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International Fertiliser Society

FUTURE SUPPLY OF PHOSPHORUS IN AGRICULTURE AND THE NEED TO MAXIMISE EFFICIENCY OF USE AND REUSE

by

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ABSTRACT.

Commercially viable reserves of rock phosphate are limited and only a few countries are significant producers. China and the US will play a much smaller role within 50 years time and the bulk of the world's mined phosphorus will come from Morocco. A conservative estimate of longevity of the resource shows that at a 1% exponential increase for the next 50 years followed by zero increase, the global reserves would last 235 years. If one uses the UN global population growth rate to determine future demand, with a stabilisation by 2100, the current global reserves would last 172 years. This estimate can be further reduced to 126 years if Africa develops its agriculture and to just 48 years if in addition bio-energy crops are given higher priority.

The phosphorus losses are significant in the mining/beneficiation/ /fertiliser production steps (35% of what is mined is not converted into usable product) and in agriculture (30% of what is added as fertiliser is not contained in agricultural output, with most being retained in the soil) but they are even higher within the areas of food processing, distribution and consumption (60% of the P in food is lost).

To reduce phosphorus losses the questions of erosion from farm fields and more effective handling of manure from high density livestock feedlots need to be addressed. When it comes to food processing, improvements in crop storage, processing facilities and trade methods are needed. At present most of the excreted phosphorus from humans ends up lost in the environment. Phosphorus extraction from wastewater, sludge, manures and other organic sources is only starting and needs worldwide promotion.

About one billion people are under-nourished and many are smallholder farmers that cannot afford chemical fertilisers. Food production in developing countries will probably have to double by 2050. More conservative policies and measures are required in the management of fertilisers to feed a world with 9 billion people. Countries need to further develop productive sanitation systems in order to safely reuse human and animal excreta. Guidelines now exist for the use of human urine as a substitute for chemical fertiliser in agriculture. There is a higher chance that food security can be achieved by maintaining soil fertility if all available sources of fertiliser resources are better managed – animal manure, crop and food residues, chemical fertilisers and human excreta.

For these reasons a much more conservative approach is needed in the exploitation of fossil phosphate-rock and that reuse and more efficient systems should be promoted and developed.

CONTENTS

Keywords: Phosphorus, recycling, sanitation, solid waste, agriculture, fertiliser.

1. LIMITED COMMERCIAL SOURCES OF MINERAL PHOSPHATE.

Phosphorus (P) used in chemical fertiliser is derived mainly from geological sources which in practice are finite and there are limits to what sources are commercially viable. The exact definition of commercial viability varies but the following points provided by Campbell (2008) provide some clarity. Commercial viability of minerals for the mining industry usually includes the following aspects:

- the existing resource and reserve base at any given time in the contexts of geographic location, average grade, existing proven and probable resources and reserves, and the perceived potential to expand the mineable deposit and timing of such expansion;
- the project's physical location and comparative geopolitical risk;
- the geology of the deposit in the contexts of extraction method (open pit versus underground), quantity, grade and metallurgy;
- what infrastructure (roads, rail lines, water access, utilities access, ore processing facilities), trained labour, weather conditions (enabling year-round exploration and drilling), and access to assaying laboratories is available to the property;
- the economics of the project in the context of forecast metal prices, mining, milling and processing costs, recovery of secondary metals, and project financing.

Indeed the terms reserve and resource are well defined by the USGS (2010). A mineral resource is:

> *"A concentration of naturally occurring solid, liquid, or gaseous material in or on the Earth's crust in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible."*
>
> "Identified resources can be subdivided into three categories: ***measured, indicated and inferred***, depending on degree of geological certainty. The reserve base is that part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices, including those for grade, quality, thickness, and depth. The reserve base is the in place demonstrated (measured plus indicated) resource from which reserves are estimated. The reserve base includes those resources that are currently economic (reserves), marginally economic (marginal reserves), and some of those that are currently sub-economic (sub-economic resources)."

Since the 1950s, phosphorus extraction from mainly sedimentary rock has increased and is now annually about 175 million tonnes (Mt) in terms of beneficiated phosphate rock material, with an annual increase of about 2-3%. Although there are some 1,600 mines in the world, the relative volume is dominated by only a few countries (Figure 1), with Morocco/Western Sahara, China and the USA containing about 85% of the global reserves according to the USGS, (2011). Whether phosphorus production will peak followed by a period where demand is higher than supply has been debated (Rosemarin, *et al.* 2009; UNEP, 2010). According to the IFDC (Van Kauwenbergh, 2010), Morocco alone controls 85% of the possibly commercially viable global reserves.

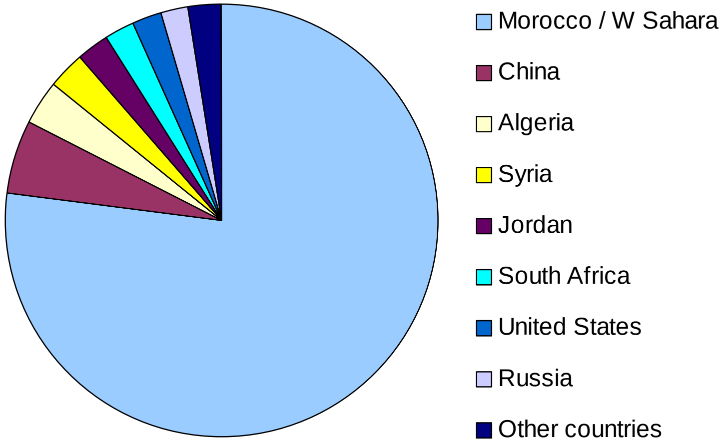

Figure 1. *Relative global distribution of phosphate rock (USGS, 2011).*

The IFDC report suggested that the global proven reserves of rock published by the USGS up to August 2010, should be increased by 4-fold to 65 Gt and that the main source of this increase was a recalculation of the reserves for Morocco, increasing these by 9-fold to 50 Gt. What was done was simply to turn the reserve base estimated some 23 years ago into the resource base. Even though the report states that the commercial viability of these additional hypothetical reserves is not known, the USGS has adopted these estimates and now publishes them as commercially viable reserves. Still there is no UN agency that has been tasked to monitor the world's phosphorus geological resources. So there is no authoritative 'second opinion' yet generated from outside the US.

