Dr. Arno Rosemarin
Senior Research Fellow
Research and Communications Manager
EcoSanRes Programme
Stockholm Environment Institute.
arno.rosemarin@sei.se

PEAK PHOSPHORUS AND THE EUTROPHICATION OF SURFACE WATERS: A SYMPTOM OF DISCONNECTED AGRICULTURAL AND SANITATION POLICIES

That phosphorus rock is being depleted from commercial fossil deposits and ends up in lakes and oceans remains of little interest to most governments. Concerns about eutrophication are centered around overzealous use of fertiliser, erosion losses from farms and non-existent or poorly functioning sewage treatment. Waste and sanitation systems have solutions to prevent eutrophication, but not linked to reuse in agriculture, nor to management of limited phosphorus mineral supplies. Most phosphorus in the world is produced by China, US and Morocco/Western Sahara, which may contain about 75 per cent of global reserves. No UN agency monitors phosphorus rock mining and no independent source of data exists. Countries need to optimise phosphorus use in agriculture and its reuse from manure, sludge, sanitation and solid waste. This paper calls for a global governance system ensuring sustainable management of phosphorus from both fossil and recycled sources providing long-term food and political security to the world.

Key words: peak phosphorus, agriculture, eutrophication, sanitation, policies.

Introduction

Shifting the focus away from just eutrophication

Phosphorus is a limited, non-renewable, but recyclable resource fundamental to all forms of life and to our food systems (Tiessen, 1995). The fact that commercially viable phosphorus rock is being depleted from available fossil deposits and is ending up at the bottom of lakes and oceans, unavailable for reuse, continues to be of little or no concern to most governments around the world. The concerns centred around water quality and eutrophication are not connected to finite resource depletion, but only to the overzealous use of fertiliser, subsequent erosion losses from arable land and non-existent or poorly functioning sewage treatment in cities. Sophisticated scientific efforts around the world led, for example, by the institutions for limnology and oceanography that assess lake, river and coastal eutrophication, remain fixed on monitoring and ecosystem changes. They are, apparently, less concerned by the call for integrated water resources management (IWRM), land-based preventive approaches including the need for radical changes in agricultural practices, sanitation and solid waste systems and a wiser use of dwindling fossil fertiliser resources.

Eutrophication of surface waters continues to be one of the most common water quality problems around the world (World Water Assessment Programme, 2009). There is extensive literature describing the eutrophication of freshwater and coastal marine zones spanning, for example, Vollenweider (1968), Schindler (1977) and Carpenter et al. (1998). Knowledge of the role played by phosphorus as a limiting factor for growth in aquatic systems led to legislation in many parts of the world to control the use of phosphate in detergents and to reduce the discharge of phosphorus from effluents, mainly municipal sewage (Dolan, 1993). To some extent, this has also had an impact on reducing fertiliser use and has changed agricultural practices along certain sensitive shorelines or coastal zones, but runoff remains a major source of phosphorus in, for example, the Baltic Sea drainage area (HELCOM, 2008).

But the driver behind all this interest for the past 40 years has been water pollution and the risk of algal growth, fish kills and anoxic lake bottoms. Much of the response, therefore, has been at the 'end of the pipeline', to remove phosphorus, and not the sustainable use of a limited natural resource. The challenges have been immense, especially when the ecosystem has not been properly the focus of clean-up strategies. Most marine systems are considered to be nitrogen limited, but when it comes to the Baltic Sea, this brackish water system can support the growth of toxic blue-green algae (Cyanobacteria) that can fix atmospheric nitrogen, thus rendering them phosphate limited (HELCOM, 2009). So to control eutrophication in the Baltic, it is necessary to manage nitrogen and phosphate from both the atmosphere and from land sources (Conley et al., 2009).

The case of the North Sea also illustrates the dangers of policy disconnections. The eutrophic and polluted rivers of northern Europe were cleaned up mainly by removing phosphorus in sewage treatment plants during the 1970s and 1980s. But even though phosphate levels decreased, eutrophication in the coastal area increased (Cadée and Hegeman, 1993). The water quality of the rivers improved with increased oxygen levels and the recovery of fish populations, but the previously polluted rivers with anaerobic zones were carrying out significant denitrification – removing nitrogen from the water phase and releasing it to the atmosphere. With improved oxygen conditions following phosphorus removal, the rivers were no longer reducing the nitrogen, but became efficient nitrate pumps from the agricultural lands to the North Sea, thus causing eutrophication of the North Sea instead. The disconnection between sanitation engineering pushing for only phosphorus removal, agricultural practices creating excess nitrate runoff and the lack of integrated management approaches illustrates why IWRM is needed.

The removal of phosphate from municipal sewage effluent, most often through flocculation of phosphate with iron chloride or aluminium sulphate, has been the priority in developed countries. Re-use and recycling have not been a central part of the pollution abatement strategy, as witnessed by the fact that the standard practice renders the phosphorus in the sludge less available for plants (Kyle and McClintock, 1995). Only recently has this been the focus of new developments to produce more plant-available products, like struvite, by using magnesium (Ashley et al., 2011).

The objective of this paper is to create interest and generate discussion about the limited mineral sources of phosphorus, their management in human systems, the respective flows and net losses and the need for increased efficiency and recycling. The paper explores the policy and technology disconnections between the practices in using phosphorus fertiliser in agriculture, the control of phosphorus in effluents, the management of the mineral reserves and products therein and the need for environment-friendly recycling systems.

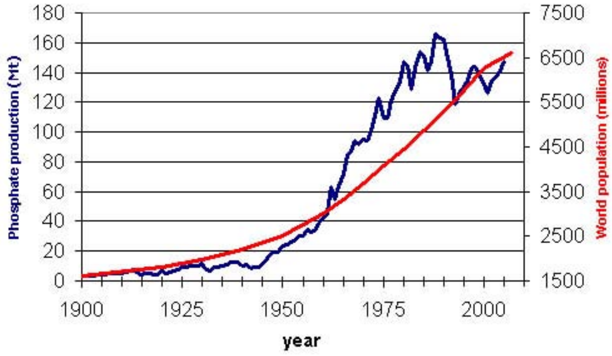

Figure 1. Trends in global extraction of phosphate rock from 1900 in relation to population growth. In 2010 almost 180 Mt of rock was extracted and the world population neared 7 billion. Source: Déry and Andersson, 2007..

