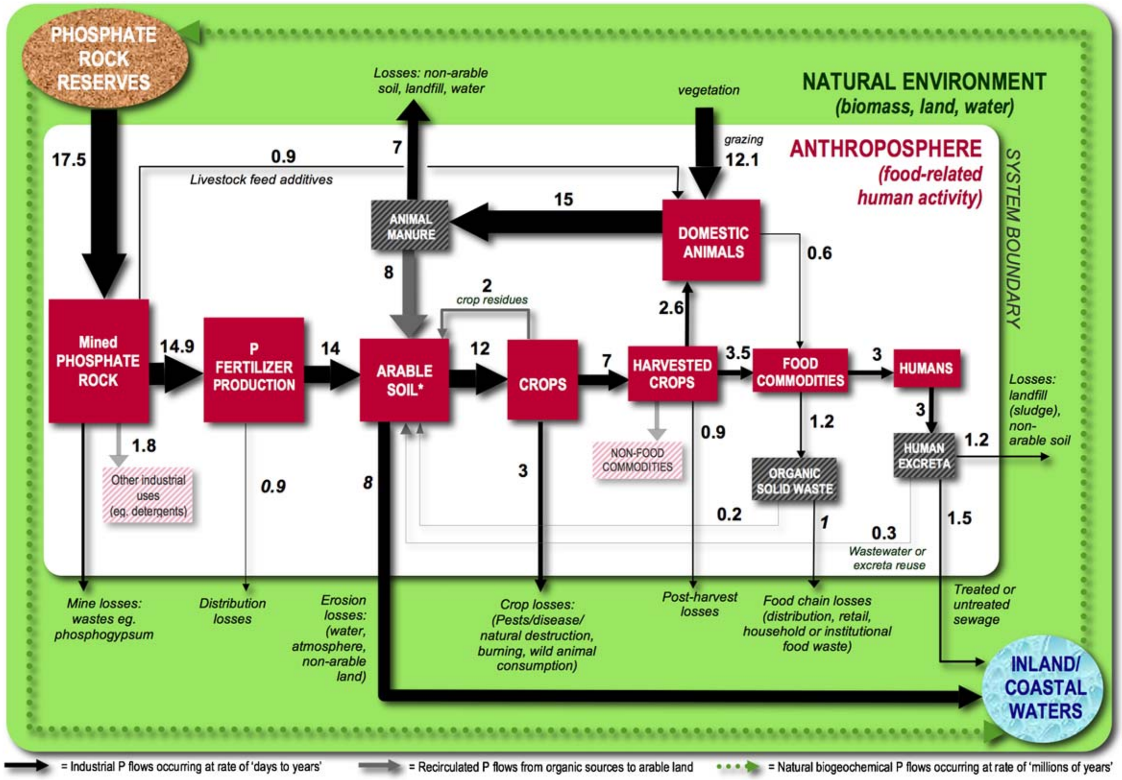
[6] Human bodies require roughly 1.2 g/(person day) of phosphorus for healthy functions, which equates to approximately 3 MT P globally.



* only a fraction of applied mineral P is taken up by crops in a given year, the balance comes from the soil stocks, either from natural soil P, or build up from previous years and decades of fertilizer application.

Fig. 3. Key phosphorus flows through the global food production and consumption system, indicating phosphorus usage, losses and recovery at each key stage of the process. Units are in Million Tonnes per year (Only significant flows are shown here, relevant to modern food production and consumption systems.). Calculations based on data in IFA (2006) and Smil (2000a,b).

In addition to analysing the global use of phosphorus based on an average diet, it is also informative to analyse different scenarios of phosphorus demand by assessing likely phosphorus losses in the various phases of the food chain. By working backwards from human excreta to the field, we can calculate the required amount of phosphate rock for vegetarian and meat-based diets. Table 1 provides an example of such a calculation with stated assumptions. A vegetarian excretes some 0.3 kg/(P year) (WHO, 2006), and if one-third of the phosphorus in a vegetarian's food is lost during food preparation, one can assume that the post-harvest material contained 0.45 kg P. Assuming that three quarters of the harvested crop ends up as organic waste, the average per capita annual harvest for a vegetarian would have contained 1.8 kg P originally. If one-third of the phosphorus taken up by plants is from mineral phosphate fertilizer and soil phosphorus provides the remaining two thirds, then 0.6 kg of mineral phosphate fertilizer is required annually for a vegetarian. It takes 4.2 kg of rock phosphate to produce 0.6 kg of phosphorus. If equivalent assumptions are made for meat production, it can be concluded that meat-eaters require some 11.8 kg of rock phosphate (for meat eaters, it is assumed that one-fifth of phosphorus uptake is from mineral phosphate fertilizer and four-fifths is from soil phosphorus).