1.1. Predicting depletion.

At present rates of exploitation of P-rock (26 Mt per year for each of the US and Morocco and 65 Mt for China) (Table 1, overleaf), the commercially viable reserves in the US are deemed to be depleted within 50 years and a similar trend is occurring for China. To prevent this from occurring, increased trade primarily with Morocco will be necessary. Morocco in turn will need to increase its production capacity several-fold to meet the increasing demand. Current annual increases in exploitation are globally higher than 6%, skewed mainly by China's 13% increase.

Table 1. *Phosphorus depletion prognosis (based on USGS, 2011).*

	P-rock		Years to depletion			Latest annual increase
	Extraction 2010	Commercial reserves	Zero annual increase - same rate as 2010	1% annual increase for 50 yrs and zero thereafter	2.5% annual increase for 50 years and zero thereafter	2009-2010
	Mt	Gt				%
World total	176	65	369	235	128	6.02
Morocco / W Sahara	26	50	1,923	1,180	580	13.04
Morocco expanded mining (2-fold)	50	50	1,000	618	312	
China	65	3.7	57	48	45	7.97
United States	26	1.4	54	49	48	-1.14

During the next 50 years, assuming a 1% exponential increase, 11.5 Gt of rock would be extracted globally while at 2.5% it would be 17.6 Gt. At zero increase and at current extraction rates it would be 8.8 Gt. The respective annual extraction rate in 50 years time would have reached 289 Mt at the 1% growth rate and 605 Mt at 2.5%. If growth stopped at these rates in 50 years time, then depletion of the 65 Gt would occur in 235 and 128 years respectively, counting from 2011. This sort of calculation is somewhat simplistic but does provide a rough picture regarding potential depletion. For the main producers, China, Morocco and the US, the data using a similar calculation are given in Table 1. China and the US have about 50 years of reserves left. Morocco has announced in 2010 that it is presently vastly expanding its capacity to the order of 2-fold to 50 Mt per year by 2015 (IB Times, 2010). If Morocco's base extraction rate is increased to this level the years required to deplete its 50 Gt of rock would be 1,000 yrs at zero annual increase and 618 years at 1% annual increase for 50 years followed by zero increase. At an annual increase of 2.5% for 50 years followed by zero increase the depletion would occur in 312 years. The conclusion from this is that Morocco will within a few decades become the largest producer of phosphorus rock, essentially as a monopoly. The commercial viability of this reserve should be further solidified on an urgent basis in order to help stabilise the fertiliser market. But the geopolitical responsibility that Morocco is quickly adopting needs to be better defined and implemented through trade agreements and broad governance agreements on sustainable development of the resource otherwise there may be negative impacts on commercial viability.

1.2. Predicting extraction rates using predicted global population growth.

An alternative approach to calculating the longevity of the world's commercially available phosphate rock is to project extraction rates according to predicted global population growth. The current annual world population growth is *ca.*1.2% (UN-DESA, 2011) but this is forecast to decrease to 0.36% by 2050 and to 0.06% by 2100. By extrapolating the amount of rock extracted per year based on the UN prognosis of world population growth (medium-variant), it can be estimated that P-extraction will reach a near asymptote by about 2100 at about 255 Mt of annual rock extraction (lower line in Figure 2). Assuming that global population growth is near zero from 2100 onwards, and the annual extraction rate stabilises then at about 260 Mt per year, the current reserve estimate of 65 Gt would last 172 years. As estimated by Cordell *et al.* (2011a) a peak in phosphorus production could occur between 2052 and 2092 with a mean of 2070. However, Vaccari and Strigul (2011) have recently pointed out that it is extremely difficult to estimate whether and when peak phosphorus will exactly occur.

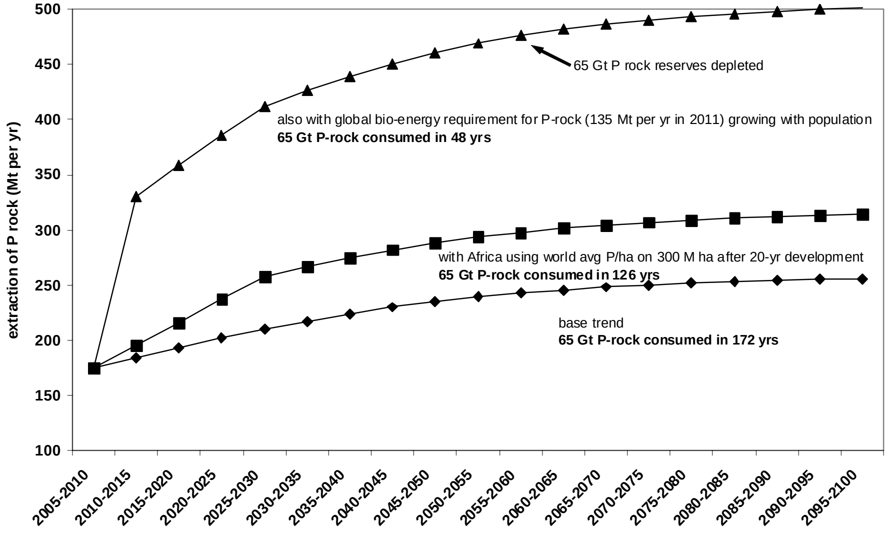

Figure 2. *Future annual extraction of phosphate rock with an extrapolation based on UN world population estimates (medium-variant prognosis) from 2010 to 2100 (lower line). This would consume a total of 21 Gt of rock during this 90-year period. Assuming no further increases beyond 2100, the 65 Gt P-rock reserves would be consumed within 172 years from now. The middle line includes increased consumption by Africa after a 20-year development period reaching in 2030 the same rate of use of P-fertiliser as the present global average, and on an expanded arable area of 300 M ha. The middle line will consume 25.4 Gt of P-rock by 2100 and assuming no further increases beyond 2100, the 65 Gt would be consumed within 126 years from now. The upper line includes in addition the demand from bio-energy crops replacing 10% of the world's energy requirement. The base year in 2011 consumes 135 Mt P-rock per year and then increases with population. The 65 Gt P-rock reserve is consumed within 48 years from now. (Data from UN-DESA, 2011; USGS, 2011; FAOSTAT, 2011; Schröder and Bos, 2008).*

Additional variables exist that could hasten depletion. One is the development of agriculture in Africa. At present the continent of Africa consumes about 415 kt of P fertiliser (FAOSTAT, 2011) on 222.8 Mha which is equivalent to about 3 Mt of P-rock (assuming a P content of *ca.*14%) and averages 1.9 kg P/ha. Mid and west Africa have the lowest application rates: 0.2 and 0.5 kg P/ha, respectively. East Africa runs at 1.9 kg P/ha while the north and south use about 4-5 kg P/ha. The world average annual application is about 13 kg P/ha of arable land (Schröder *et al.*, 2010). For Africa to come up to the world average would require almost an 8-fold increase or a consumption of about 33 Mt of P-rock per year. In addition Africa has a potential arable area of 300 Mha, which if also developed over the next 20 years would contribute to a global annual P-rock extraction rate of 314 Mt by 2100 (middle line in Figure 2). Depletion of the current 65 Gt estimated reserve of P-rock would occur within 126 years if Africa can accomplish such a green revolution.