Problem analysis

Phosphorus: a limited resource

Historically the main source of phosphorus in agrarian communities was manure. Eventually when agriculture became more intensive, bone-meal and guano were used as rich sources of phosphorus. But it was not until the 1900s that significant amounts of phosphorus were mined for fertiliser production. Once the Haber-Bosch technique became streamlined and produced essentially unlimited amounts of ammonia for fertiliser production, phosphorus mining became much more intensive in order to match the growth in nitrogen fertiliser products. Indeed the population explosion since then has been fuelled by abundant and relatively inexpensive fertiliser and food (Fig. 1).

The 'Green Revolution' created a mindset that there was apparently no practical limit to the availability of fertiliser and, if a country was undernourished, that food could be shipped there from the bread baskets of the world. But the number of undernourished in the world is still increasing and is now greater than one billion. We also know that the world will have to double the amount of food it currently produces if we are to support 9 billion people by 2050 (WFP, 2009). One might ask: what are the planetary limits for the production of fertiliser, knowing that we have already exceeded the safe operating space for nitrogen through the production of ammonia (Rockström et al., 2009)?

More than 80 per cent of the phosphorus mined is used in fertiliser, but there are many other important functions served by phosphorus including detergent, fire retardants, pesticides, food additives, explosives, etc. But there are signals now that commercially viable mined phosphorus sources are dwindling and these call for a more sustainable approach to exploiting this precious resource (Schröder et al., 2010). Peak phosphorus has been suggested as a possible threat to food security and human development by several authors (Cordell et al., 2009; Rosemarin et al., 2009; Déry and Andersson, 2007). There is some controversy about exactly when such a peak could occur (Van

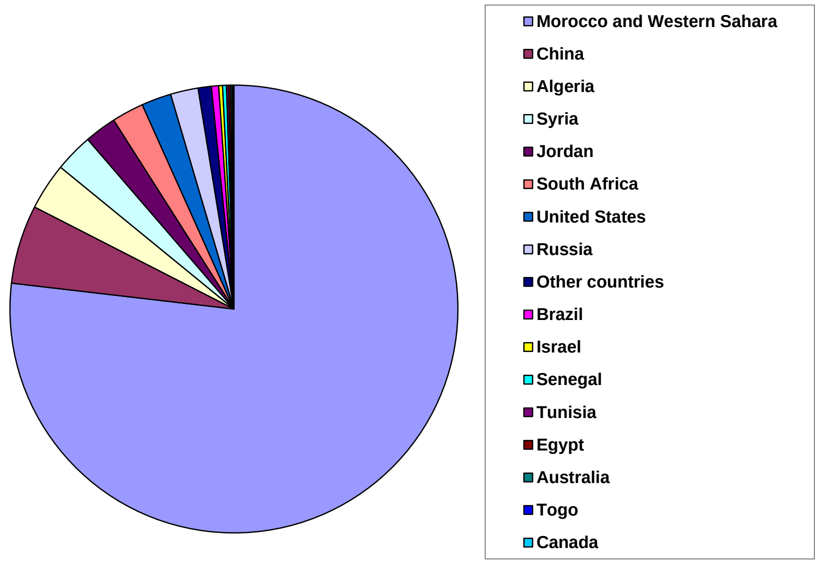

Figure 2. Relative distribution of phosphate rock reserves in 2010. In total, there are an estimated 65 Gt of rock containing 20 to 30 per cent P2O5. Source: USGS, 2011.

Kauwenbergh, 2010) although the U.S., which for many decades was the world's largest producer, peaked already in the mid-1990s (USGS, 2011; Vaccari, 2009; Déry and Andersson, 2007). Exactly how much rock there is left to exploit depends of course on what the price is. What is of interest is that, up to 2009, the US Geological Survey (USGS) provided two classes of rock – one that was commercially viable (reserves) and one that also included what was currently non-viable (reserve base), based on, for example, a technology constraint or low ore content level. But this was abandoned and, along with a new revision, brought on by the International Fertiliser Development Center (IFDC) report (Van Kauwenbergh, 2010) sponsored by USAID, the base reserves have been in effect incorporated into the classification 'reserves'. Thus, Morocco's rock reserves were increased from 5.7 Gt to 50 Gt without any substantive international review. The raw data and assumptions regarding commercial viability made by both the IFDC and USGS are unavailable for scrutiny. The IFDC revised estimate was based on theoretical calculations using areal data from a geological survey from 1989 and the phosphate content of the rock is not provided. No UN agency is involved in monitoring the resource, so the only open and published source of data is that from the USGS. The present data (USGS, 2011) provide an estimate of the reserves at 65 Gt of rock of which Morocco/W. Sahara stand for 75 per cent (Fig. 2).

The USGS also provides extraction data (Fig. 3). In total there were 176 Mt of rock extracted during 2010, with China dominating at 65 Mt, followed by the U.S. and Morocco/W. Sahara at 26 Mt each.