This simple calculation using phosphorus losses in each phase highlights two things. Firstly, that a vegetarian diet demands significantly less phosphate fertilizer than a meat-based diet. And secondly, that returning biomass from plants to the soil is by far the most important measure to retain soil phosphorus in a meat-based diet. This also requires no transport back to the field. For the vegetarian diet, the use of human excreta is the most important recovery measure but this involves collection and transport back to the field.

Table 1

Phosphorus fertilizer demand in a meat-based and vegetarian diet. Magnitudes of phosphorus in kg per person and year (kg/(P year)) (Current data availability in the literature is minimal, hence this table is an indication of what can be done at the local level where the relevant data are available.) (SEPA, 1995).

Consumption type	P in human excreta (most in urine)	P in post-harvest food preparation	P in harvested crops	Total extracted[a]
Vegetable-based diet	0.3 kg/(P year)	0.45 kg/(P year) [if 2/3 eaten and 1/3 is organic waste]	1.8 kg/(P year) [if 1/4 becomes food and 3/4 organic waste]	0.6 kg/(P year), or 4.2 kg of phosphate rock [plant uptake of p comprise 1/3 from rock P and 2/3 from soil P]
Meat-based diet	0.6 kg/(P year)[b]	0.8 kg/(P year) [if 3/4 eaten and 1/4 is organic waste]	8.0 kg/(P year) [if 1/10 becomes food and 9/10 organic waste]	1.6 kg/(P year), or 11.8 kg of phosphate rock [plant uptake of P comprise 1/5 from rock P and 4/5 from soil P]

[a] 7 kg of phosphate rock contains approximately 1 kg of P.

[b] SEPA (1995).

Data from two recent material flow analyses (MFA) of phosphorus through urban centres in Sydney, Australia (Tangsubkul et al., 2005) and in Linköping, Sweden (Schmid-Neset et al., 2005) suggest that a change from the average western diet to a vegetarian diet could decrease phosphorus demand of fertilizers by at least 20–45%. Tangsubkul et al. (2005) further suggest a change in Sydney residents' current diet to one with no excess phosphorus consumption (i.e. recommended daily intake per person) could decrease the city's total phosphorus demand by 70%. On the other hand, a switch in the current Indian diet to meat would increase India's demand for phosphorus three-fold.

From the analysis in Fig. 3, we can infer that significant losses occur throughout the system—from mine to field to fork. Globally, we are mining five times the amount of phosphorus that humans are actually consuming in food. This analysis tells us that to simultaneously address phosphate scarcity and water pollution due to phosphorus leakage, an integrated approach must be taken that considers:

- minimizing phosphorus losses from the farm (estimated at around 8 MT P),
- minimizing losses in the food commodity chain (losses estimated at 2 MT P),
- alternative renewable phosphorus sources, like manure (around 15 MT P), human excreta (3 MT P) and food residues (1.2 MT P),
- other important mechanisms to reduce overall demand (such as optimizing soil carbon to improve phosphate availability and influencing diets).

These options are covered further in Section 5.

3.5. The environmental costs of the phosphate rock industry

As well as the problem of eutrophication due to the leakage of excess phosphorus into waterways, the production of fertilizers from rock phosphate involves significant carbon emissions, radioactive by-products and heavy metal pollutants.

Processing and transporting phosphate fertilizers from the mine to the farm gate, which up to now have relied on cheap fossil fuels, involve an ever-increasing energy cost. Phosphate rock is one of the most highly traded commodities on the international market. Each year around 30 million tonnes of phosphate rock and fertilizers are transported across the globe (IFA, 2006). With growing concern about oil scarcity and climate change, there is a need to reconsider the current production and use of phosphorus, particularly with respect to energy use and other environmental impacts.