Additional factors that could increase demand of P fertiliser are expanded agriculture in Latin America, Eastern Europe and various parts of Asia but also a change in diet towards increased meat consumption in developing countries which would increase demand for cereals and fertiliser. Promotion of bio-energy crops may further contribute to an increased demand for P fertiliser. Assuming that one hectare of bio-energy crop produces 90 GJ of net-energy and contains 30 kg P, around 135 Mt additional rock would have to be extracted each year if 10% of the global energy demand were to be covered through these crops, unless the P in the resulting ashes and press-cakes were to be fully recycled (Schröder and Bos, 2008). If the bio-energy P-demand is added to the one created by a green revolution in Africa, and increases according to population growth, the rate of exploitation would reach 475 Mt per year by 2060 and depletion of the 65 Gt would occur within 48 years from now (Figure 2, upper line). This is why it is so imperative now to develop aggressive policies and measures to ensure proper reuse of P in order to minimise exploitation of the commercially viable reserves.

1.3. Price of phosphorus is a key determinant.

Of course a major concern will be the price of P-fertiliser and which countries will be able to afford chemical fertiliser, considering the fact that fossil fuels will continue to increase in price. The threat of global depletion of commercially viable geological sources of phosphorus will come into focus as the high grade and easily accessible deposits decrease in size and number. The price hike experienced in 2008 shows how plastic the market can become and recent data show the intimate connection to food prices (Figure 3). The spike experienced in 2008 was dampened considerably by the global financial crisis but the price of food is already back at the 2008 level and that for phosphorus is steadily increasing now 3-4 times the pre-2008 level.

That large investments are currently being made to extract relatively low concentrate P-rock containing about 9-10% P_2O_5, for example the Mantaro Project in Peru (Stonegate, 2011) is an indication of the present situation. The significant amount of beneficiation required to provide a raw product which the fertiliser industry can use will add to the cost of production. Already over 1 billion people in the world are undernourished – many of whom are small-scale farmers (FAO, 2010) and these cannot afford chemical fertiliser. So a business-as-usual approach using fertiliser is no longer solvent with the goal of feeding all of humanity, expected to increase by a further 2 billion people within 40 years. As phosphate rock becomes more expensive to extract, fertiliser and food prices will increase. Clearly for the world to shift towards more sustainable practices in the use of phosphorus, major changes are necessary over the entire chain from production to consumption and reuse.

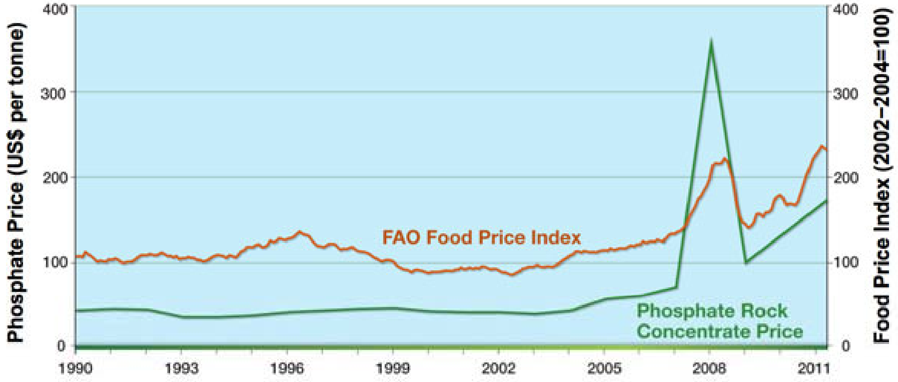

Figure 3. *Trend in phosphate rock price and the FAO food price index. Price of phosphate rock concentrate 32-33% P_2O_5 FOB Morocco and FAO Food Price Index (2002-2004 = 100) (Stonegate, 2011).*

2. EXTENSIVE LOSSES OF PHOSPHORUS ALONG THE DELIVERY CHAIN.

MacDonald *et al.* (2011) calculated that globally *ca.*14 Mt of P fertiliser was applied to arable land (per year) in 2000 plus an additional *ca.*10 Mt of P was added from manure. Removal through harvested crops amounted to about 12 Mt of P. The balance of 12 Mt is what is left in the ground or lost to erosion. Indeed there is great regional variation in the size of the deficit or surplus (Figure 4, overleaf).

Carpenter and Bennett (2011) also computed P discharge to freshwater to complement the earlier estimates for planetary boundaries relating to ocean discharge of P (Rockström *et al.*, 2009). They found that the discharge levels of P already exceed the boundary guideline of 10-times the pre-industrial level.

IFA (Prud'Homme, 2010) reported that *ca.*17-18 Mt of P are mined for fertiliser production each year and about 15 Mt end up in fertiliser products. Earlier work by Cordell *et al.* (2009) estimated that 7 Mt ends up in harvested crops and of that, 3 Mt ends up being consumed in food by humans. That meant that 20% of the phosphorus used in fertilisers ended up in the food humans consume. The conversion efficiencies from mining, to rock processing, to fertiliser production, to agricultural production and finally food processing and consumption are identified in Table 2. The conversion efficiencies for mining/beneficiation/fertiliser production (65%) and agriculture (70%) are higher than that for food processing and consumption which is 40%.

