Phosphorus in agriculture

Problems and solutions

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Phosphate mining

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Executive Summary

Agriculture is by large the main user of phosphorus globally, accounting for between 80-90% of the total world demand. An input of phosphorus is crucial for food production since all plants need an adequate supply of it for successful growth. A shortfall in phosphorus will result in a reduction of crop yield. Phosphorus is essential for all living organisms. Agriculture is heavily dependent on mined rock phosphate, the only known primary source of phosphorus, but this is a non-renewable resource. Morocco holds the vast majority of global supplies of rock phosphate, with China in second place. Phosphorus reserves are only present in some regions, with large parts of the world – including Europe, India and Australia – being almost totally dependent on imports.

Phosphorus consumption

China and India are the largest consumers of phosphorus fertilisers demanding 34% and 19% of global consumption, respectively. Phosphorus consumption in China and India show increasing trends (20% and 80% increase from 2002 to 2009, respectively), while in Europe consumption decreased by about 20% in the same period (reflecting price increases and environmental restrictions). On a worldwide scale, population growth, changes towards meat-rich diets and growing demands for bioenergy crops will push an increasing demand for phosphorus fertilisers in the future.

Phosphate rock environmental hazards

Some phosphate rocks contain low levels of radionuclides, and some studies show increased radioactivity around phosphate mining areas. Phosphogypsum is a by-product of phosphate rock processing, and contains appreciable quantities of uranium. Phosphogypsum stockpiles present a serious environmental problem, with potential hazard for human health and pollution of the groundwater. Levels of radioactivity in phosphate fertilisers vary widely worldwide, but they might represent a concern because of their potential contribution to increased natural radioactivity in agriculture soils in the long term.

Some rock phosphate fertilisers contain small amounts of the heavy metal cadmium. Because cadmium is highly toxic to humans, there are concerns about its accumulation in agriculture soils and transfer through the food chain. The EU is currently reviewing permitted levels of cadmium in phosphorus fertilisers, with a view of lowering and harmonising safe levels. In Western countries, 54-58% of the cadmium found in the environment comes from the application of mineral phosphate fertilisers to agricultural land. In China, for example, recent analysis shows that high intensity use of phosphate fertilisers in the Yangtze-Huaihe region lead to elevated levels of cadmium in pond sediments of the watershed.

Peak phosphorus?

Phosphate rock reserves are being exploited at growing rates following increasing demand. The quality of existing phosphate rock is declining, making its extraction more expensive. Estimates of remaining phosphate reserves are very variable and contested, ranging between about 100 to 300 years at current production rates, up to millennia if more reserves appear and with better mining and more recycling. In any case, even the more conservative estimates acknowledge that a peak in phosphate rock may be looming. Peak phosphorus refers to the moment when production of phosphorus from mining reaches a maximum, and after that point the quality of remaining phosphorus reserves decreases and becomes harder to access making it more expensive to mine and process.

In 2008, phosphate rock prices increased by 800%. Prices went down quickly, but never to the pre-peak values: prices are now about four times higher than they were before 2006. This volatility makes import-dependent countries and farmers more vulnerable and financially insecure.

A very leaky phosphorus flow

On a worldwide scale, we are mining five times the amount of phosphorus that humans are consuming in food, and only about one tenth of the phosphorus entering the agriculture system is actually consumed by humans. This lost phosphorus ends up in water systems causing widespread pollution in lakes, rivers and coastal areas, algal blooms and dead zones in the oceans (together with nitrogen). Thus, ironically, phosphorus represents both a scarce non-renewable resource for living beings and a pollutant for living systems.

Phosphorus applied to soils ends up in water

When phosphorus fertilisers are applied, only a small proportion of it is immediately available to plants. The rest is stored in soils in varying degrees of availability. It is common for farmers to apply phosphorus in excess to make it more available to crop plants, although this also increases the risk of most phosphorus being lost via run-off, leaching or soil erosion, finally ending up in lakes, rivers and oceans. This represents a financial loss and environmental damage.

Too much of a good thing

An excess of nutrients in water systems – eutrophication – is a major and common problem worldwide, driven mostly by overuse of phosphorus and nitrogen fertilisers. The planetary boundaries for both phosphorus and nitrogen cycles are exceeded, causing widespread damage to the Earth's systems, especially water systems.

Global studies of phosphorus imbalances found that phosphorus deficits covered 29% of the global cropland area and 71% had overall phosphorus surpluses. On average, developing countries had phosphorus deficits during the mid-20th century, but current phosphorus fertiliser use may be contributing to soil phosphorus accumulation in some rapidly developing areas, like China, together with relatively low phosphorus use efficiency. Even the notion of African soils being phosphorus depleted is contested by new analysis; there are vast areas where phosphorus excesses are more common although inefficiently used for food production.

High use of synthetic fertilisers resulted in a greater proportion of intense phosphorus surpluses globally than manure application. Where there were high concentrations of livestock, there were typically some phosphorus surpluses, while phosphorus deficits were apparent in areas producing forage crops used as livestock feed. The disconnection between livestock and land is behind some of these imbalances in phosphorus use. Optimising the use of land for food and livestock in ecological farming systems will help in using nutrients efficiently and avoiding massive losses of phosphorus (and other nutrients) into the environment.

Solutions for a broken phosphorus cycle

Ensuring phosphorus remains available for food production by future generations and preventing pollution in water systems is possible by working towards closing the broken phosphorus cycle. This requires strong actions in two main areas: reducing phosphorus losses, especially from agricultural lands; and increasing phosphorus recovery and reuse to agricultural lands from all sources, including livestock wastes, food waste and human excreta. Closing the broken phosphorus cycle should follow two main drivers:

- Stop or minimise losses, by increasing efficiency in the use of phosphorus, mostly in arable land and the food chain. Additionally, sustainable phosphorus use will benefit from shifting to plant-rich diets that are more efficient users of phosphorus (and other resources) than meat-rich diets, and from minimising food waste.
- Maximise recovery and reuse of phosphorus, mostly of animal and human excreta, and thus minimise the need for mined phosphorus.