Each tonne of phosphate processed from phosphate rock generates 5 tonnes of phosphogypsum, a toxic by-product of phosphate rock mining. Phosphogypsum cannot be used in most countries due to unacceptably high radiation levels (USGS, 1999). Global phosphogypsum stockpiles are growing by over 110 million tonnes each year and there is a risk of leakage to groundwater (Wissa, 2003). Phosphate rock naturally contains radionuclides of Uranium and Thorium, most of which end up in the phosphogypsum by-product and to a lesser extent in the processed phosphate fertilizers (Kratz and Schnug, 2006; Saueia et al., 2005). If crushed phosphate rock is applied directly to soils, radionuclides of the decay series are distributed to agricultural soils, risking overexposure to farmers and phosphate industry workers (Saueia et al., 2005). While radiation levels can vary above and below acceptable radiation limits, there are no standard procedures for measuring soil radioactivity due to applied phosphate rock (or phosphate fertilizers) (Saueia et al., 2005). Despite this, crushed rock phosphate is currently permitted as a fertilizer in organic agriculture in at least the European Union (EU, 2007), India (Department of Commerce, 2005) and Australia (Organic Federation of Australia, 2005). Similarly, associated heavy metals like cadmium can also be present in phosphate rock at levels which are either too toxic for soils or too costly and energy intensive to remove (Steen, 1998; Driver, 1998).

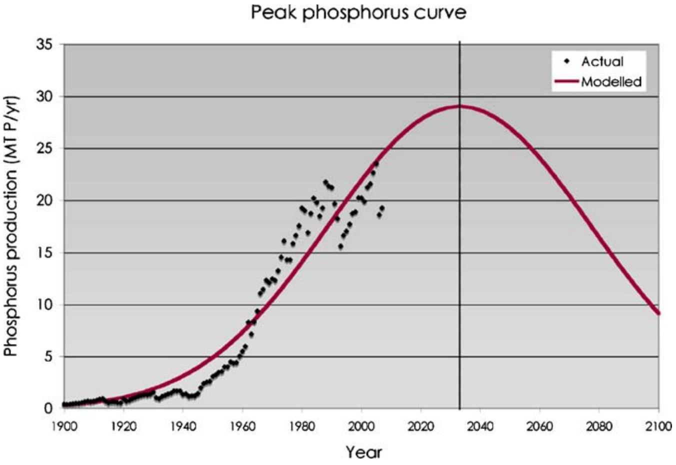


Fig. 4. Indicative peak phosphorus curve, illustrating that, in a similar way to oil, global phosphorus reserves are also likely to peak after which production will be significantly reduced (Jasinski, 2006; European Fertilizer Manufacturers Association, 2000).

4. Peak phosphorus—a sequel to peak oil?

As first highlighted by Hubbert in 1949 (Hubbert, 1949), production of oil reserves will at some time reach a maximum rate or 'peak' based on the finite nature of non-renewable resources, after which point production will decline. In a similar way, the rate of global production of high-grade phosphate rock will eventually reach a maximum or peak. Hubbert and later others argue that the important period is not when 100% of the reserve is depleted, but rather when the high quality, highly accessible reserves have been depleted. At this point, production reaches its maximum. After this point, the quality of remaining reserves is lower and they are harder to access, making them uneconomical to mine and process. Therefore while demand continues to increase, supply decreases year upon year. A conservative analysis using industry data suggests that the peak in global phosphorus production could occur by 2033 (Fig. 4). This analysis of peak phosphorus is based on estimated P[7] content in remaining world phosphate rock reserves (approximately 2358 MT P[8]) and cumulative production between 1900 and 2007 (totaling 882 MT P) based on US Geological Survey data (Buckingham and Jasinski, 2006; Jasinski, 2007, 2008), data from the European Fertilizer Manufacturers Association (2000) and the International Fertilizer Industry Association (2006). The area under the Hubbert curve is set equal to the depleted plus current reserves, totaling approximately 3240 MT P.

The data for annual production is fitted using a Gaussian distribution (Laherrere, 2000), based on the depleted plus current reserves estimate of 3240 MT P, and a least squares optimization which results in a production at peak of 29 MT P/a and a peak year of 2033. However the actual timing may vary due to changes in production costs (such as the price of raw materials like oil), data reliability and changes in demand and supply.

The concept of the 'peak' production of non-renewable resources such as oil or phosphorus is the subject of limited

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[7] Units of phosphorus are presented as elemental P, rather than P_2O_5 (containing 44% P) or phosphate rock (containing 29–34% P_2O_5) as commonly used by industry.

[8] Estimated from 18 000 MT phosphate rock (Jasinski, 2008).

Table 2

Supply and demand-side factors influencing uncertainty of lifetime of global phosphate reserves and hence the timeline of peak phosphorus.