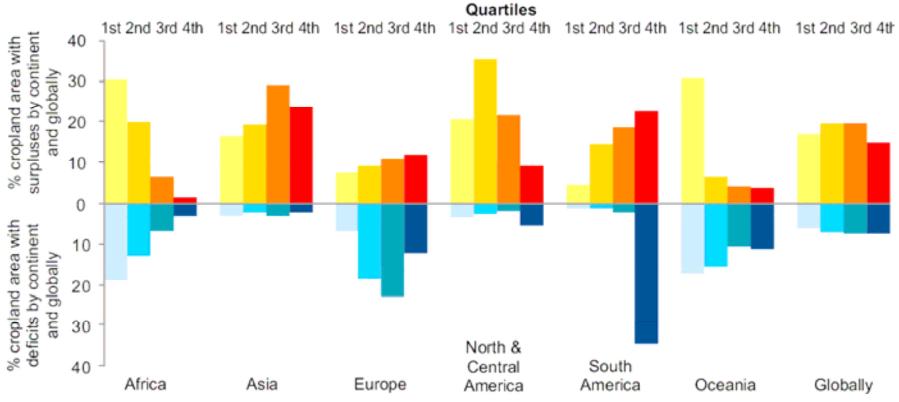

Figure 4. *Distributions of P surpluses and deficits by quartiles shown as percent of total cropland area in each continent and of global cropland area. The P surplus ranges in kg P/ha for the 4 quartiles are 0 to 2.5, 2.5 to 6.2, 6.2 to 13 and 13 to 840. The P deficit ranges in kg P/ha for the quartiles are 0 to -0.8, -0.8 to -1.9, -1.9 to -3.2 and -3.2 to-39. (MacDonald et al., 2011).*

Beneficiation losses can also vary depending on location, running at between 20 to 60% with an average of 35% (Van Kauwenbergh, 2010). As reported by Cordell *et al.* (2009) and reiterated by Rittmann *et al.* (2011) the two largest flows of lost P are in agricultural run-off and erosion and animal wastes. .So there is much that can be done in order to reduce all the losses and to introduce reuse practices.

Regional and national P-budgets will be required so that each government can identify where improvements can be carried out in efficiency of use and also where reuse is possible. As observed by Schröder *et al.* (2010) including the work of Richards and Dawson (2008), 70% of the arable land within the EU is used to grow animal feed so that much more phosphorus flows through the livestock sector than through the arable sector. Of the nearly 2 Mt P in crops in the EU, only 0.5 Mt is transferred to human food production while the rest is fed to animals. The bulk of the P in manure is reapplied to soil but the system is far from a closed loop since there are large losses through erosion and leaching. Moreover, there is an ongoing accumulation of P in soils wherever there are regional concentrations of livestock, as manure P is dumped rather than returned to the stockless regions that have produced the feed for that livestock. The losses of P and the disrupted return flows of manure-P need to be compensated by large inputs of mineral fertiliser (1.5 Mt P).

Table 2. *Conversion efficiencies (%) 'from mine to fork' per separate step and integrated over the entire trajectory (Schröder et al., 2010).*

	Deposits	Mined rock	Beneficiated rock	Finished fertiliser	Food from farm	Ingested by humans
Mining	100	82				
Rock processing		100	84			
Fertiliser production			100	95		
Agricultural production				100	70	
Food processing, distribution, consumption					100	40
From mining to consumption	100	82	69	65	46	19

For the US, a recent study by Suh and Yee (2011) shows that only 15% of the total P extracted from nature to grow food is ingested by humans and the rest ends up in soil and waste flows (Figure 5, overleaf). Major losses (66%) occur in the production of meat and dairy products and crops. The other losses (19%) are from household food waste, mining waste and fertiliser production waste.

3. INCREASING EFFICIENCY OF USE, REUSE AND RECYCLING.

Taking into account the above and that there are significant losses in the agriculture and food production/consumption chains, there is a need to optimise user practices, reuse and recycling. There are inherent advantages in designing user practices in order to optimise possibilities of recycling systems for fertilisers. These need to be spear-headed by policies strengthening fertiliser and food security for domestic markets, environmental protection against diffuse sources of phosphorus (and nitrogen) and reduced use of fossil fuels and greenhouse gas emissions. Of particular concern is that a growing segment of the world's population cannot compensate for these losses by using increasingly expensive chemical fertilisers. As the global population increases to an estimated 9 billion by 2050, that segment, which is already over one billion, will be increasing. Food and political security will go hand in hand with more efficient use and reuse of recyclable fertiliser components including phosphorus.

Several opportunities exist to improve the efficiency of extraction and use of phosphorus including mining and processing improvements, changed diets and food-chains, changes in agricultural practices, including improved erosion management and the recovery from manure, crop residues, waste and sanitation systems (Schröder *et al.*, 2010; Cordell *et al.*, 2011b). The latter reference provides a framework for phosphorus recovery and reuse options.

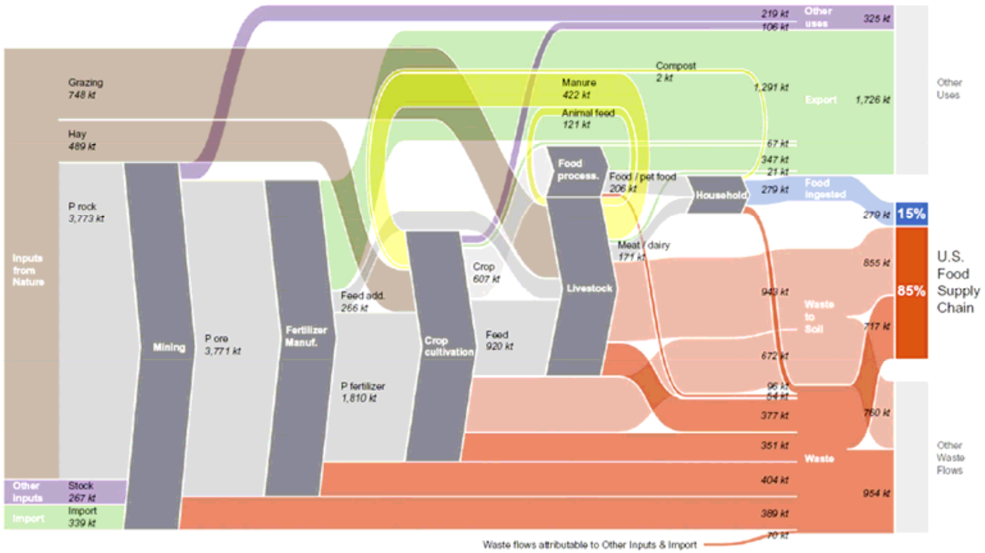

Figure 5. *Phosphorus flows in the United States (Suh and Yee, 2011).*

3.1. Agriculture.

As the population of the world increases with an increasing consumption of meat, more food and feed will need to be produced. Indeed a doubling of the present production in developing countries will be required by 2050 (FAO, 2009). This will inevitably lead to increased use of phosphorus and concomitant losses but at the same time increased opportunities to close the loop in order to decrease these losses. As reported by Schröder *et al.* (2010) globally speaking, erosion is probably contributing most to the worldwide loss of phosphorus and subsequent soil degradation. Also soils can accumulate phosphorus, often rendering it unavailable to growing plants. High concentrations of soil phosphorus are associated with high livestock densities and use of phosphorus-rich feed in intensive livestock farming. This leads to phosphorus surpluses and to excessive phosphorus inputs from manure. Farmers are often encouraged to use large amounts of P to increase the fertility status of the soil. For annual crops with short growing periods, relatively high amounts of phosphorus are advised in order to achieve ideal harvests.