Arable Land: In arable land, reducing phosphorus losses will require actions to stop overuse of synthetic fertilisers, by moving away from mineral phosphorus and optimising land use. It will also require measures to avoid erosion by improving soil management and improve soil quality.

Farmers should aim at maintaining phosphorus levels in the soil that ensure economically optimal yields while diminishing risk of phosphorus losses to surface water. For that aim, policies and capacity building that enables farmers to decide in critical values of phosphorus soil nutrition are needed. Supporting farmers in any interventions to reduce phosphorus overuse is a first necessary step.

Avoiding the overuse of phosphorus in the 70% of the world's agriculture land with phosphorus surpluses will save millions of tonnes of phosphorus that will not need to be mined and applied. This will obviously benefit the farmer's finances, the sustainability of phosphorus reserves and the amount of clean water bodies worldwide.

In livestock systems: Reducing phosphorus losses will require maximising use of phosphorus in manure for soil fertility in croplands and pastures, and adjusting livestock diets. This will simultaneously work for recovering the phosphorus (and other nutrients) being lost when they are not incorporated into crop plants. Industrial animal operations concentrate nutrients in areas far away from the land where these nutrients will be essential to crop production, including their own feed production. Working towards the (re)integration of crop lands and livestock systems will be necessary at the regional scale.

Given that animal production already uses directly or indirectly a shocking 75% of available agricultural land and an additional high share of all nutrients needed for food production, reducing average global levels of industrial animal production and consumption will be needed.

Evidence shows that farming without synthetic fertilisers can still produce enough food for all. This is especially true if we consider a vision aimed at farming with biodiversity, closing nutrient cycles, recycling nutrients from non-conventional sources (sewage, food waste, etc.) and with more sustainable diets. Many scientists, institutions like FAO, UNEP and farmers associations are documenting remarkable success from ecological farming in achieving high yields and fighting poverty in low-income regions.

<u>Sanitation systems:</u> Current sanitation systems in industrialised countries treat human excreta as an unwanted residue, wasting large quantities of clean drinking water and energy in sewage plants to manage it ("flush and forget" systems). At the same time, half of people living in the planet, 72% of them in Asia, do not have access to sanitation facilities.

About 11% of phosphorus entering Earth systems is lost in human urine and excreta, and phosphorus and nitrogen in it could be recovered up to about 90%. If recovered, this could supply 22% of the current global demand for phosphorus. The best long-term solution for recovering nutrients from human excreta is the creation of ecological sanitation systems that work simultaneously for closing nutrient cycles, saving water and energy, and improving livelihoods. This is the best option and it is immediately feasible and cost-effective in regions where sanitation facilities are not well developed or in rural areas, newly constructed homes and public buildings in economically developed countries. Interim measures for current flush and forget systems include the extraction of struvite (a phosphate salt) at sewage treatment plants and its use as a phosphorus fertiliser.

image Groundnut seedling in an organic field, in the outskirts of Bangalore, Karnataka.

image Phosphate mining.

01

Introduction

Phosphorus is an essential element needed in all living organisms, and it is also a non-renewable resource dependent exclusively on mined rock phosphates. An input of phosphorus is crucial for food production since all plants need an adequate supply of it for successful growth. A shortfall in phosphorus will result in a reduction of crop yield. Since the late 19th century, processed mineral phosphorus from mined phosphate rock has been used routinely in European agriculture as a source of phosphate fertiliser. Its use grew significantly in the 20th century and today much of the crop production on a worldwide scale is reliant on inputs of mineral phosphate fertiliser. Feedstuffs for livestock also contain added mined phosphorus to supplement animal nutrition. Agriculture is by far the main user of mined phosphorus globally, accounting for between 80–90% of the total world demand (Childers et al, 2011).

However, only about 20% of the phosphorus used in agriculture reaches the food we consumed, most of the rest is lost in inefficient steps along the phosphorus cycle (Cordell et al, 2011) (Figure 4). Globally, this lost phosphorus ends up in water systems causing widespread pollution in lakes, rivers and coastal areas, algal blooms, and dead zones in the oceans (together with nitrogen). Thus, ironically, phosphorus represents both a scarce non-renewable resource for living being and a pollutant for living systems.

Recent scientific debates warn of future supplies of phosphate rock becoming scarcer and more expensive to mine (MacDonald et al, 2011, Elser and Bennett, 2011, Cordell et al, 2011, Childers et al, 2011, Jasinski, 2010). The increasing scarcity of this finite resource is of great concern for global food security, since phosphorus cannot be produced synthetically and there is no substitute for it in farming.

Cordell et al (2009) noted that: "It is known that addressing energy and water issues will be critical for the growing world population. For instance about 70% of the world's water demand is for agriculture. However, the need to remedy the issue of limited phosphorus availability in the future has not been widely recognised".

Planetary boundaries, or upper tolerable limits of impacts, have become a symbol of major threats to the planet (Rockström et al, 2009a, Rockström et al, 2009b). In its original assessment, both nitrogen and phosphorus cycles were presented as part of the critical boundary of biogeological cycles that support life on Earth, with nitrogen being grossly overshot while phosphorus still within safety limits. However, a most recent assessment by experts in phosphorus cycles estimates that phosphorus flow into water systems is also already massively overshot, surpassing its safety limits by something between 3 and 20 times its planetary boundary (Carpenter and Bennett, 2011).

Ensuring phosphorus remains available for food production by future generations and preventing pollution with phosphorus in water systems is possible by working towards closing the broken phosphorus cycle (section 5). This requires strong actions in two main areas: reducing phosphorus losses, especially from agriculture lands; and increasing phosphorus recovery and reuse to agriculture lands from all sources, including livestock wastes, food waste and human excreta (section 5).

In brief, this report discusses current usage of phosphorus in world farming, its environmental problems and options for transforming it into a sustainable phosphorus cycle.