	Supply-side	Demand-side
Factors indicating peak P production could occur sooner	Some scientists (e.g. Ward, 2008; Michael Lardelli pers comm 9 August 2008) suggest USGS phosphate rock reserve data (on which the peak P estimate in Fig. 4 is based) is likely to represent an over-estimate, as has been the case with reported oil reserves (Pazik, 1976), hence the real peak phosphorus is likely to occur much sooner than 2033.	Sustained demand for non-food crops like biofuel crops, and changing diets, could increase phosphate fertilizer demand at rates faster than previously projected, thus depleting reserves sooner.
	China's reported reserves doubled following joining WTO in 2003–2004, however there are no 3a party analyses that can confirm the size of these reserves (Rosmarin, 2004; Arno Rosmarin, pers. comm., 5th September 2007).	Increased demand for fertiliser in regions that have historically used limited amounts (e.g. Asia, Africa).
		Increased oil prices can reduce economic feasibility of phosphate reserves as mining and production rely on oil.
Factors indicating peak P production could occur later	USGS reserve estimates for China are based on official government data, which excludes production/reserve data from smaller mines (Jasinski, 2008). This means China could have more reserves than officially reported.	The collapse of the Soviet Union in 1991 resulted in dramatically lower fertilizer demand from this region, thus contributing to the decline following the mini-peak around this time (Prud'homme, 2006; Smil, 2000a,b),
	According to USGS staff, Moroccan and Western Saharan reserves, which account for a significant proportion of today's global production, are currently being mined at a relatively constant rate that is less than the maximum production capacity (USGS 2007, pers. comm., 5th September).	Demand for phosphate fertilizers decreased in the 1990's in North America and Western Europe following increased awareness of soil saturation (i.e. after decades of over-application, there was a sufficient soil P stock so that applications rates could be reduced) (EFMA, 2000).
	Smil (2000a,b) and Steen (1998) note that while annual production averaged 140 MT of phosphate rock in the late 1990's (following the mini-peak production year of 1989), the capacity at this time was over 190 MT phosphate rock.	Awareness of eutrophication problems has also reduced phosphate demand in the developed world to reduce leakage to waterways (EFMA, 2000; FAO, 2008a,b). The increasing number of dead zones globally is likely to further drive the efficient use of P fertilizers, thus reducing future demand (World Resources Institute, 2008).

dispute today, but the exact timeline for the peak in production is debated. According to Déry and Anderson (Déry and Anderson, 2007), global phosphorus reserves peaked around 1989.[9] However it is likely that this observed peak was not a true maximum production peak, and was instead a consequence of political factors such as the collapse of the Soviet Union (formerly a significant phosphate rock consumer) and decreased fertilizer demand from Western Europe and North America. Indeed, data from the International Fertilizer Association indicates that the 2004–2005 production exceeded the 1989–1990 production (IFA, 2006). Table 2 outlines both supply- and demand-side factors leading to potential over- or under-estimates of phosphate rock reserves and the timeline of peak phosphorus.

While the timing of the production peak may be uncertain, the fertilizer industry recognises that the quality of existing phosphate rock is declining, and cheap fertilizers will soon become a thing of the past. The average grade of phosphate rock has declined from 15% P in 1970s to less than 13% P in 1996 (Stewart et al., 2005; IFA, 2006; Smil, 2002).

While some scientists (such as Stewart et al., 2005) suggest market forces will stimulate new technologies to improve the efficiency of phosphate rock extraction and beneficiation in the future, there are no known alternatives to phosphate rock on the market today that could replace it on any significant scale. While small-scale trials of phosphorus recovery from excreta and other waste streams exist (CEEP, 2008), commercialisation and implementation on a global scale could take decades to develop. Significant adjustments in institutional arrangements will also be required to support these infrastructure changes.

While it is understood that phosphate rock, like oil and other key non-renewable resources, will follow a peak production curve, peak oil and peak phosphorus differ in at least two key ways. Firstly, while oil can be replaced with other forms of energy once it becomes too scarce, there is no substitute for phosphorus in food production. Phosphorus is an element and cannot be produced or synthesized in a laboratory. Secondly, oil is unavailable once it is used, while phosphorus can be recovered from the food production and consumption chain and reused within economic and technical limits. Shifting from importing phosphate rock to domestic production of renewable phosphorus fertilizers (such as human excreta and biomass) can increase countries' phosphorus security and reduce the reliance on increasingly inaccessible phosphate fertilizer markets.

5. Options for sustainable phosphorus use and management

There is no single 'quick fix' solution to current dependence on phosphate rock for phosphorus fertilizers. However there are a number of technologies and policy options that exist today at various stages of development – from research to demonstration and implementation – that together could meet future phosphate fertilizer needs for global food production. Implementing these measures will inevitably require an integrated approach that looks beyond the current focus on reducing agricultural phosphorus leakage into waterways. Such an approach, incorporating a combination of supply- and demand-side measures, is described below.