Efficiency of P use within agriculture can be increased through several areas of improvement such as:

- optimising land use by removing yield-reducing and yield-limiting factors other than P (e.g. irrigation and drainage, cover-cropping, pest control);
- erosion control measures;
- soil quality improvement;
- differentiated fertiliser recommendations based on regular soil sampling;
- fertiliser placement techniques;
- selecting cultivars with high yields per unit P applied;
- adjusting livestock densities to local feed production potential;
- optimising manure handling and treatment;
- adjusting livestock diets.

The above measures are treated in detail in Schröder *et al.* (2011).

3.2. Food processing.

There are also several areas where improvements are possible within the food commodity chain such as crop storage, bulk food processing/storage/trade, food retailing, food preparation and consumption. As reported by Schröder *et al.* (2010), up to 50% of the 7 Mt P per year in harvests is estimated to be lost in these steps as follows:

- **Crop storage, processing and trade** - harvested crop losses can potentially occur during storage (such as spoilage due to pests and disease and spillage), processing (such as by-product crop residues not required for primary processing) and trade (e.g. spillages or losses).
- **Bulk food processing, storage, trade** - losses that occur when converting processed agricultural commodities into food commodities, ranging from

removal of husks of grains (for processed white rice, bread for example), to losses due to damage, spoilage or below-standard products during trade. Many products today have extensive associated food miles due to the longer distances and more processing steps involved in the global food commodity chain, leading to increased wastage (Ericksen, 2008; Lundqvist *et al.*, 2008).

- **Food retailing** - losses that occur during retailing of food items, including spoilt or unspoilt food discarded at supermarkets, markets, other food outlets. Food safety is important in food retailing, however many supermarkets are under consumer pressure or even legal obligation to discard (not sell) food past the stated expiry date, even if the food is perfectly edible (Lundqvist *et al.*, 2008).
- **Food storage, preparation and consumption** - losses that occur typically at the final destination prior to or during consumption (such as spoilage in household fridges or pantries, potato peelings during preparation to edible or inedible dinner plate scraps). In some parts of the developed world (such as the UK), 60% of food waste is estimated to be edible and hence avoidable by improved food and meal planning (WRAP, 2008).

3.3. Waste streams.

Phosphorus can be recovered from mixed wastewater streams, or from separate organic waste fractions, including urine, faeces, grey water, animal manure excreted ex-farm, animal carcasses and slaughterhouse waste (bones, blood, hooves etc), food waste, detergents (laundry, dishwashing), other industrial wastes, crop residues generated ex-farm (e.g. by the food processing industries).

As reported by Schröder *et al.* (2010) almost 100% of the phosphorus consumed in food by humans is excreted in urine and faeces. This means the 3 Mt P per year in food (Cordell *et al.*, 2009) actually eaten is excreted. This estimate is corroborated by that made by Mihelcic *et al.*, (2011) at 3.4 Mt which represents about 22% of the total global phosphorus demand. Globally, only a small fraction of human excreta is actually treated before disposal or reuse. It is estimated that approximately 10% is currently reused either as untreated or treated wastewater, sludge, ash from incinerated sludge or use directly via composting toilets or direct defecation. The remaining 2.7 Mt P per year either ends up discharged to water or non-agricultural land as effluent or landfill (Cordell *et al.*, 2009). The 1.2 Mt P per year in food waste is either informally dumped, centrally disposed of, incinerated (containing around 1 Mt P per year) or processed and reused (around 0.2 Mt P per year).

Over the last hundred years major shifts in the developed countries have occurred in diet, food supply and sanitation practices. Food is traded globally now and most of the nutrients in sanitation systems are no longer reused. This means that the developed countries are very much handicapped if they decide to close the loop on critical nutrients like phosphorus using current day systems. A review of the situation for the Swedish city of Linköping between 1870 and 2000 was carried out by Schmid Neset *et al.* (2008) showing that in 1870, nearly all phosphorus contained in the human diet came from local agriculture and was recycled back to local agriculture, with a per capita dietary intake of 1.2 g P/person/day. Centralised sewers were installed in the 1950s and almost the entire phosphorus excreted was emitted to the nearby surface waters. In 2000 after phosphorus removal was installed, only around 20% of human dietary phosphorus was returned to agriculture (nearly 80% goes to landfill as sewage sludge). Dietary phosphorus intake increased over the 130 years by >25% to 1.6 g P/person/day. But 40% of food consumed in Sweden today is imported.

As the price of fertiliser remains high and unaffordable for large parts of the developing world, alternative sources such as reuse from sanitation and solid waste systems will become more and more economic. The economic value of urine and composted organic wastes and faeces from both livestock and humans will make these products more and more attractive alternatives. There will be pressure to develop these options. It is thus highly relevant to examine the potential for replacement of chemical fertilisers and to also reduce present nutrient losses by using conservation agricultural methods and so-called productive sanitation that allows for reuse of excreta in agriculture – this is of particular importance for the world's *ca.* 2 billion smallholder farmers (Onumah *et al.*, 2007) that cultivate limited areas and that at present cannot afford chemical fertilisers. That sub-Saharan Africa uses such low levels of chemical fertiliser (less than 10 kg of NPK/ha/yr) provides an immediate opportunity for the use of sanitation-based reuse systems. It was calculated that nutrients available in human excreta correspond to the amount of nutrients applied today as chemical fertilisers (Figure 6).