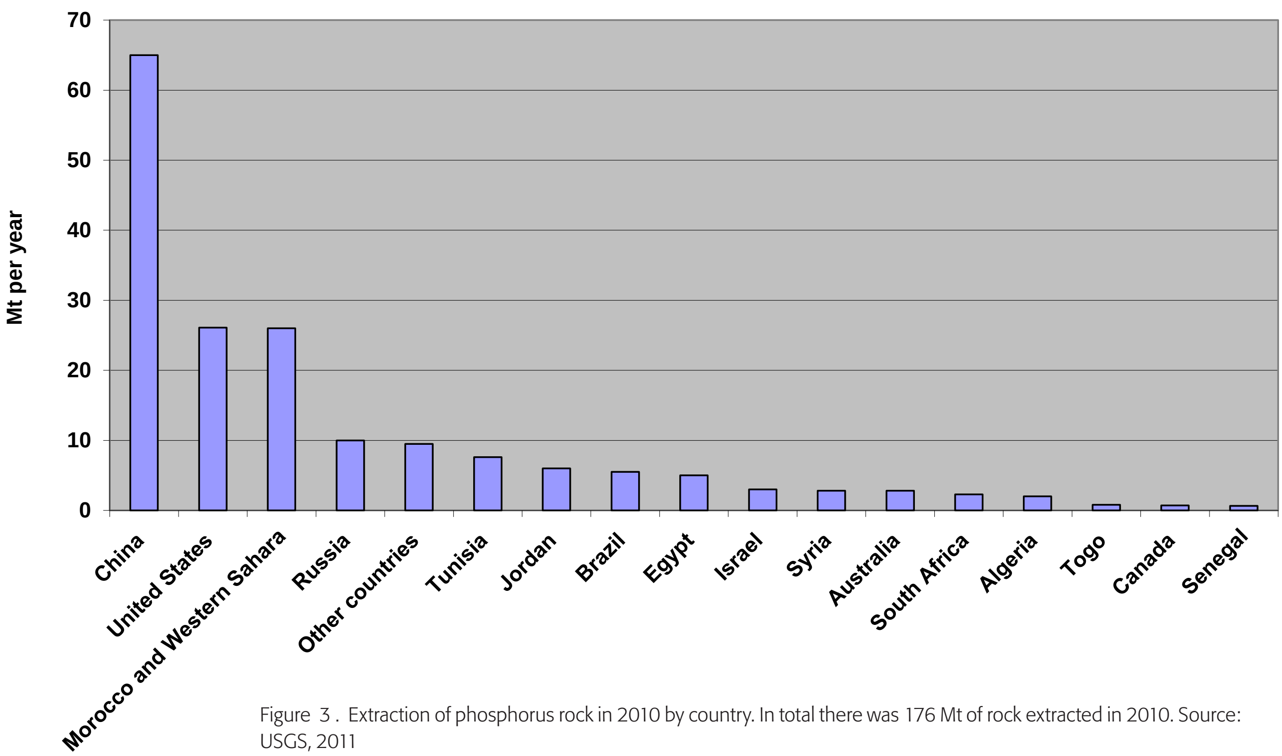

Figure 3 . Extraction of phosphorus rock in 2010 by country. In total there was 176 Mt of rock extracted in 2010. Source: USGS, 2011

Table 1. Prognoses for depletion of phosphorus at the global level and for Morocco, China and the U.S., the three largest producers
Source: USGS, 2011

	P-rock		Years to depletion			Current annual increases (%)
	Extraction 2010 Mt	Commercial reserves Gt	Zero annual increase	1 per cent annual increase	2.5 per cent annual increase	
World total (rounded)	176	65	369	155	93	6.02
Morocco & Western Sahara	26	50	1 923	300	156	13.04
China	65	3.7	57	45	20	7.97
United States	26,1	1.4	54	43	34	-1.14

At current rates of extraction, both China and the U.S. would deplete their commercially viable reserves within 40 to 50 years (Table 1). Globally, depletion could occur within 155 years assuming a compounded annual growth of 1 per cent. Population growth is at present running exponentially at 1.18 per cent (UN-DESA, 2011), so a 1 per cent exponential increase in phosphorus consumption to 2050 or 2060 is not inconceivable. Even with zero growth, China and the U.S. would deplete their reserves within 55 to 60 years.

The question is whether other limiting factors will come into play, such as fertiliser or agricultural production capacity or even fertiliser and fossil fuel affordability. Other compounding factors that can also come into play are those relating to geopolitics, recognizing that Morocco's monopoly role will have significant global market effects. Morocco has recently announced that it will significantly increase its capacity to produce phosphorus rock and respective products by about 70 per cent within the next 4 to 5 years (Ghanmi, 2010). So Morocco's role of taking up the slack left by the US and China will become central to global food security strategies. That the world should be already aiming for zero or even negative growth within this sector would appear to be the wisest approach. But this, surprisingly, is not yet on the UN or EU agenda, nor is there a single government in the world that has taken the lead in taking up this critical question. This inconvenient truth still has yet to come to the surface and remains one of the most important neglected sustainable development issues of our time.

Cadmium: a natural contaminant

As phosphorus mineral reserves dwindle and the quality of the available apatite ore diminishes, the issue concerning the relatively high levels of cadmium in phosphate fertiliser will raise its head. Relatively high levels of natural cadmium are present in the sedimentary phosphate rock that is used to produce fertiliser (Oosterhuis et al., 2000). The levels for the rock available from the mines in Morocco range from 55 to 120 mg Cd/kg P_2O_5 (Demandt, 1999). The EU has been considering a 15 year programme to reduce cadmium in phosphate fertiliser in an attempt to bring it down to approximately 20 mg Cd/kg P_2O_5, which is considered a safe level (EU, 2003). Anything above 60 mg Cd/kg P_2O_5 is considered unsafe. Removal of cadmium from the fertiliser is conceivable at additional costs. What is of interest is that sludge and organic sources that can be rendered recyclable often have lower levels of cadmium than the fertiliser sources. Human urine contains around 0.5 mg Cd/kg P_2O_5 (Kirchmann and Pettersson, 1995).

Global trends in fertiliser use

Fertiliser consumption has been dropping since the 1990s in the EU and most of the OECD countries and this has resulted in major water quality improvements in these countries. But agricultural practices using excessive amounts of fertiliser leading to runoff losses to both fresh water and coastal zones remain a problem in many other parts of the world (Fig. 4). Fertiliser use has increased in Asia, Africa and South America over the past several decades.