Conventional supply-side approaches look for solutions similar to those of the past 150 years, such as further exploration and more intensive exploitation of existing phosphate rock resources, including off-shore and/or lower grade deposits. Some advocates of conventional processed fertilizer production argue these potential reserves will become economically viable once all high-grade reserves have been depleted and prices have increased

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[9] If production is assumed to have been at maximum capacity in the period to about 1990, this would suggest that peak production would have occurred at about that time (Déry and Anderson, 2007), but that reserves are approximately half of the amount estimated by the USGS.

(FAO, 2004b; Stewart et al., 2005). However this approach fails to address several key issues, including the finiteness of phosphate rock reserves in the long term; poor farmers' limited access to globalised fertilizer markets, the energy intensity of the current production and use system, and the accumulation of phosphorus and associated toxic wastes in soils and waterways.

As discussed in Section 3, phosphorus can be recovered from the food production and consumption system and reused as a fertilizer either directly or after intermediate processing. These recovery measures include: ploughing crop residues back into the soil; composting food waste from households, food processing plants and food retailers; and using human and animal excreta. Such sources are renewable and are typically available locally. However, due to their lower phosphorus concentrations, they are also bulkier than fertilizers processed from phosphate rock. Leading-edge research and development on phosphorus recovery is increasingly focusing on recovery of struvite (ammonium magnesium phosphate crystals high in phosphorus) from both urban and livestock wastewater (Reindl, 2007; SCOPE, 2004). Struvite crystalisation and recovery is a promising technological process that has the potential to both remove phosphorus from wastewater by-products more efficiently, and, provide an alternative source of phosphate fertilizer (Jaffer et al., 2002).

The International Fertilizer Industry Association (IFA) indicates it is committed to a sustainable fertilizer industry and while the industry does not explicitly advocate the reuse of human excreta as a potential alternative to mined phosphate rock, the European Fertilizer Manufacturers Association does state:

> Two major opportunities for increasing the life expectancy of the world's phosphorus resources lie in recycling by recovery from municipal and other waste products and in the efficient use in agriculture of both phosphatic mineral fertilizer and animal manure (European Fertilizer Manufacturers Association, 2000, p.9).

Already in some urban areas in Pakistan and elsewhere in Asia, more than 25% of urban vegetables are being fertilized with wastewater from cities (Ensink et al., 2004). The International Water Management Institute estimates that 200 million farmers worldwide use treated or untreated wastewater to irrigate crops (Raschid-Sally and Jayakody, 2008). Currently 67% of global yields of farmed fish are fertilized by wastewater (World Bank, 2005) because wastewater is a cheap and reliable source of water and nutrients for poor farmers. However it is essential that farmers and those working with wastewater take precautionary measures to avert associated health risks. The World Health Organization has recently developed comprehensive guidelines on the safe reuse of wastewater in agriculture (WHO, 2006). Another drawback is that wastewater-fed agriculture and aquaculture rely on water-borne sanitation systems, rather than on systems such as dry or ultra-low flow toilets.

Reuse is safer if sanitation service providers and urban planners avoid infrastructure that mixes human excreta with other wastewater streams, such as industrial wastewater. Industrial and non-residential wastewater may contain heavy metals and other toxic wastes. Moreover, if urine is not mixed with faecal matter in the toilet, the urine can be used safely through simple storage (WHO, 2006). Urine is essentially sterile and could provide more than half the phosphorus required to fertilize cereal crops (Drangert, 1998; WHO, 2006; Esrey et al., 2001). In Sweden for example, two municipalities have mandated that all new toilets must be urine-diverting (Kvarnström et al., 2006; Tanums Kommun, 2002). While there are numerous practical ways urine can be collected, stored, transported and reused, the typical arrangement in these Swedish cases involves either a dry or flush urine-diverting toilet to collect the urine (see Fig. 5). The urine is then piped and stored in a simple 1–3 kl storage tank under the house or piped to a communal urine storage tank. Local farmers then collect the urine approximately once a year for use as liquid fertilizer (see Kvarnström et al., 2006 for further details). Sanitized faecal matter can also be used as a soil conditioner (WHO, 2006).