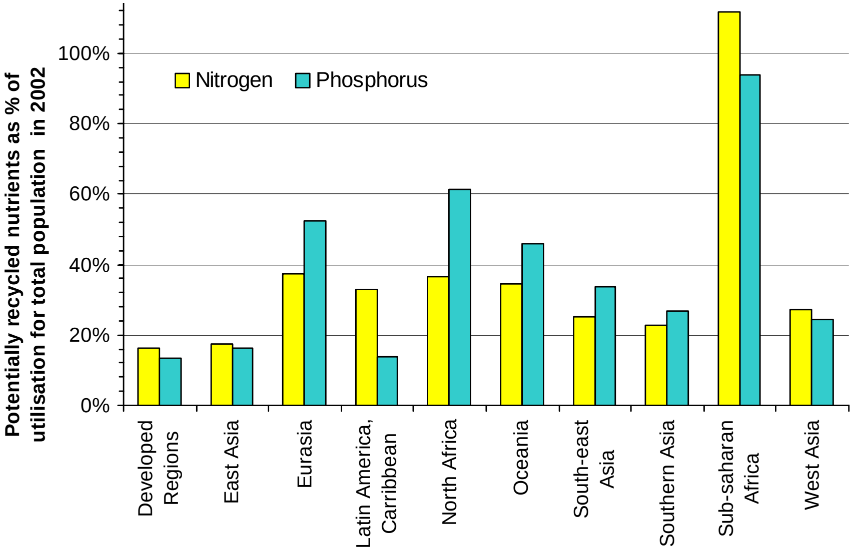

Figure 6. *Potential capacity of ecological sanitation systems to replace chemical fertiliser in different parts of the world. (Rosemarin et al., 2008).*

This is not the case for the most developed countries since so large a proportion of the fertiliser is associated with animal manure. So these countries will need to emphasise reuse from both human and animal excreta sources. Losses due to imperfect recycling due to the spatial disruption of feed production and livestock production undermine P-use efficiency (e.g. around the North American Great Lakes and in Denmark, Netherlands, Po Valley (Italy), Flanders (Belgium), Brittany (France), southern Sweden, etc.). So improvements will be necessary as phosphorus increases in economic value.

There is a need to promote the use of industrial and urban 'wastes', either directly as fertiliser by farmers or as feedstock for fertiliser industry. In order to make this happen the following measures can be considered:

- the right balance needs to be found between transport distances and the scale of waste treatment plants in order to save on energy expenditure;
- reductions need to be made in the dilution of wastewater with flush water, grey water and storm water in order to optimise recovery and again to save on energy;
- reductions are necessary in the contamination of wastes with pathogens, heavy metals, hormones and medicine residues;
- use of magnesium to produce struvite could be encouraged instead of the standard practice of using iron or aluminium flocculants in sewage treatment plants when precipitating phosphate;
- septic tank and uncontaminated sewage sludge can be incinerated and the ash used as a feedstock in fertiliser production;
- improvements are necessary in the quality of sludge from sewage treatment plants by reducing inputs of metals so that the material can be used on arable soils.

3.3.1. Struvite.

Significant efforts are now being made to develop methods of producing struvite (ammonium magnesium phosphate, $NH_4MgPO_4{\cdot}6H_2O$) as a means of recovering phosphorus from wastewater effluents in, for example, agriculture, food production and sewage treatment plants (Mavinic *et al.*, 2009). The resulting crystalline product is a slow-acting fertiliser containing a ratio of 5-28-0 ($N\text{-}P_2O_5\text{-}K_2O$) plus 10% Mg. Several full-scale operations have been installed in North America, Europe and Asia. Struvite is also being produced from urine in Nepal (Gantenbein and Khadka, 2009) and soon in South Africa.

3.3.2. Use of sludge from sewage treatment plants in the EU.

The largest single source of phosphorus in the sanitation systems of urban areas in the EU-15 is in the sludge accumulated in sewage treatment plants. The amount of sewage sludge available is directly related to population size and the degree that sewage treatment is installed. Germany therefore produces the most sludge (2 Mt dry substance per year), followed by the UK, France, Italy, Spain, etc. This totals 9 Mt dry sludge produced per year in EU-15 (Figure 7). About 1 Mt is produced in the expansion EU-12 countries and this should increase as treatment capacity is built.

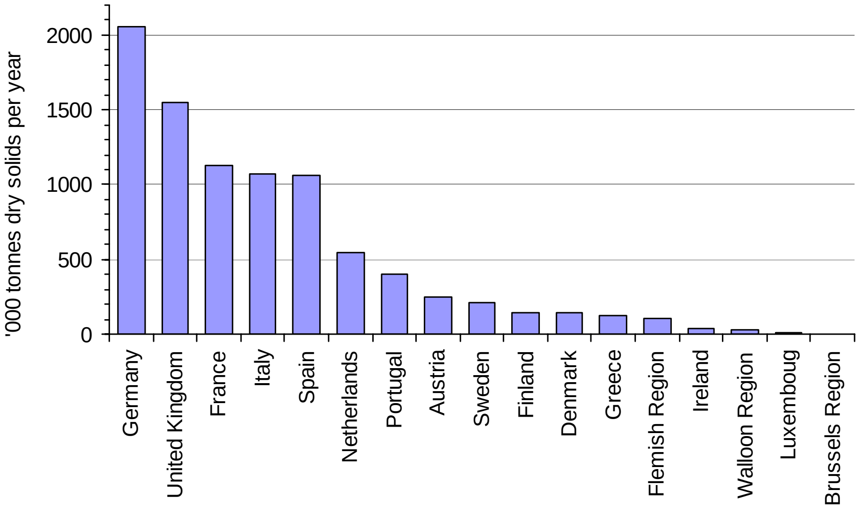

Figure 7. *Sludge produced by municipal sewage treatment plants within the EU-15 countries in 2005-2007 as tonnes of dry substance per year. Data from Milieu Ltd et al. (2009).*

Relatively high amounts of this sludge are reused in agriculture, with France, the UK, Spain and Ireland applying between 60 and 70% and Denmark and Portugal 50-60% (Figure 8). On the average more than 40% of the sewage sludge within EU-15 is being reused in agriculture.