"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" (Cordell et al, 2009).

02

Sources, global consumption and toxicity

2.1 Sources of phosphate rock

Mined phosphate rock is principally used for agricultural fertiliser (80%), the remainder being used for animal feed additions (5%) and industrial applications (15%) including detergents and metal treatment (Smit et al, 2009).

"Reserves" of phosphate rock refers to the resources of phosphate rock that are easily accessible and can be mined economically. In 2009, it was reported that China held 37% of reserves, Morocco and West Sahara 32%, South Africa 8%, and the US 7%, with some other countries holding less reserves (Smit et al, 2009).

However, estimates are uncertain and updated analysis suggests, for example, that Morocco could hold much more phosphorus reserves than previously estimated (Figure 1). Deposits are very irregularly distributed geographically and mainly limited to a few countries of which Morocco and China hold the biggest reserves. Large parts of the world – including Europe, India and Australia – are almost totally dependent on the imports of phosphate from other countries.

Global imbalance

Morocco holds the majority of global supplies of phosphorus: but these estimates can change disturbingly quickly.

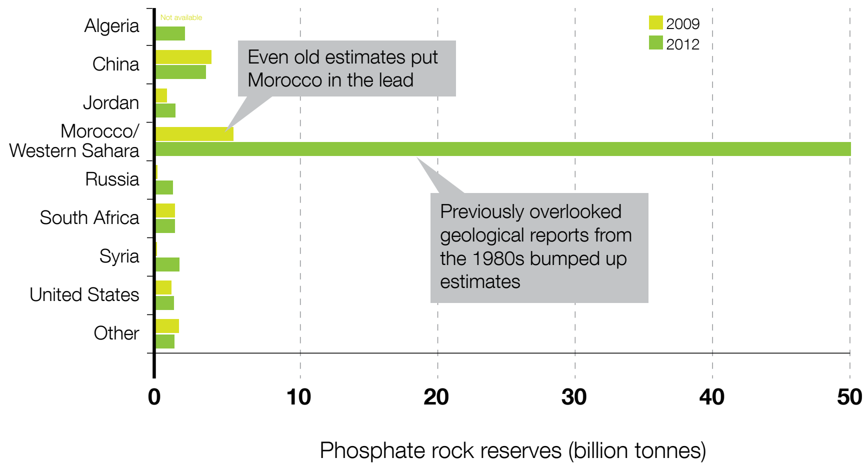

Figure 1. Phosphate rock reserves estimates as in Elser and Bennet 2011, Nature 478:29-31. (Reproduced with permission from Nature Publishing Group).

2.2 Consumption of phosphate rock fertilisers

According to FAO data up to 2009, China, India and Europe already consume about 60% of the global use of phosphate fertiliser (Figure 2). China is the largest consumer of phosphorus fertilisers in the world with 34% of world total and India is second with 19% of global consumption (FAOSTAT 2012, Figure 2).

Between 2002 and 2009, global use of phosphate fertilisers increased by 12% (Figure 2). India showed the largest increase in phosphate use, almost doubling in quantity between 2002 and 2009 (80% increase). China also showed strong increases with 20% growth in phosphorus consumption between 2002 and 2009. Europe, in contrast, decreased use by about 20% from 2002 to 2009, reflecting market price increases and environmental restrictions (see details in section 4.3.1).

On a worldwide scale, population growth, changes towards meat-rich diets, and growing demands for bioenergy crops will push an increasing demand for phosphate fertilisers in the future. Higher meat, milk and egg consumption need a higher input of phosphorus in farming than a vegetarian based diet. Growing demand for bio-energy crops will also require further phosphate fertiliser inputs (Smit et al, 2009). For example, in 2009, 32% of all corn grown in the US was used for ethanol production, representing 10% of all phosphorus fertiliser used in the US in that year (CENR 2010 as cited in Childers et al, 2011).

2.3 Toxicity of phosphate rock fertilisers

As with all mining extractions and processing, phosphate mines deeply transform the landscape, extract large amounts of water from neighbouring water systems, and can contaminate water, soil and air around mines. Phosphate mines are implicated in significant changes to water systems, as in Florida where residents near a large phosphate mine are in legal dispute about damages to their drinking water supplies[2].

Generally, phosphate mining is a low efficiency process. For example, in China, only about 40% of the phosphorus mined in the rock phosphate ends up being used as phosphorus fertilisers, the 60% of remaining material is stockpiled or dumped (Zhang et al, 2008). The million