There are numerous documented practical examples of ecological sanitation around the world in places such as Southern Africa, India, China, Vietnam, Mexico (Gumbo and Savenije, 2001; Drangert, 1998; Stockholm Environment Institute, 2004). According to the Stockholm Environment Institute (2005), the cost of such ecological sanitation systems globally

Fig. 5. (a) A urine-diverting dry squat toilet from India (photo: S.Vishwanath www.rainwaterclub.org); (b) a urine-diverting dry toilet from Sweden (photo: Dana Cordell).

could be offset by the commercial value of the phosphorus (and nitrogen) they yield.

Most of the projected 2 billion new mouths to feed in the coming decades are expected to reside in peri-urban areas of mega-cities in developing countries (FAO, 1999). Urban and peri-urban agriculture involves growing crops and raising livestock within urban areas and bordering urban settlements (FAO, 2007b). Fertilizing urban agriculture with phosphorus recovered from organic urban waste could be a significant step towards reaching the Millennium Development Goals on eradicating hunger and poverty, and providing access to safe sanitation. While this opportunity has been largely neglected at the global level to date (Cordell, 2007), a preliminary examination of the relationship between the land area required for food intake, the quantities of nutrients in human excreta, the capacity of the soil to absorb urine, crops' requirements for nutrients and population densities in peri-urban areas is outlined in Drangert (1998). Gumbo (2005) further studied the potential of reusing human excreta in urban Zimbabwe to 'short-cut' the urban phosphorus cycle. Gumbo found that the fertilizer value of the urine produced by urban dwellers in the case study catchment could sustain the agricultural activities in the surrounding area.

There is still significant scope to further explore the individual and combined potential for recovering organic urban waste products such as human excreta, food waste, garden waste, and manure. Bone meal, ash, and aquatic vegetation such as algae and seaweed are also potential sources of phosphorus.

Options aimed at reducing the demand for phosphorus in food production vary widely and can include: increasing agricultural efficiency to increase phosphorus uptake from the soil, reducing organic losses throughout the food chain and encouraging diets which contain fewer phosphorus-intensive foods.

Approaches to fertilizer efficiency range from high-tech solutions such as precision agriculture (FAO, 2000, 2008a; Johnston, 2000) through to organic farming techniques that seek to optimize soil conditions to increase soil phosphorus availability for plants (FAO, 2006, 2007c). Other approaches focus on the addition of microbial inoculants to increase soil phosphorus availability. The fertilizer industry, governmental institutes and research organizations have been actively supporting more efficient fertilizer application practices for over a decade (International Fertilizer Industry Association, 2006; European Fertilizer Manufacturers Association, 2000; Food21, 2005; FAO, 2006). Such initiatives have mainly been triggered by concerns about nutrient leakage to waterways causing eutrophication. However, much agricultural land is still subject to an over-application of phosphorus, resulting in unnecessary accumulation in soils in addition to runoff to water bodies (Steen, 1998; Gunther, 1997). Indeed, only 15–30% of applied phosphorus fertilizer is actually taken up by harvested crops[10] (FAO, 2006). At the same time, agricultural land in other regions are phosphorus-deficient due to naturally low soil phosphorus levels and fertilizer applications at rates which are far lower than would be required to replace the phosphorus lost through agriculture (Smaling et al., 2006).

Smil (2007) suggests that shifting to a 'smart vegetarian' diet, combined with reducing over-consumption, would be one of the most cost-effective measures to reduce agricultural resource inputs (including water, energy, land and fertilizers) and would also minimize greenhouse gas emissions and other forms of pollution. Food preferences are generally more strongly correlated with taste, advertisements and price than they are with nutritional value (SIWI-IWMI, 2004). Therefore, potential strategies to reduce the demand for phosphorus include encouraging the move to foods which require the input of less phosphorus, water and energy. This could be done through appropriate communication strategies or economic incentives in both the developed and developing worlds. In areas where there is a move away from vegetarian diets, communication strategies to combat this trend could be employed.

No analyses have yet been done that integrate such supply- and demand-side options in the same framework and assess the implications for global phosphate security. There is also a need to systematically assess potential options according to criteria[11] such as: economic cost; life cycle energy consumption; other environmental impacts; synergies between phosphorus and other resources (such as water, energy); logistics and technical feasibility, and cultural values and preferences.