As populations continue to increase, especially in the developing countries, food production and fertiliser availability will need to increase accordingly. What agricultural policies, therefore, are being currently put forward to ensure food security within the confines of sustainability? Which countries will be feeding the world and increasing their requirements for fertiliser? The OECD countries do not have obvious action plans for sustainable agriculture. The EU subsidises agriculture to the tune of €1 billion each week as part of the CAP (Common Agricultural Policy) (EC, 2010). The result is overproduction and over-consumption of food with the ensuing environmental and health impacts. Similar trends can be seen in the U.S. It appears China, Malaysia, Brazil, Vietnam, Chile and South Africa are expanding their capacity to grow food and at significant growth rates – currently between 2 and 3 per cent per year (Global Harvest Initiative, 2010). Sub-Saharan Africa is still falling behind, but can be expected to grow over the next few decades.

Global phosphorus flows

Bennett et al. (2001) reviewed the literature on the global phosphorus cycle and concluded that phosphorus applied as fertiliser accumulates in the soil and eventually becomes eroded creating nutrient loading to

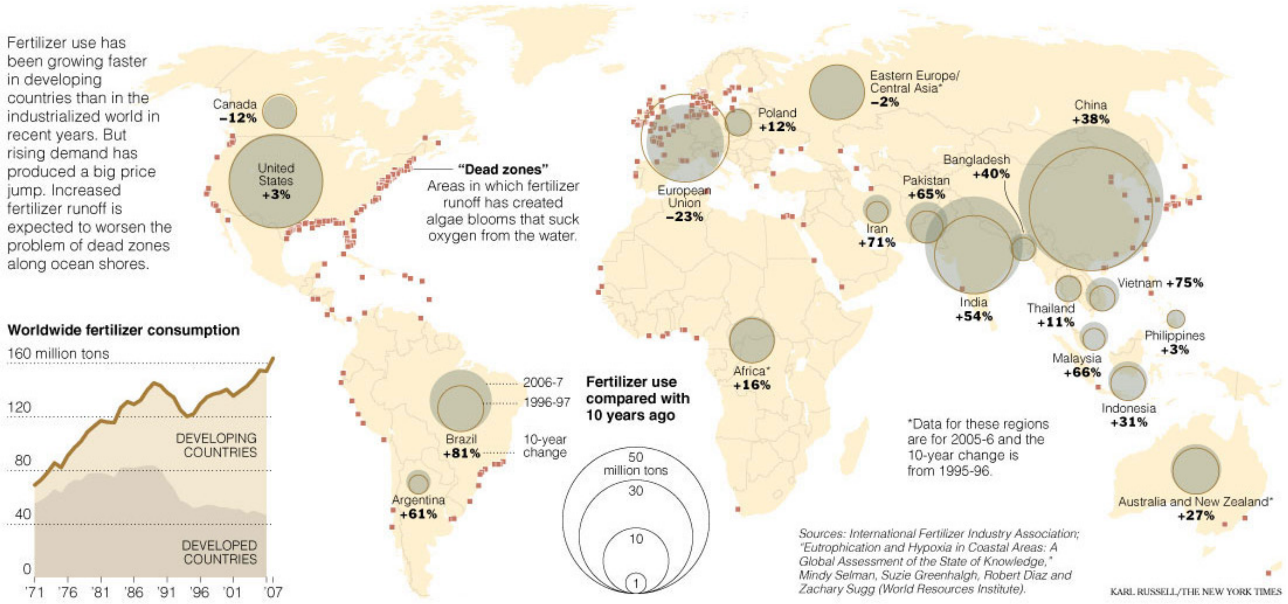

Figure 4 . Global trends in fertiliser use including the 'dead zones' in coastal areas due to excessive nutrient runoff and discharge
Source: New York Times, 2008.

receiving water bodies. Cordell et al. (2009) also estimated the global flows of phosphorus (Fig. 5), showing that of the 15 Mt of phosphorus that is used each year in fertiliser, only 3 Mt ends up being consumed in the form of prepared food. Significant losses to the soil and erosion amount to approximately 8 Mt. Domestic farm animals produce about 15 Mt of phosphorus in the form of manure and about half of this is added back to arable lands to grow crops. The bulk of the phosphorus in the manure (12 Mt) is from grazing natural vegetation and only about 2.5 Mt enters from feed. The grazers therefore are an important source of phosphorus for agriculture and, as mineral sources become more depleted and more expensive, the role of grazers, especially on rain-fed, natural grasslands, may become even more important also as a source of food protein.

The largest losses are from agriculture, which uses and loses the most phosphorus. Reforms are necessary to reduce the erosion losses and optimise the amounts used as fertiliser. Losses from manure handling also need to be reduced. Waste and sanitation systems are presently not designed for reuse and recycling. Source separation of organic fractions is necessary both in food processing and preparation. Nutrient capture from sludge and wastewater systems plus onsite collection of solid waste and latrine fractions will become more and more economically attractive as the price of fertiliser increases. Poor countries will be able to close the loop on phosphorus faster than the rich countries – since they are less locked into the large mixed waste and sanitation systems that developed countries have adopted (Rosemarin et al., 2008). These, unfortunately were designed to get rid of waste and not to refine, recycle and reuse it as a valuable, readily available resource. The present tendency is to continue building and expanding these mixed waste systems as the world becomes more and more urbanised (now over 50 per cent of the global population). Urban agriculture in an ideal world would be receiving nutrients from the cities it supports. But there is a long way to go before such systems are put into place. At the present time, over 700 million people in 50 countries consume food from 20 million ha of land irrigated with untreated sewage (Scott et al., 2004). This practise will increase as cities become larger and the need to produce food increases. If such systems had been designed from the start for agricultural reuse, the spreading of pathogens and parasites could have been reduced.

Market response to high oil prices and production of biofuels

Phosphate prices are set essentially by only three countries – the U.S., China and Morocco – that produce the bulk (almost 70 per cent) of the product for fertiliser use (Fig. 3). Phosphate fertiliser prices soared in 2007/2008 (600 per cent increases in product and 800 per cent in rock) (Fig. 6) when oil prices were over US$100 per barrel and the U.S. and other countries increased the use of food crops to produce ethanol as a liquid fuel. After the economic crash of 2008, prices are gradually increasing again. Triple superphosphate increased by 100 per cent in price during 2010 (World Bank, 2010).