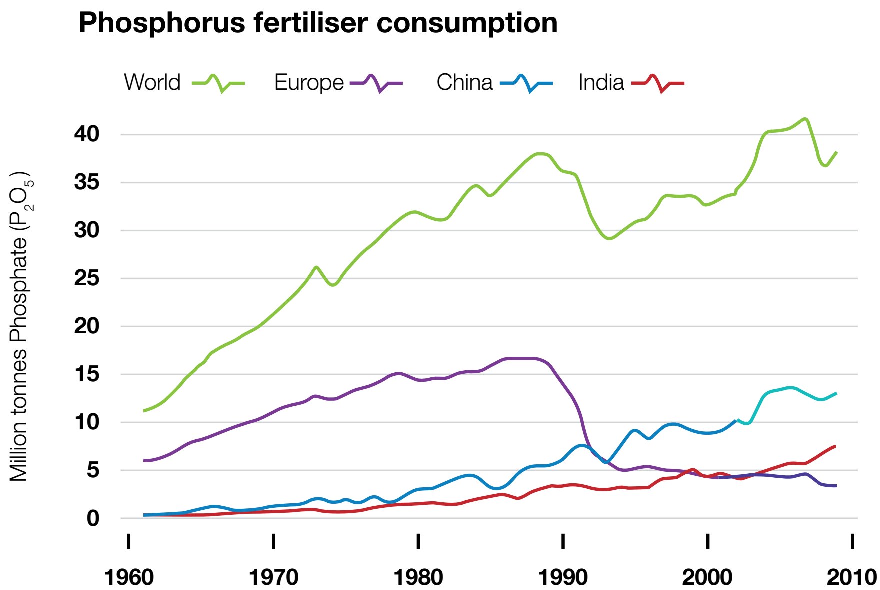

Figure 2. Phosphate fertiliser consumption in the world and in China, India and Europe from 1961 to 2009. There has been a steady global increase in phosphorus consumption, while in 1995 there was a brief reduction in the mineral phosphorus use by 21% due to the economic crisis in ex-communist countries and environmental restrictions in Western European countries. After 1995 there was another increase in world phosphate use mainly caused by the development of fertiliser use in Asia, especially steeper in China. [Data source is FAOSTAT 2012. FAO discourage the combination of the two datasets presented here (1961-2002 and 2002-2009) due to discontinuity in methodology in the time series. They are presented here for illustration only, acknowledging they represent distinct datasets.] [1]

tonnes of mine waste resulting from phosphate rock mining and processing contain significant levels of contamination (from radioactivity to heavy metals). Phosphate rock contains radionuclides of uranium and thorium, and the surroundings of phosphate mines often show increase radioactivity from various chemical elements (Cordell et al, 2009). For example, a study in phosphate mining areas in Syria found levels of radioactivity in air and soil sampled around mines was much higher than natural levels (Othman and Al-Masri, 2007). This study considered radon gas, a radioactive gas, to be the main hazard to workers and public in the area of phosphate mines. The study concluded that the phosphate industry in Syria (both mining and processing of phosphate ore) is the main source of enhancement of naturally occurring radionuclides in the Syrian environment. Another study on radioactive contamination from phosphate mining was conducted on the Red Sea coast (El Mamoney and Khater, 2004). Samples of sediment in the region of Safaga-Quseir-Marsa Alam city had elevated levels of radioactivity (radium) and it is possible that this can be attributed to phosphate mining in the Safaga-Quseir region.

After phosphate rock has been mined, it is processed and the by-product of this process is phosphogypsum. Phosphogypsum contains appreciable quantities of uranium and its decay products, such as radium-226, due to the high content of these substances in phosphate ores (EPA, 2011). Phosphogypsum stockpiles are growing by over 110 million tonnes every year and there is a risk of leakage to groundwater (Cordell et al, 2009). Phosphogypsum also contains significant amounts of the heavy metal cadmium and of fluoride. From 1961 to 2003, the processing of rock phosphate in China accumulated about 5 kg of phosphogypsum for each kg of final high-grade phosphate produced (P_2O_5) (Zhang et al, 2008). Although most of the radioactivity is contained within the phosphogypsum, some ends up in the phosphate fertiliser. If crushed phosphate rock is applied to agricultural soils, there is a risk of over-exposure to farmers and phosphate industry workers. Currently, radiation levels may vary above and below what is deemed as an acceptable level of radiation, but there is no standard procedure for monitoring radioactivity on land due to applied phosphate rock or phosphate fertilisers. Even so, crushed rock phosphate is permitted for use as a fertiliser in conventional and organic agriculture in most of the world.

Levels of radioactivity in phosphate fertilisers vary widely worldwide (Khater and Al-Sewaidan, 2008). High levels of radioactivity (radium) in phosphate fertilisers from Brazil has been found, which is of concern because of the potential contribution of radioactivity to agricultural lands (Saueia et al, 2005). However, this contribution is not easily quantified because the quantity of radioactivity spread along with the fertilisers in agricultural fields depends upon the quantity of fertiliser used, the type of crop and area of its cultivation. Conversely, another study in Brazil found that radionucluide levels in Brazilian fertilisers fell within worldwide levels and calculated that fertilisers applied to Brazilian crops do not raise the concentration of radionuclides in soils to harmful levels (da Conceciāo and Bonotto, 2006). Similarly, measured radioactivity in phosphate fertilisers from Saudi Arabia and estimated public radiation exposure from their use as agricultural fertilisers was found to be negligible in another review (Khater and Al-Sewaidan, 2008).

Other studies also indicate that the application of phosphate fertilisers to agricultural land does not significantly affect the dose received by farmers and the general population (Righi et al, 2005). However, it is also important to point out that it is not yet known which long-term consequences might stem from the release of these small amounts of natural radioactivity (Righi et al, 2005). It is possible that continued application of phosphate fertilisers to soil over a period of many years could eventually raise the uranium and radium content of the soil. These authors concluded: “therefore, it is not possible to exclude that, over the long period, a prolonged use of fertilisers containing natural radionuclides might induce significant radiological impacts on the environment”. In addition, use of phosphate fertilisers for prolonged periods may thus entail “a possible dose increase to the population”.

Significant levels of uranium have been found in the groundwater in the intensively farmed state of Punjab in India (Mehra et al, 2007). Sources of this uranium are uncertain, and potentially might include fly ash from two large coal thermal plants in the state. However, recently a newspaper article claimed that the Indian Bhabha Atomic Research Centre (BARC) reported that the use of phosphate fertilisers might be behind the high uranium found in the groundwater[3].

Another concern with the use of phosphate fertilisers derived from mined phosphate rock is the quantity of the heavy metal cadmium. Cadmium is highly toxic to humans. The transfer of small quantities of heavy metals to soils via phosphate rock fertilisers was first identified in 1973 and was confirmed by analysis of archived soil samples at Rothamsted Agricultural Research Institute (UK). Analysis of the samples confirmed that long-term phosphate fertiliser application was a major source of cadmium in soil (Nziguheba and Smolders, 2008). Application of phosphate fertilisers could, over time, cause cadmium to accumulate in soil and this increases the risk of uptake by crops and transfer through the food chain (Chen et al, 2007).