6. Institutional and attitudinal barriers and opportunities

Since a global phosphorus scarcity crisis is imminent, as we have demonstrated in the sections above, why is it not being discussed in relation to global food security or global environmental change? What are the current barriers to addressing a phosphorus 'crisis' and what are the underlying reasons for the lack of attention to nutrient recirculation options such as urine reuse?[12]

Despite increasing global demand for non-renewable phosphate rock, and phosphate rock's 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 any explicit mention within official reports of the UN's Food and Agricultural Organization (FAO, 2005a, 2006, 2007a), the International Food Policy Research Institute (IFPRI, 2002b, 2005), the Millennium Ecosystem Assessment (Millennium Ecosystem Assessment, 2005), the Global Environmental Change and Food Systems programme (GECAFS, 2006), the International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD, 2008) or the recent High-level Conference on World Food Security hosted by the FAO (FAO, 2008b). The implications of declining global phosphate availability and accessibility have been mentioned in a limited number of discussions by a few concerned scientists.[13]

We are entering a new and unprecedented era of global environmental change. As we are learning from climate change and global water scarcity, a long-term time frame is required to address phosphate scarcity. Decision-makers need to consider the next 50–100 years, rather than just the next 5–10 years. Young et al. (IDGEC, 2006) suggest that some global environmental problems occur due to the 'lack of fit between ecosystems and institutions' (IHDP, 2002). In the case of phosphorus, existing international institutional arrangements are inconsistent with the natural phosphorus cycle. This is most evident in the divide between the agricultural sector, where phosphorus is perceived as a fertilizer commodity, and the water and sanitation sector, where phosphorus is perceived as a pollutant in wastewater. This may hinder opportunities to find integrated solutions to the scarcity problem, since it is necessary for several sectors to be involved. In the case of

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[10] Because phosphorus is one of the most chemically reactive nutrients, it readily transforms to forms of phosphorus unavailable to plants.

[11] Such an analysis is addressed further in Cordell et al. (in press).

[12] A noteworthy exception to this lack of attention is the World Health Organisation issuing recommendations on safe use of excreta and greywater in agriculture (WHO, 2006).

[13] However the situation is in a state of change and as recent as 2008 a published paper on "Long-term global availability of food: continued abundance or new scarcity?" (Koning et al., 2008) identifies phosphorus scarcity as a likely key factor limiting future food availability. Similarly, the closing ceremony of the 2008 World Water Week for the first time highlighted mineral phosphate scarcity, noting "in a time of rising peak oil, of rising costs of fertilisers, and of dwindling phosphorus-mineral sources" Falkenmark (2008).

phosphorus scarcity, part of the alternative resources and strategies are located in the sanitation sector (e.g. reuse of nutrients), whilst others are located in the household sector (e.g. the reduction of food waste, the reduction of meat and dairy consumption, etc.).

The recycling of urine is a socio-technical process that has no institutional or organizational home (Cordell, 2006; Livingston et al., 2005). Rather, a lack of institutional fit means it is seen as peripheral by all stakeholders and sectors (such as water service providers, town planners and farmers) and is not currently perceived as important enough for any single stakeholder group to make it a priority. Drangert suggests a 'urine-blindness' has prevented modern societies from tapping into this abundant source of plant nutrients in urine (Drangert, 1998). Both the professionals managing urban water and sanitation systems and residents using these systems avoid thinking about the character of individual fractions within wastewater and instead adhere to the routine of 'flush and discharge' (p157).

There are some significant similarities in the way in which the contemporaneous issues of climate change, water scarcity and phosphorus scarcity manifest themselves and can be addressed as potential solutions emerge. Climate change mitigation comprises a wide range of measures, and the same goes for water scarcity. World leaders have embraced the concept that limited water availability and accessibility is threatening food security, and discussions on solutions have followed. For example, it has been argued that reducing wastage in the entire food production and consumption chain will also reduce significantly the amount of water used to produce food (Lundqvist et al., 2008). The good news is that climate change, water and phosphorus scarcity can all be ameliorated with a concerted effort by the global community. In the extreme scenario where all wasted phosphorus would be recovered and recirculated back to agriculture, no additional phosphate rock inputs would be required. Scarcity of phosphate rock would then be of little concern. The crucial task however is to reduce the demand for phosphorus in addition to harnessing the measures needed to recirculate wasted phosphorus back to food production before it is dispersed into water bodies and non-agriculture soils. At present, there is a scarcity of management of phosphorus resources, rather than simply a physical scarcity of phosphate rock. With this in mind, institutional and other constraints can be better addressed.

The recent price spike in phosphate rock is likely to trigger further innovations in and adoption of phosphorus recovery and efficiency measures. However, the current market system alone is not adequate to manage phosphorus in a sustainable, equitable and timely manner in the longer term.