Globally, food prices rose 40 per cent in 2007 and even in the poorest countries, the food index rose 25 per cent. For rural smallholder farmers in developing countries, chemical fertilisers are still no longer affordable even following the global economic collapse of 2008/2009. The relative price hike in food was the highest in over 100 years, exceeding the peaks during the oil crisis of the early 1970s and the two world wars. (Fig. 7).

The UN held three food security summits following this rapid increase in fertiliser and food prices, but only recommended short-term remedies, like increased food aid to poor countries unable to afford the high costs of chemical fertiliser. No systems or integrated view was taken questioning the excessive use of chemical fertilisers, the need for eco-friendly and climate-smart agricultural practices or examining the world's limited fertiliser resources. Phosphorus was not

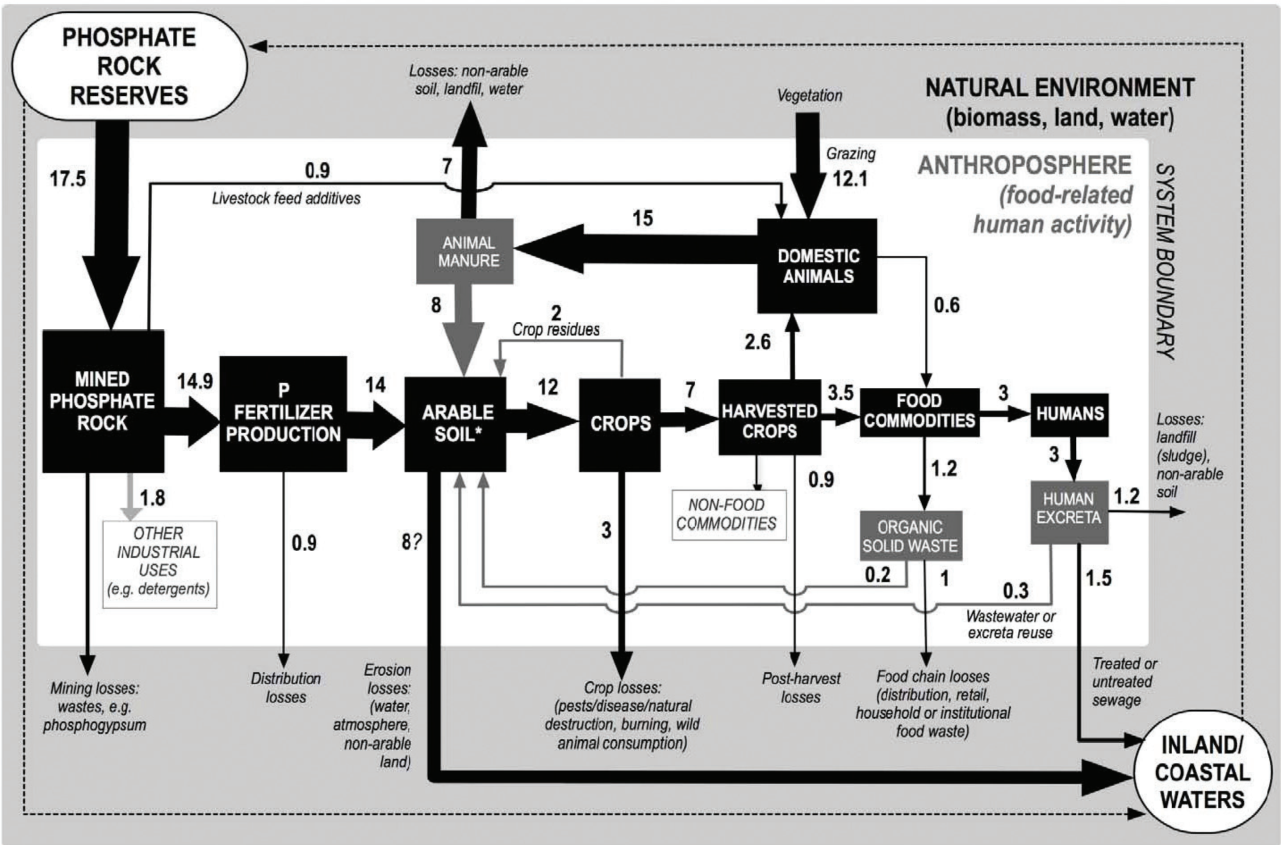

Figure 5. Global flows of phosphorus (Mt). Source: Cordell et al., 2009

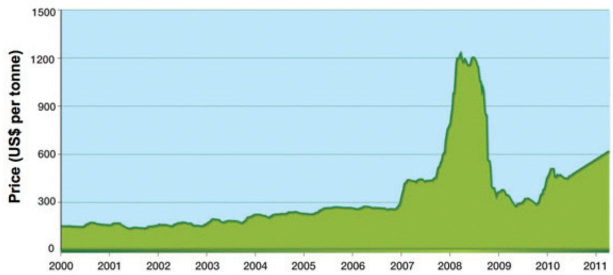

Figure 6. Trends in the world price of diammonium phosphate to 2011 (Bulk FOB US bulk US$ per tonne). Source FMB Weekly Phosphates Report, May 2011.

Figure 7. Trends in the FAO food price index to 2008. Source: World BankUNEP, 2009.

recorded as an issue of long- or medium-term concern in the resolution of June 2008 (FAO, 2008). A new form of global governance of phosphorus is thus called for. Phosphorus reserves are limited and will become more expensive as the high-grade commercially viable rock becomes depleted. The geographic distribution is highly skewed, which can lead to shortages caused by unpredictable political turmoil in some of the larger producer countries. A governance capacity is needed to provide global fertiliser and food security by monitoring rock extraction and the size of reserves, promoting more efficient agricultural practices and reuse from manure and waste sources.