The phosphate rock is the source of the cadmium in fertilisers and the final concentration of cadmium in fertilisers is not very different from the rock itself. Phosphate rock from China, Florida and Russia is typically low in cadmium whereas many rock phosphates from Africa (Morocco, Togo) contain high cadmium concentrations (Nziguheba and Smolders 2008). In China, in spite of cadmium content in rock phosphate being relatively low, it was been estimated that the cost of reducing this cadmium contamination would reduce gross profits of the entire phosphorus fertiliser industry in about 50% (Zhang et al, 2008).

In Western countries, previous studies estimated that 54–58% of the cadmium found in the environment might come from the application of mineral phosphate fertilisers to agricultural land (Pan et al, 2010), although the current concentrations are estimated to have decreased in Europe more recently (Nziguheba and Smolders 2008). Nevertheless, according to Pan et al (2010), the use of these fertilisers "represents a direct input of cadmium to arable soils and subsequently to the environment as well. Concentrations can be as high as 500 ppm in phosphorites (rock phosphates) used for the manufacture of fertilisers". Accumulation of cadmium in food crops is a great concern due to the increased dietary exposure in consumers (Pan et al, 2010). Recently, the EU has announced a revision of the legislation around permissible cadmium levels in phosphate fertilisers based on concerns about its toxicity in farm soils and food.

A recent study in China has shown that high intensity use of phosphate fertilisers in the Yangtze-Huaihe region of China has led to elevated levels of cadmium in pond sediments of the watershed (Zhang and Shan 2008). Relatively small amounts of phosphate fertiliser were used in the region prior to 1980 but subsequently use increased greatly. Sampling of sediments showed that the average cadmium concentration in 1980 was only 0.13 μg/g but had increased to 0.33 μg/g in 2004. The cadmium levels and their chemical form implied there was a moderately high ecological risk. This was clearly due to extensive use of fertilisers in the region which now "threatens water quality of the watershed and downstream water bodies". Cadmium can accumulate in crops "leading to concentrations in the edible portions of the crop that may be harmful for human health"(Zhang and Shan 2008).

In Sri Lanka, research has been undertaken to assess cadmium levels in agricultural soils and drinking water in the River Mahaweli catchment area after a significantly higher level of chronic renal failure was found in people (mostly rice farmers) in the region. It was found that long-term use of a phosphate fertiliser has contributed to excessive levels of cadmium in the River Mahaweli. The sediments from the river release cadmium into reservoir waters and consequently there is a high level of cadmium in irrigation water and in drinking water that exceeds acceptable levels given by the US EPA (Bandara et al, 2011).

Another chemical element associated with phosphate rock is fluoride. In China, for example, phosphate rock contains relatively high levels of fluoride, and soils and air around phosphate mines showed some enrichment with it (Zhang et al, 2008, WHO, 2006). Fluoride has beneficial effects on teeth at low concentrations in drinking water, but excessive exposure to fluoride in drinking water and/or from other sources, can adversely affect human health (WHO, 2006). Effects range from mild dental fluorosis to crippling skeletal fluorosis[4], a significant cause of morbidity in a number of regions of the world. Increased levels of fluoride in drinking water wells have been associated to high use of phosphate fertilisers, for example in intensive agriculture areas in West Bengal, India (Kundu and Mandal, 2009a, Kundu and Mandal, 2009b).

In conclusion, both mining of phosphate rocks and application of mined phosphorus fertilisers to farm soils implies some level of environmental and health risks. This arises particularly from increased levels of radioactivity in air and soils around phosphorus mines and increased concentration of the heavy metal cadmium in farm soils with long-term application of phosphorus fertilisers. Increased concentration of fluoride associated with phosphate rock or phosphorus fertilisers may also affect human health. All this phosphorus-associated pollution represents a potential health risk for mine workers, farmers and farm labourers directly, and further a potential risk for consumer if pollution is carried upwards the food chain.

03

Peak phosphorus and global trends in phosphate consumption

3.1 The concept of peak phosphorus

In 1956 Hubbert brought to the world's attention the concept of "peak oil": problems arise not when a resource is completely gone, but when the high quality, highly accessible reserves have been depleted.

After production reaches a maximum (its peak) the quality of the remaining reserves decreases and become harder to access, making it increasingly uneconomical to mine and process. The result is that supply declines and prices rapidly rise (Cordell et al, 2009). Some researchers have applied Hubbert's concept of "peak oil" to phosphate rock mining and estimated "peak phosphorus" (Cordell et al, 2009, Cordell et al, 2011b, Van Vuuren et al, 2010). Other researchers have used different methodology to estimate how long phosphate reserves will last (discussed below).

3.2 Estimations of longevity of mined phosphorus reserves

According to recent data from the US Geological Survey (Jasinski 2010), the known global reserves of phosphorus total about 16 billion tonnes and this is currently being mined at a rate of 158 million tonnes (Mt) a year (reserves are defined as that considered recoverable under current economic conditions). A simple calculation from these figures, divides that reserve by current consumption rates to estimate the longevity of phosphate rock. The result, assuming the estimate of reserves and rate of extraction are correct, predicts that we would expect to deplete this resource of phosphate rock in a century (Vaccari and Strigul 2011).

This is very worrying given that much of current farming relies on phosphate rock as fertiliser. The reserve base (resources that have a reasonable potential for becoming economically available within planning horizons beyond those that assume proven technology and current economics) was estimated to be 47,000 Mt, which would be enough to last for 281 years at current production rates (Vaccari and Strigul 2011).

Different researchers have noted that there are significant uncertainties in the simplistic way that the US Geological Survey predicted the longevity of phosphate reserves. For example all resources may not be 100% extractable and demand for phosphate rock is likely to increase as population increases.