Opportunities also exist for integrating phosphorus management into existing discussions. For example, the issue of phosphorus scarcity could be given a higher profile in leading interdisciplinary international networks such as the Earth System Science Partnership (ESSP) which is addressing other important global biogeochemical cycles (GCP, 2008). The ESSP Global Environmental Change and Food Systems (GECAFS) program is an obvious place where this could occur.

The emergence of peak oil, the likelihood of a global emissions trading scheme for carbon, and the associated increases in energy costs will increase the cost of phosphate rock mining. This will provide an incentive for recirculating phosphorus found in organic sources, which will become more cost-effective relative to mining, processing and shipping rock phosphate. The energy required to produce mineral phosphate fertilizers is greater than that of organic phosphate fertilizers. The Earth Policy Institute reports that fertilizer production (including phosphorus) accounts for 29% of farm energy use in the US, excluding transporting chemicals to the field (Earth Policy Institute, 2005). A British study (Shepherd, 2003) indicated that organic agriculture uses less energy per crop output than industrial agriculture, mainly due to the significant amounts of energy required to produce mineral fertilizers. Johansson (2001) note that urine can be transported up to 100 km by truck and remain more energy-efficient than conventional systems of mineral fertilizer production, transportation and application.

Another incentive for increasing the reuse of phosphorus in this way is the avoidance of the environmental and financial costs associated with the discharge of phosphorus to waterways. The environmental cost of phosphate pollution of waterways is deemed unacceptable in many parts of the world and thus high levels of phosphorus must be removed from wastewater. Collecting urine, excreta and manure at the source will reduce phosphorus entering the wastewater treatment plant and thereby can achieve removal targets using less energy and at lower costs (Huang et al., 2007).

Sustainability initiatives in other sectors, such as materials manufacturing, can also be applied to the use of phosphorus. For example, concepts of 'design for the environment' and 'extended producer responsibility' involve capturing and reprocessing valuable substances directly after use, for reuse in production and manufacturing processes (OECD, 2001). Examples range from recovery and reuse of copper piping (Giurco and Petrie, 2007), to reusing vehicle parts under the European Union Directive for End-of-Life Vehicles (European Commission, 2000). In the case of nutrients, residents, local councils or entrepreneurs could be involved in recovering phosphorus from urban waste streams. Small and medium-scale examples already exist in sites around the world, including West Africa (Kvarnström et al., 2006), Inner Mongolia (EcoSanRes, 2008), and Stockholm (Kvarnström et al., 2006). There are clear synergies with sustainable sanitation strategies, which aim to decrease the mixing of water, faeces and urine in order to better contain, sanitise and reuse the water and nutrients. The World Health Organization is active in rethinking approaches to sanitation and has recently issued guidelines for the use of grey water, urine and faecal matter in agriculture (WHO, 2006). These guidelines map out ways that nutrients and water can be recovered, treated and reused. This is likely to play an important role in 'legitimizing' the use of human excreta among authorities and contribute to our understanding of the role of urban sanitation in the global nutrient and water cycles. For example, Sweden has recently proposed that 60% of phosphorus in sewage should be returned to land by 2015 (Swedish Environmental Objectives Council, 2007).[14]

7. Conclusions

This paper outlines how humanity became addicted to phosphate rock, and examines the current and future implications of this dependence on a non-renewable resource. Global demand for crops will continue to rise over the next half century, increasing the demand for phosphate fertilizers. However, modern agriculture is currently relying on a non-renewable resource and future phosphate rock is likely to yield lower quality phosphorus at a higher price. If significant physical and institutional changes are not made to the way we currently use and source phosphorus, agricultural yields will be severely compromised in the future. This will impact poor farmers and poor households first. However, there are opportunities to recover used phosphorus throughout the food production and consumption chain. Reducing losses in the food

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[14] This target was recommended to the Swedish government by a Swedish EPA Action Plan. See Sweden's National Environmental Objectives at http://www.miljomal.nu/englizh/englizh.php.

chain and increasing agricultural efficiency are also likely to contribute significantly to averting a future phosphate crisis.

Despite the depletion of global reserves and potential geopolitical tensions, future phosphate scarcity and reduced accessibility to farmers is not yet considered a significant problem by those who decide national or international policy. There are currently no international organizations or intentional governance structures to ensure the long-term, equitable use and management of phosphorus resources in the global food system. In order to avoid a future food-related crisis, phosphorus scarcity needs to be recognized and addressed in contemporary discussions on global environmental change and food security, alongside water, energy and nitrogen.

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