Conclusions and recommendations

Closing the loop between agriculture and sanitation

The agriculture challenge

The agriculture challenge is truly gargantuan when one sees that nearly one billion people living in 46 countries are malnourished (FAO, 2010), 40,000 die every day of hunger and hunger-related diseases and famine remains a threat in at least nine African countries where the lives of 20 million people are at risk. Some 75 to 80 per cent of Africa's farmland is degraded. Africa loses between 30 and 60 kg of nutrients per ha per year – the highest rate in the world. In 2002/2003 sub-Saharan Africa used 8 kg of fertiliser per ha compared to South America (80 kg/ha), North America (98 kg/ha), Western Europe (175 kg/ha), East Asia (202 kg/ha), South Africa (61 kg/ha) and North Africa (69 kg/ha). The cost of fertiliser prior to 2007 in the U.S. was US$150/t, but in landlocked African countries it was as high as US$600/t largely as a result of the severe underdevelopment of the transport infrastructure – rail and road. Phosphorus fertiliser, although produced on the African continent, is not available to African smallholder farmers. Reforms within the sector are necessary in order to make use of alternative sources of fertiliser and even alternative agricultural practices. In order to cope, more sustainable conservation agricultural practices are necessary, such as strategic cropping and low- or no-tillage practices, water harvesting and recycling of nutrients from various organic sources including manure and humanure.

The sanitation challenge

While the agriculture challenge is daunting, the human sanitation challenge remains (Rosemarin et al., 2008). Currently 5000 children die every day in the world from water-borne diseases linked to a lack of basic sanitation; 700 million people in 50 countries eat food from crops irrigated with untreated sewage; 60 million DALYs (disability-adjusted life years) are lost due to diarrhoea every year; 3.5 billion people are infected with helminth worm parasites; and half the world lacks basic sanitation systems. Meeting this, the largest MDG target, will have a cross-sector social impact by improving livelihoods and general productivity. Productive sanitation linked to agriculture can provide new growth opportunities for poor countries. So, in order to meet the MDG target for sanitation coverage, the question of disposal and reuse should be put clearly into focus especially knowing that the potential fertiliser capacity from these systems can be a significant contribution towards fertiliser and food security.

Linking sanitation and agriculture

A closer look is necessary to understand how sanitation and agriculture can be linked. The concept of ecological sanitation seeks to develop sanitation systems for human excreta that close the nutrient and water cycles. For example, nutrient recycling from human waste can be achieved by using soil composting and urine-diverting dry toilets (Morgan, 2008). Such systems are particularly appropriate in rural and peri-urban areas of developing countries where farmers cannot afford chemical fertilisers. Ecological sanitation has the potential to be a useful alternative to generate fertiliser in subsistence farming (Rosemarin et al., 2008).

The average human produces 500 L of urine and 50 L of faeces per year. This is equivalent to about 5.5 kg of NPK (4 kg of nitrogen, 1 kg of potassium and 0.5 kg of phosphorus) per capita per year varying from region to region depending on food intake (Jönsson et al., 2004). The rule of thumb is that one day's urine from an adult is sufficient to fertilise a square metre of cropped area for each cropping period. This means one year of urine from a person can support agriculture over an area of about 300 to 400 m2. If used mainly as a phosphorus fertiliser (i.e. requiring a supplement of nitrogen), one person's urine over a year can support even larger areas of between 500 and 600 m2. Calculations show that sub-Saharan Africa could become self-sufficient in fertiliser supply if it were to adopt productive or ecological sanitation practices (Rosemarin et al., 2008). This would provide the necessary supply of nutrients to smallholder farmers and provide food security and new opportunities for income.

In trials in seven villages in Niger, Dagerskog and Bonzi (2010) found that ten persons (the average family size is nine) annually excrete in their urine the equivalent of about 50 kg of urea in purchased chemical fertiliser. In their faeces and the non-nitrogen part of the urine they excrete about 50 kg of prepared NPK fertiliser (14-23-14), worth about US$80. Plots using urine as a fertiliser produced comparable or 10 to 20 per cent higher yields of sorghum and millet compared with plots receiving chemical fertiliser at the same nitrogen application rate. In trials with tomato, onion, cabbage, lettuce and pepper, urine, which contains potassium, phosphorus and nitrogen, acted as a complete fertiliser producing consistently 20 to 45 per cent higher yields in comparison to urea alone. The objective in this IFAD project was to encourage farmers to use urine instead of the expensive synthetic urea. The rule of thumb from this project was that one person excretes in urine and faeces per year on the average 2.8 kg N, 0.4 kg P and 1.3 kg K and this is sufficient to fertilise a cereal or vegetable crop covering 300 m2. To avoid loss of ammonia from stored urine, sealed containers are used. Responding to the increasing interest in recycling of phosphorus and other nutrients from sanitation systems, WHO, UNEP and FAO developed guidelines for the safe reuse of human excreta in agriculture (WHO, 2006). Struvite is now being produced using urine as the sole source of phosphorus in villages of Nepal (Gantenbein and Khadka, 2009). The phosphorus loop for rural populations can therefore be closed without too much change in the make up of the present systems. For urban systems the challenge is much larger since the waste systems have not been designed with agricultural reuse in mind. For those cities with sewage treatment systems, the sludge is a significant source of phosphorus. The organic fraction of municipal solid waste is also a significant source of phosphorus since this constitutes between 50 and 70 per cent of the waste produced (UNEP/GRID-Arendal, 2004).

In order to make this jump to sustainable or productive sanitation requires a paradigm shift in the way we design and use sanitation and solid waste systems. Mixing reduces the quality of the various products. So this calls for source separation of urine, faeces and greywater, containment of the various fractions, treatment (e.g. through composting of the faeces fraction) and then reuse of the nutrients in agriculture of various kinds. In urban settings where sludge can be collected from pit latrines, septic tanks and sewage treatment plants, considerable amounts of phosphorus can be collected and made available for agricultural reuse. For EU-27, it is estimated that one-third of the phosphorus used as fertiliser can be obtained from the sludge in sewage treatment plants (based on data from an EU assessment by Milieu Ltd. et al., 2009). If the manure from domestic farm animals is included, then the entire fertiliser requirement can be covered through recycled sources (Haarr, 2005). In Sweden, with improved fertiliser and manure practices, municipal sludge could, within a decade, replace 50 to 65 per cent of the P originating from chemical fertiliser (Finnson, A., 2011).