To take account of such factors, different studies have calculated "peak phosphorus" based on Hubbert's concept, resulting in various estimates to date:

- Cordell et al (2009) published a peak phosphorus curve based on 2009 US Geological Survey data that estimated the peak year around 2035. A more recent revised peak phosphorus analysis, taking into account a higher reserve figures of 60,000 Mt, showed a probable peak between 2051 and 2092 with a mean of 2070 (Cordell et al, 2011b). While exact timelines may vary, the fundamental problem of phosphorus scarcity would not change.
- Van Vuuren et al (2010) calculated that depletion of extractable phosphate rock is not very likely in the near term. Under best estimates, by 2100, depletion would be around 20-35% (maximum 40-60% of the current reserves and reserve base would be extracted under worst case scenarios). Production costs would have increased as well.
- A different estimate published by the International Centre for Soil Fertility and Agricultural Development calculated much higher reserves (3.8 times the US Geological Survey estimate), and the reserve base as 7.4 times the US Geological Survey estimate (see Vaccari and Strigul 2011). Based on these figures, the reserve would be expected to last an additional 90 years. The reserve base would be sufficient to last over two millennia as opposed to 281 years predicted by US Geological Survey data. If this is the case in reality, then the problem of potential scarcity of rock phosphate is less urgent. But, in any case Vaccari and Strigul (2011) note that phosphate rock is a finite resource subject to eventual depletion.

A recent study suggested that the Hubbert's curve for phosphate rock is not robust for predicting the ultimately recoverable reserves or year of peak production of phosphate. This paper suggested that data other than historical production should be included in forecasts such as expected population growth and economic factors. "More likely what is needed is not an empirical prediction, but rather theoretical models such as those based on discovery of phosphate reserves or economic modelling". The paper suggests that even so, a number of indicators suggest the idea that a peak may be looming. It was suggested that we seek both better models and better data to support out decision-making (Vaccari and Strigul 2011).

Cordell et al (2011) state: "While the critical point in time for phosphorus scarcity is highly uncertain and contested, all agree that demand for phosphorus is growing and remaining phosphate rock is becoming increasingly scarce and expensive". Cordell et al (2009) noted that the fertiliser industry recognises that the quality of the existing phosphate rock is declining, making phosphate more expensive. At the same time, demand of phosphorus fertilisers continues to increase.

Models predict that for coming decades phosphate rock depletion may lead to concentrating production to a few countries, thereby increasing production costs. The main current producers are in North Africa (Morocco, Tunisia, Algeria), China, the US, the Middle East, and Russia. The model results show for the best guess estimate, that by 2050, North African countries would dominate the market with more than half of the global output unless new important resources are identified in other regions. Conversely, production in the US is expected to decrease. It was predicted that the resource base (reserves and reserve base), under worst case scenario, shows that only North African countries would have more than 50% of resource base remaining by 2100 while phosphate resources would be totally depleted in Canada, Central and South America, Western and Central Europe, India, Southeast Asia and Japan. But note that for Central and South America, there may be larger resources in Peru and Mexico than previously estimated (Van Vuuren et al, 2010).

3.3 Recent price increases

It is of concern that prices of phosphate rock have increased substantially in recent years, a phenomenon predicted by the concept of "peak phosphorus". In 2008 prices increased by 800%. They went down quickly, but never to the pre-peak values: prices are now about 4 times higher than they were before 2006 (Figure 3). "Price spikes of phosphate commodities can be expected more frequently making importers in place like, India, Sub-Saharan Africa, Australia and the European Union more vulnerable." (Cordell et al, 2011).

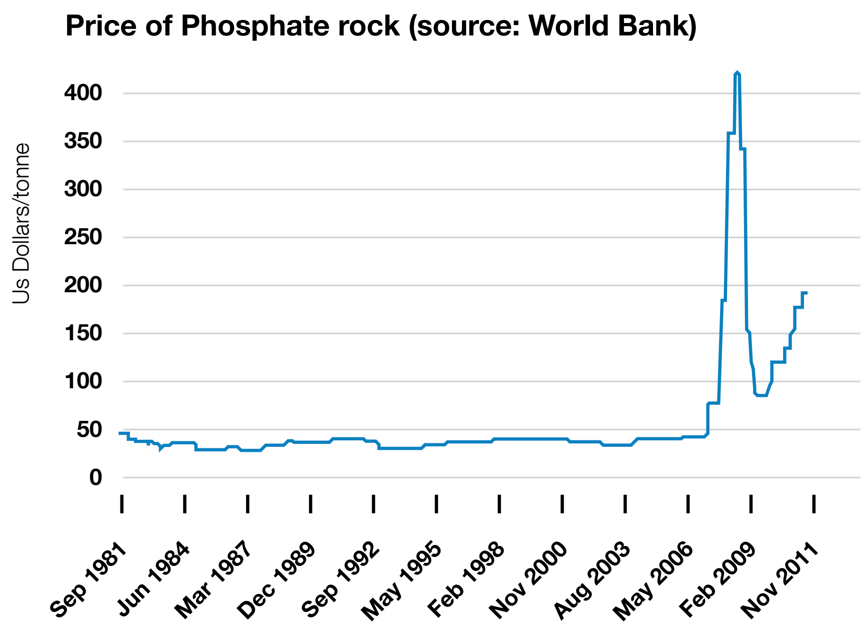

Figure 3. Fluctuations in the price of phosphate rock in commodity markets from 1981 to end of 2011. Data source is http://www.indexmundi.com

3.4 Geopolitical sensitivity

Cordell et al, (2009) noted that, together, Moroccan and Western Sahara reserves represent more than one third of the world's supply of high-quality phosphate, and the last estimates tell of a much higher percentage (Elser and Bennet 2011). US companies import significant amounts of rock from Morocco to make phosphate fertilisers. This is geopolitically sensitive as Morocco currently occupies Western Sahara and controls its phosphate rock reserves. Such trade is contrary to international law and is condemned by the UN. Several Scandinavian companies have boycotted this trade in recent years.

3.5 Environmental considerations

It is often suggested that market forces will lead to new technological developments that will improve the extractability of phosphate rock extraction so that off-shore and low-grade phosphate deposits will become economically viable once the high grade reserves have been depleted. This was considered in the calculations of longevity of phosphate reserves calculations discussed above. However, in a similar fashion to oil extraction, as phosphorus extraction becomes more expensive and difficult, it is also becomes more environmentally damaging. For example, after the price peak in 2008 some companies started to invest in lower grade reserve mining. However, in addition to being much more expensive, mining lower grade reserves will pollute soils with cadmium, which is highly toxic to plant and animal life, even in low doses (Gilbert 2009).