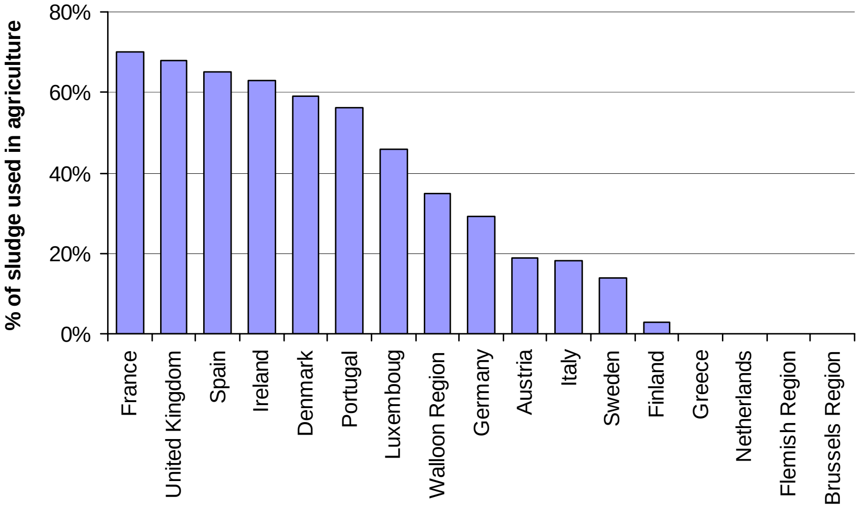

Figure 8. *Proportion of sludge reused in agriculture in 2005-2007. Data from Milieu Ltd et al. (2009).*

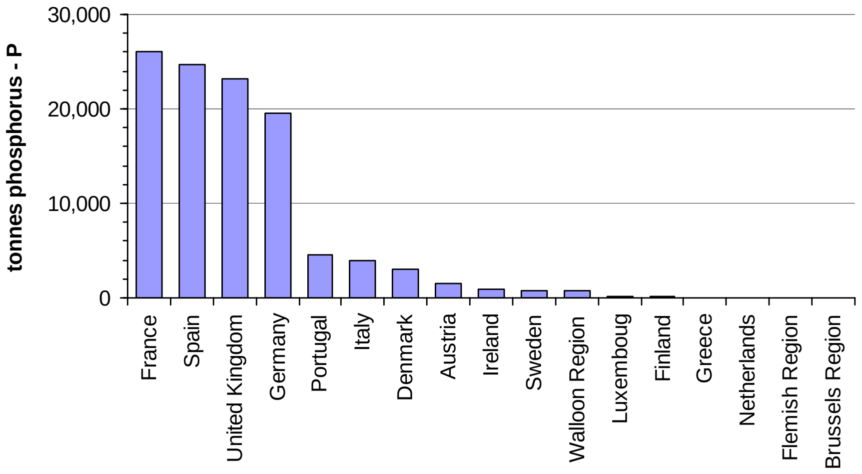

Figure 9. *Amounts of phosphorus in sludge used each year in agriculture within the EU-15 countries in 2005-2007. Data from Milieu Ltd et al. (2009).*

This translates into about 120 kt of P (Figure 9). If all 9 Mt of dry sludge were to be reused this would supply about 300 kt of P or about 23% of the amount added as chemical fertiliser in this region. With optimised use of animal manure and reuse of organic solid waste, the EU would be on the road towards significantly reducing the dependency of its agriculture on imported mineral P fertiliser.

4. NEW BREAKTHROUGHS IN PRODUCTIVE OR ECOLOGICAL SANITATION.

Ecological or productive sanitation systems safely recycle plant nutrients in excreta to crop production (Rosemarin *et al.*, 2008). The approach is based on three principles: containment preventing pollution rather than attempting to control it after the fact; sanitising the source-separated urine and the faeces; and using the safe products for agricultural purposes (Winblad *et al.*, 2004).

Essentially the same quantity of plant nutrients present in the consumed food will be excreted via urine and faeces. A growing human body will incorporate and accumulate a minor part of the nutrients (<5%), but in general there is equilibrium between consumption and excretion (Jönsson *et al.* 2004). The diet determines the amount of nutrients excreted and Jönsson *et al.* (2004) show that the quantity of nitrogen (N) and P in human excreta can be estimated based on protein intake. Strauss (2000) reports that each day, humans excrete in the order of 30g of carbon (90g of organic matter), 10-12g of nitrogen, 2g of phosphorus and 3g of potassium. Most of the organic matter is contained in the faeces, while most of the N (70-80%) and potassium are contained in urine. Phosphorus is equally distributed between urine and faeces (Jönsson *et al.*, 2004).

Recycling human excreta without proper treatment is a major health threat. Nutrients from sanitation systems are being used in a clandestine and high risk fashion. It is known that approximately 700 million people in 50 countries eat food from crops irrigated with untreated or inadequately treated wastewater from sewage systems on a total surface area of at least 20 Mha (Scott *et al.*, 2004).

Extensive use of wastewater also exists in the production of fish, for example in the Calcutta wetlands, and in the production of duckweed as fish and duck feed in Taiwan, Thailand and Bangladesh, as reviewed by Strauss (2000). If sanitation systems were designed from the start with reuse of water and nutrients as a prime objective, the risk of infection by pathogens could be greatly reduced and valuable water and nutrients could be exploited with lower risk to human health (WHO, 2006). The guidelines published by WHO (2006) emphasise a multi-barrier approach to minimise risks when using human excreta in agricultural production.

The global phosphorous flow analysis by Cordell *et al.* (2009) estimates that presently only 10% of phosphorous in human excreta is recycled to arable soil, while 50% ends up in water and 40% underground or on non-arable soil. These losses are equivalent to around 20% of the annual phosphorous mined (Cordell *et al.,* 2009).

In developing countries where mineral fertilisers are often not affordable by smallholder farmers, improved management of locally available nutrients is crucial to reduce the decline in soil fertility. This is especially true for Africa where Henao and Baanante (2006) estimated that 85% of African farmland had net nutrient losses of more than 30 kilograms[1] of nutrients per hectare per year during the period 2002–04. Major losses due to erosion and leaching are being addressed by the agriculture sector by various integrated land use approaches. However, the fate of nutrients present in the harvested crops destined for human consumption is often neglected, falling into the void between the agriculture and sanitation sector. Setting the quantity of nutrients in human excreta into perspective Rosemarin *et al.* (2008) report that N and P available in human excreta in Sub-Saharan Africa is roughly the same as the total amount applied as chemical fertiliser in these countries, while Drangert *et al.* (2010) estimate the total nitrogen flow via human excreta in Africa is comparable to the that of animal manure.

A paradigm shift is needed to see human excreta as a potential resource rather than a waste, and the agriculture sector will need to be engaged in the process. Extensive experience is now being accumulated in the area of reuse of human urine and composted faeces, especially in subsistence smallholder farming in developing countries. Local excreta recycling onsite in rural areas has several advantages over urban areas, as the transport distances are shorter, there is no lack of land and the households have a strong incentive to recycle in order to

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[1] In terms of $N+P_2O_5+K_2O$

grow more food. In Sub-Saharan Africa 500 million people (64% of total population) live in rural areas (IFAD, 2010).