As fertiliser prices continue to increase, 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. And there will be more pressure to develop these options. There are major stumbling blocks preventing widespread development in these directions resulting from general ignorance and cultural taboos and attitudes about human excreta. There is a serious lack of capacity in the world today to carry out large-scale productive sanitation with agricultural applications. Policies and regulations are also lacking to help promote and main-stream these practices. So much work through extension services and training is required before we can make the leap to close the loop on nutrients to benefit mankind.

The urgent need for policies and governance

The above discourse identifies gaps in policies and governance that may already be jeopardizing the food security of several nations. There is an acute need for a directive and governance capacity to dictate policy on the sustainable management and use of phosphorus. A global convention and implementation commission are required in order to secure the limited supply of commercially viable phosphorus and to begin using it in a much more conservative manner than up to now. The commission would fulfil the need for an independent monitoring capacity in order to increase transparency about the extent of viable phosphorus reserves. The commission would also promote more efficient agricultural practices, both in the use of chemical fertiliser (e.g. through better fertiliser placement and reduced applications) and in the use and storage of manure in order to minimise losses. Implementation in developing countries could be catalyzed through FAO and IFAD extension interventions. There is also a need to develop new recycling systems from waste and sanitation sources that are designed around agricultural requirements (e.g. to produce floc in sewage treatment plants that is crop-available and to introduce source separation of waste components in order to optimise fertiliser quality). Implementation could be catalyzed through UN Habitat and UNEP, which has already shown an interest in the phosphorus question (UNEP, 2011). Tax incentives could be introduced to promote investments in closed-loop systems. It is of prime importance that the various waste and sanitation sectors better integrate themselves in the agriculture sector to provide new and more sustainable solutions that will secure a high level of efficiency in the use and reuse of phosphorus.

References

Ashley, K., Cordell, D. and Mavinic, D. (2011) A brief history of phosphorus use and abuse: from the philosopher's stone to nutrient recovery and reuse. In: *Proceedings of the International Conference on Nutrient Recovery from Wastewater Streams* (Eds. Mavinic, D., Ashley, K. and .Koch, F.) Vancouver, Canada. London, UK: IWA Publishing.Chemosphere (in press).

Bennett, E.M., Carpenter, S.R. and Caraco, N.F. (2001) Human impact on erodable phosphorus and eutrophication: a global perspective. *BioScience* 51(3): 227-234.

Cadée, G.C. and Hegeman, J. (1993). Persisting high levels of primary production at declining phosphate concentrations in the Dutch coastal area (Marsdiep). *Netherlands Journal of Sea Research* 31: 147-152.

Carpenter, S.R., Caraco, N.F., Correll, D.L., Howarth, R.W., Sharpley, A.N. and Smith, V.H. (1998) Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecological Applications* 8: 559-568.

Conley, D.J., Paerl, H.W., Howarth, R.W., Boesch, D.F., Seitzinger, S.P., Havens, K.E., Lancelot, C. and Likens, G.E. (2009) Controlling eutrophication: nitrogen and phosphorus. *Science* 323:1014-1015.

Cordell, D., Drangert, J-O. and White, S. (2009) The story of phosphorus: global food security and food for thought. *Global Environmental Change* 19: 292-305.

Dagerskog, L. and Bonzi, M. (2010) *Opening minds and closing loops – productive sanitation initiatives in Burkina Faso and Niger.* Sustainable Sanitation Practice no. 3, 2010. Available at: www.ecosan.at/SSP.

Demandt, I. (1999) *The world phosphate fertilizer industry. Research project Environmental regulation, globalization of production and technological change.* Background Report No. 10. Maastricht, Netherlands: The United Nations University, Institute for New Technologies.

Déry, P. and Anderson, B. (2007) Peak phosphorus. *Energy Bulletin*: Available at: www.energybulletin.net/node/33164.

Dolan, D.M. (1993) Point source loadings of phosphorus to Lake Erie: 1986-1990. *Journal of Great Lakes Research* 19(2): 212-223.

European Commission (EC) (2010) *The Common Agricultural Policy Explained*. Brussels, Belgium. European Commission,. Available at: ec.europa.eu/agriculture/publi/capexplained/cap_en.pdf.

European Union (EU) (2003) *Draft proposal relating to cadmium in fertilizers. Chemicals Unit of DG Enterprise*. Brussels, Belgium. European Commission. Available at: ec.europa.eu/enterprise/newsroom/cf/_getdocument.cfm?doc_id=2966.

FAO (2008) *Declaration of the High-Level Conference on World Food Security: the challenges of climate change and bioenergy.* Rome, Italy: Food and Agriculture Organization of the United Nations. Available at: www.fao.org/fileadmin/user_upload/foodclimate/HLCdocs/declaration-E.pdf.

FAO (2010) *The state of food insecurity in the world*. Rome, Italy: Food and Agriculture Organization of the United Nations. Available at: www.fao.org/docrep/013/i1683e/i1683e.pdf.
Finnson, A. (2011) Personal communication.

FMB (2011) *FMB Weekly Phosphates Report*, May 2011. Available at: www.stonegateagricom.com/s/PhosphatePrices.asp

Gantenbein, B. and Khadka, R. (2009). *Struvite recovery from urine at community scale in Nepal:* final project report phase 1. Dübendorf S witzerland EAWAG,S witzerland.: EAWAG.

Ghanmi, L. (2010) *Morocco's OCP to build four fertiliser units.* Reuters: Available at: af.reuters.com/article/idAFJOE6AP05D20101126.

Global Harvest Initiative (2010) *The 2010 gap report: measuring global agricultural productivity.* Global Harvest Initiative, Washington, DC, USA. Available at: www.globalharvestinitiative.org.

Haarr, A. (2005) *The reuse of phosphorus*. Position paper, EU2-04-SL09.Brussels, Belgium. European Union of National Associations of Water Suppliers and Waste Water Services.