One potential improvement is that mining of phosphorus could be made more efficient. Syers et al (2011) wrote: "New management systems have been responsible for improved environmental performance, which also yields economic benefits. Increasing phosphorus recovery during mining operations can extend the life expectancy of reserves". Work is currently being carried out to recycle the process water and treat the waste stream of the mining operation to increase recovery rate (Syers et al, 2011).

04

Use and overuse of phosphate fertilisers in agriculture

4.1 Phosphorus flows through global food production and consumption

Recent analysis of the flow of phosphorus from "farm to fork" illustrated the amount of phosphorus that is "lost" along the way when passing from mine to field to fork (Cordell et al 2009, 2011). We have summarised this flow in a simplified figure, focusing on the agriculture system's losses. From this, it is possible to visualise where interventions for a more sustainable use of phosphorus could focus (based on absolute and relative inefficiencies within each subsystem) (Figure 4). The losses are significant, and overall major losses in absolute amounts are concentrated in two main subsystems: arable land and livestock production.

Arable land losses are due to inefficiencies in farm management: 33% of the phosphorus entering the soil is lost by erosion (both wind and water). Only between 15-30% of the applied phosphorus fertiliser is actually taken up by harvested crops. Losses at the livestock production level are mostly due to improper management of manure, about half of the phosphorus entering the livestock system is lost into the environment instead of reapplied to farm soil where it could be used by subsequent crops.

Both sectors (arable and livestock) have also internal low efficiencies in the use of phosphorus (33% and 45% losses, respectively). Humans are the other subsystem where absolute losses are not very large, but relative capture of phosphorus into the agriculture system is very low (90% is lost) (see Figure 4). On a worldwide scale, we are mining five times the amount of phosphorus that humans are consuming in food, and only about one tenth of the phosphorus entering the agriculture system is actually consumed by humans.

Overall, about 90% of the phosphorus entering the system is lost into the environment. Because of the increasing scarcity of high-grade phosphate reserves, and the huge problem of losses to surface waters and subsequent nutrient pollution and eutrophication (see section 4.2, 4.3), it is imperative that we "close the loop" on the losses of phosphorus. In order to achieve a sustainable use of phosphorus, two main strategies should be apply to any system (options for closing the phosphorus cycle are developed further in Section 5):

1) Stop or minimise losses, by increasing efficiency in the use of phosphorus, mostly in arable land and the food chain. Additionally, sustainable phosphorus-use will benefit from shifting to plant-rich diets that are more efficient users of phosphorus (and other resources) than meat-rich diets, and from minimising food waste.

2) Maximise recovery and reuse of phosphorus, mostly of animal and human excreta, and thus minimise the need for mined phosphorus (see further in section 5).

4.2 Phosphorus in soil and the process of loss to water

Phosphorus within the soil maybe in solution in water or bound to the soil particles themselves: the more strongly phosphorus is bounded to a soil particle, the less available it is for uptake by plant roots.

Scientists describe phosphorus in soils as existing in four different "pools" on the basis of their accessibility to plants (Syers et al, 2008):

- The first pool of phosphorus is that which is in the soil solution and is immediately available for uptake by plants.
- The second pool is that phosphorus which is held on sites on the surface of soil particles. This phosphorus can be readily transferred into soil solution for uptake by plants if the concentration of phosphorus in the soil solution is lowered by plants uptaking the phosphorus already in solution.
- The third pool of phosphorus is more strongly adsorbed to the soil particles and is less readily extractable by plants but it can become available to plants over time.
- The phosphorus in the fourth pool is very strongly bonded to the soil components and is only very slowly available to plants for uptake, often over a period of many years.