Recently several productive sanitation projects with strong reuse focus have been implemented with EU and IFAD food security funds both in Niger and Burkina Faso. Treated urine and faeces have been introduced as 'liquid and solid fertiliser' and toilets and urinals are the 'fertiliser factories' that allow for the production of the new fertilisers (Dagerskog and Bonzi, 2010). The good and frequent use of these facilities maximises the production of safe fertiliser, which in turn contributes to sustained behaviour change. Dagerskog and Bonzi (2010) found that a typical family of ten persons excretes annually the equivalent in purchased chemical fertiliser of about 50 kg of 14-23-14 (N P_2O_5 K_2O) and 50 kg of urea. Agriculture extension officers have been in the forefront of these projects, using the farmer field school approach to show the effect of treated urine and faeces as fertilisers. As a replacement for urea it was found that urine produced equivalent or higher (by 10-20%) yields of sorghum and millet (Table 3). All test plots (T0-T3) of 200 m^2 had organic matter (OM) as base fertiliser at a dose of 20 t/ha. T1 and T2 also had 50 kg/ha of single super-phosphate (SSP, ~19% P_2O_5) as extra base fertiliser. The N-application was either through 5 grams of urea (T1) or 0.5 litres of urine (T2 and T3) per plant, which with 10,000 millet plants/ha gives around 25 kg N/ha.

Table 3. *Millet harvests (kg/ha) at four farmer field schools in Aguié, Niger (Dagerskog and Bonzi, 2010).*

Village	Dan Bidé	Tsamiya Bakoye	Malloumey Saboua	Zabon Moussou
T0 (OM)	781	660	1244	1209
T1 (OM+SSP+Urea)	1160	893	1318	1000
T2 (OM+SSP+Urine)	1257	1072	1637	1111
T3 (OM + Urine)	1161	948	1773	1399
Surplus yield T2 compared to T1 (%)	8	20	24	11
Surplus yield T3 compared to T0 (%)	49	44	42	16

Urine as a liquid fertiliser has been promoted in many projects, and recently several practical guidelines have been published on the use of urine in agriculture both on global level (Richert *et al.*, 2010) and at country levels such as Niger (Baragé, 2010) and Philippines (Gensch *et al.*, 2011). The Philippine publication is a field guide and specifies in detail various crops, planting densities, urine quantities to be applied at planting and the first and second dressings and methods of collection and application.

Depending on the local context various technologies can be used to achieve the goal of sanitising and recycling human excreta. Separate collection of urine and faeces using urinals or urine diverting toilets, can facilitate the treatment of both fractions and reduce odours. It is important to keep in mind that reuse of human excreta complements rather than replaces other fertilisers. Conscious reuse of human excreta contributes to reduce losses from the farming system, but to increase the fertility of degraded soils, all available resources are needed: animal manure, crop and food residues, chemical fertilisers as well as human excreta. External inputs and nutrient recycling need to be accompanied by soil conservation measures to combat erosion and leaching, to increase the agricultural production to feed a growing world population while minimising environmental impacts.

5. CONCLUSIONS.

Commercially viable reserves of rock phosphate are limited and only a few countries (China, Morocco/Western Sahara and United States) are significant producers. Extraction trends indicate that that China and the US will play a much smaller role within 50 years time and the bulk of the world's mined phosphorus will come from Morocco. Exactly how large these reserves are and how commercially viable they are is not clear. There is no UN body that monitors rock phosphorus and the only data that are collected and published openly come from the US Geological Survey. A conservative estimate of longevity of the resource shows that at a 1% exponential increase for the next 50 years followed by zero increase, the global reserves would last 235 years. However, if one uses the UN global population growth rate to determine the growth rate of phosphorus demand, which assumes a gradual decrease in growth to 2100 and no growth beyond then, the current global reserves of 65 Gt P-rock would last 172 years. If one assumes that Africa undergoes a green revolution over the next 20 years, acquiring more arable land and increasing its use of phosphorus fertiliser to the current world average, the current global reserves would last 126 years. If one were to combine in addition the demand from bio-energy crops at a level of 10% of global energy requirements, to the base and green Africa scenarios, the global P-rock reserves will only last about 48 years. It is for these reasons that a much more conservative approach be taken to the exploitation of fossil P-rock and that reuse and more efficient systems be promoted and developed.

There are major losses of phosphorus along the chain of production and use from mining and fertiliser production, to agriculture and food production and to waste systems. The conversion efficiency in the mining/beneficiation/ /fertiliser production steps is 65% and in agriculture it is 70% but the conversion efficiency in the areas of food processing, distribution and consumption is only 40%. The largest single flows of lost P are in agricultural runoff and erosion and animal wastes. Taking the broader picture it is estimated that about 20% of the mined phosphorus fertiliser ends up in the food consumed by humans. For the US it is estimated that 15% of the total P extracted from nature to grow food is ingested by humans and the rest ends up in soil and waste flows. Major losses (66%) occur in the production of meat and dairy products and crops.

To reduce phosphorus losses the question of erosion from farm fields needs to be dealt with as a top priority. Also, more efficient handling of manure is needed in order to optimise reuse. A major problem is the high density livestock feedlots that are not designed around reuse. Several other aspects of agriculture can be improved in order to save on P use and losses. When it comes to food processing, large gains can be made by improving crop storage and processing facilities and by reducing losses in trade. Further gains can be made in improving bulk food processing, food retailing, and food storage, preparation and consumption. Then come the losses in the waste streams from both humans and animals that can be reduced. At present most of the excreted phosphorus from humans ends up lost in the environment. Phosphorus extraction from wastewater, sludge, manures and other organic sources is only starting and needs worldwide promotion. Reuse of sewage sludge is practised in many countries and needs to be further promoted. Concerns surrounding trace contaminants in wastewater and sludge will eventually have a positive effect on management of toxic compounds at source in order to ensure that waste systems are safe for reuse.

Already there are about one billion people who are under-nourished and many of these are smallholder farmers that cannot afford chemical fertilisers. As the world population further increases to about 9 billion by 2050 that segment of the population may also grow. While food production in developing countries will probably have to double by 2050, much more conservative policies and measures will be required in the management of fertilisers if we are to feed a world at that level. The poorest countries that cannot afford chemical fertiliser need to further develop productive sanitation systems in order to safely reuse human excreta. Guidelines now exist for the use of urine as a substitute for chemical fertiliser in agriculture. There is a higher chance that food security can be achieved by maintaining soil fertility if all available sources of fertiliser resources are better managed – animal manure, crop and food residues, chemical fertilisers and human excreta.

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