HELCOM (2008) Spatial distribution of the winter nutrient pool. Helsinki, Finland. Helsinki Commission. Available at: www.helcom.fi/BSAP_assessment/ifs/ifs2008/en_GB/Spatial DistrNutr/

HELCOM (2009) Cyanobacterial blooms in the Baltic Sea. HELCOM Indicator Fact Sheet. Helsinki, Finland. Helsinki Commission. Available at: www.helcom.fi/BSAP_assessment/ifs/ifs2009/en_GB/cyanobacterial_blooms/.

Jönsson, H., Richert Stintzing, A., Vinnerås, B. and Salomon, E. (2004) *Guidelines on the use of urine and faeces in crop production*. Stockholm, Sweden: Stockholm Environment Institute. Available at: www.ecosanres.org/pdf_files/ESR_Publications_2004/ESR-2web.pdf.

Kirchmann, H. and Pettersson, S. (1995) Human urine chemical composition and fertiliser use efficiency. *Fertiliser Research* 40: 149-154.

Kyle, M.A. and McClintock, S.A. (1995) The availability of phosphorus in municipal wastewater sludge as a function of the phosphorus removal process and sludge treatment method. *Water Environment Research* 67(3): 282-289.

Milieu Ltd., WRc and RPA (2009) *Environmental, economic and social impacts of the use of sewage sludge on land*. Summary report 1. Assessment of existing knowledge. Study contract DG ENV.G.4/ETU/2008/0076r.

Morgan, P. (2008) *Toilets that make compost.* Stockholm, Sweden: Stockholm Environment Institute/ Rubgy, UK: Practical Action Publishing. 101p.

New York Times. (2008) *World Growth in Fertiliser Use.* New York, USA. NY Times. Available at: www.nytimes.com/imagepages/2008/04/30/business/20080430_FERTILIZER_GRAPHIC.html

Oosterhuis, F.H., Brouwer, F.M. and Wijnants, H.J. (2000) *A possible EU-wide charge on cadmium in phosphate fertilisers: economic and environmental implications.* Final Report to the European Commission. Amsterdam, The Netherlands. Inst for Environmental Studies, Vrije University. 75p.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin III, F.S.C., Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., Wit, C.A.d., Hughes, T., v.d. Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P. and Foley, J.A. (2009) A safe operating space for humanity. *Nature* 461: 472-475.

Rosemarin, A., de Bruijne, G. and Caldwell, I. (2009) Peak phosphorus: the next inconvenient truth. *The Broker* 15: 6-9.

Rosemarin, A., Ekane, N., Caldwell, I., Kvarnström, E., McConville, J., Ruben, C. and Fogde, M. (2008) *Pathways for sustainable sanitation: achieving the Millennium Development Goals.* London, UK: IWA Publishing. 56p.

Schindler, D.W. (1977) Evolution of phosphorus limitation in lakes. *Science* 195: 260-262.

Schröder, J.J., Cordell, D., Smit, A.L. and Rosemarin, A. (2010) *Sustainable use of phosphorus*. Wageningen University and Stockholm Environment Institute report to EU DG Environment. Wageningen, The Netherlands. DLO Foundation.

Scott, C.A., Faruqui, N.I. and Raschid-Sally, L. (2004) *Wastewater use in irrigated agriculture: coordinating the livelihood and environmental realities*. CABI IWMI/IDRC. Oxfordshire, UK CABI Publishing. Available at: www.idrc.ca/en/ev-31595-201-1-DO_TOPIC.html.

Tiessen, H. (ed.) (1995) *Phosphorus in the global environment: transfers, cycles and management.* SCOPE 54. ICSU. Chichester, UK: John Wiley.

UN-DESA (2011). *World Population Prospects*. New York, USA. UN. Available at: esa.un.org/unpd/wpp/unpp/panel_indicators.htm UN (2009) World population prospects. DB1_F20 Population growth rate. Available at: esa.un.org/undp /wpp2008/peps_period-indicators.htm

UNEP/GRID-Arendal (2004) *Municipal solid waste composition: for 7 OECD countries and 7 Asian cities*. Arendal, Norway: UNEP/GRID-Arendal Maps and Graphics Library. Available at: maps.grida.no/go/graphic/municipal_solid_waste_composition_for_7_oecd_countries_and_7_asian_cities.

UNEP (2009) *The Environmental Food Crisis – The Environment's Role in Averting Future Food Crises. Nairobi, Kenya*. UNEP. Available at: maps.grida.no/go/collection/the-environmental-food-crisis-the-environment-s-role-in-averting-future-food-crises

UNEP (2011). Phosphorus and food production. In: *UNEP Year Book 2011: emerging issues in our global environment*. Nairobi, Kenya: UNEP. pp. 34-45. Available at: www.unep.org/yearbook/2011/pdfs/UNEP_YEARBOOK_Fullreport.pdf.

USGS (2011) *Phosphate rock statistics and information.* Washington, DC, USA. USGS. Available at: minerals.usgs.gov/minerals/pubs/commodity/phosphate_rock/mcs-2011-phosp.pdf.

Vaccari, D.A. (2009) Phosphorus, a looming crisis. *Scientific American* June 2009: 42-47.

Van Kauwenbergh, S. (2010). *World phosphate rock reserves and resources*. IFDC Technical Bulletin T-75. Muscle Shoals, Alabama, USA: International Fertilizer Development Center.

Vollenweider, R.A. (1968). *The scientific basis of lake and stream eutrophication with particular reference to phosphorus and nitrogen as eutrophication factors.* Technical report. DAS/C81/68. Paris, France: OECD.

WFP (2009) *World must double food production by 2050*. Press release 26 Jan 2009. Rome, Italy: World Food Programme. Available at: www.wfp.org/content/world-must-double-food-production-2050-fao-chief.

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

World Bank (2010) *Commodity price data*. Washington, DC, USA: The World Bank. Available at: siteresources.worldbank.org/INTDAILYPROSPECTS/Resources/Pnk_0410.pdf

World Water Assessment Programme (2009) *The United Nations world water development report 3: water in a changing world*. Paris, France: UNESCO/London, UK: Earthscan.