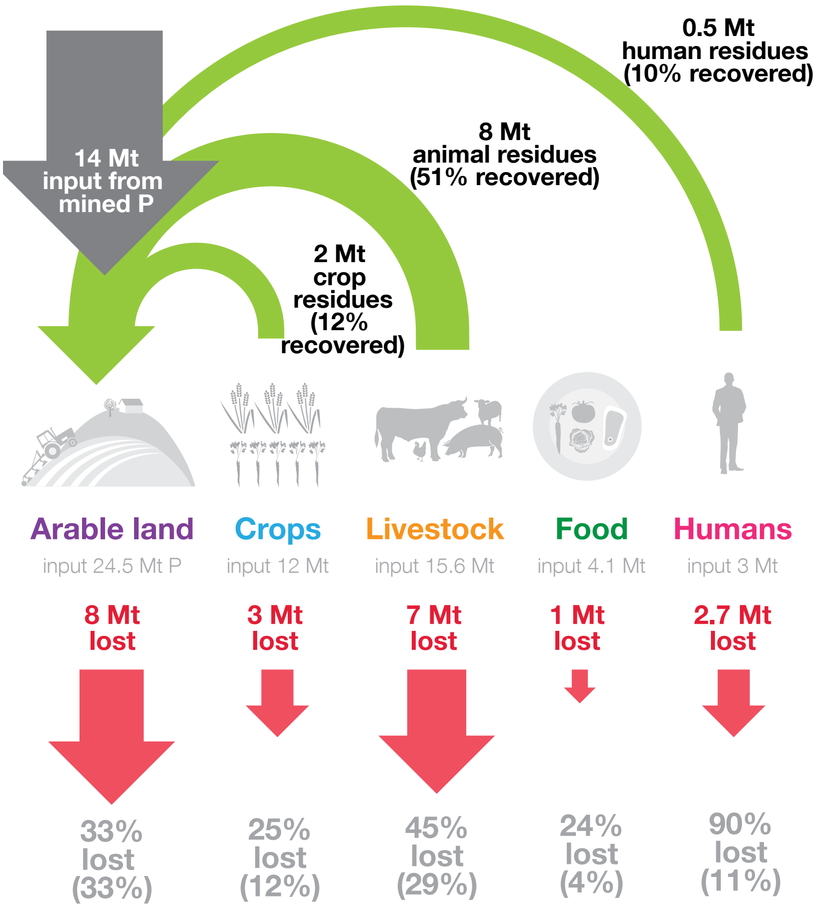

Figure 4. Simplified cycle of phosphorus in agriculture based on data from Cordell et al, 2009 and Cordell et al, 2011. Red arrows represent losses into water systems ultimately, and green arrows represent current recoveries into arable land from the different subsystems. The percentages under the red arrows represent the percentage losses from each subsystem, and shown in brackets are the percentage losses relative to the total input into agriculture land. For example, the livestock system loses about 45% of the phosphorus entering the livestock system itself, and this represents about a 29% loss of the phosphorus entering the agriculture system overall. (We have excluded the flow up to the input into farm system, but for example, losses in phosphorus mining and processing can also be significant.)

When a fertiliser containing water-soluble phosphorus is added to soil, only a small proportion (15-25%) remains in the soil solution (pool 1) and is immediately available to plants, most is stored between the readily-available and less readily available pools (pools 2, 3 and 4) and can only be used by plants later on. Experiments show that the phosphorus in the readily available pool (pool 2) supplies the bulk of available phosphorus to plants. Therefore it is only necessary to accumulate a certain amount of phosphorus in pool 2 to achieve optimal yield of the crop. When too much fertiliser is applied, the soil cannot hold increasing amounts of phosphate in the insoluble form without that in soluble form also increasing. This increases the risk that phosphate will be lost via soil run-off or leaching through the soil (Soil Association, 2010).

This is in agreement with the concept that there is a "critical phosphorus" value for specific crops, above which, there are no further increases in crop yield. Applying just the "critical" amount of phosphorus to a specific soil growing a given crop is the most efficient use of phosphorus fertiliser (see further section 5.1). But, applying excessive fertiliser to a soil can result in losses of phosphate to ditches, streams and rivers and lakes, causing negative effects on waterways due to excessive nutrients and eutrophication (Syers et al, 2008). Applying excessive fertiliser also represents financial loss to farmers. It is therefore very important that only the most efficient, minimum amount of phosphorus fertiliser is applied. Testing soils to calculate the exact amount of fertiliser to add is an effective tool in avoiding phosphorus overuse.

Soil erosion by wind or water occurs especially on heavy textured soils subject to severe cracking or drying, sandy soils, hilly areas, and in areas without vegetation cover due to overgrazing, for example (Johnston and Dawson 2005). Phosphorus losses by water erosion include runoff and drainage processes after rainfall events. It is a particular problem when rainfall occurs soon after fertiliser or manures have been applied to the soil.

Phosphorus loss from agriculture can come from both point and diffuse sources (Figure 4).

Diffuse sources are usually spread over larger areas and relate to farm fields where phosphorus is lost mostly by wind or water erosion. Diffuse sources usually have low concentration of phosphorus over a large area, and thus high volume of flow (Johnston and Steén, 2001). Losses of phosphorus in arable soils account for about one third of all phosphorus entering the agriculture system (Figure 4).

Point sources are concentrated in specific locations and usually have a high concentration of phosphorus and a low volume of flow. Examples of point sources of phosphorus pollution are manure stores and wastewater from livestock farms. High phosphorus loading can occur when animals are kept close to streams and water bodies (James et al, 2007). Losses of phosphorus in manure account for about half of the phosphorus entering the livestock system.

Dairy farms can be high contributors of phosphorus to the surface waters. A study by Ghebremicheal and Watzin (2011) looked in detail at phosphorus balances from three different dairy farms in Vermont, USA. The study used a model to assess the phosphate balance for each farm. All three dairy farms had a positive phosphate balance implying that more phosphate is being imported onto the farm than exported off the farm. However, the balances differed significantly. A small organic farm had the lowest balance of 5.5 kg phosphorus/hectare, a medium-sized conventional farm a balance of 15.2 kg phosphorus/hectare and a large intensive farm had a surplus of 18.7 kg phosphorus/hectare.

The study found that there were a number of reasons why dairy farms can to accrue large positive balances of phosphorus. These included when "there is a high animal density with insufficient land area for forage production and for manure application" i.e. farms with a low animal density are less likely to have a shortage of cropland area to recycle manure phosphate produced on the farm and conversely those with high animal densities do not; "overfeeding of mineral phosphate supplements"; "under utilisation of farm land coupled with a lower use of home-grown feed in animal diets; reliance on purchased protein and energy feed supplements to meet animal requirements for growth and production".

4.3 Losses of phosphorus from fertilised land in different countries and eutrophication of surface waters

In the last 50 years, the quantity of mineral phosphorus used has tripled worldwide (Figure 2). Even though there are differences in use of phosphate fertilisers and manures between different countries, and differences in climate and erosion patterns that influence pollution of surface waters with phosphorus, it is clear that eutrophication is a major and common problem worldwide. We look more in detail to eutrophication problems both in European and Asian countries.

In Europe, it was estimated that "with no human activity, it is estimated that phosphorus levels in water would only be 5-10% of current amounts" (Johnston and Steen 2001).

It is known that the phosphorus originating from crop production and animal husbandry is a major contributor to the eutrophication of lakes, rivers and coastal waters. Overall, losses from the agriculture system (both arable land and livestock systems) account for more than half the losses in phosphorus to the environment (Figure 4). The phosphorus losses to surface waters may however be very different due to the diversity of agricultural production systems practised under contrasting environmental conditions (Ekholm et al, 2005). Both phosphorus and nitrogen loadings are responsible for eutrophication worldwide. Nitrogen seems to be a more important pollutant in estuaries and other marine areas (Diaz et al, 2004, UNEP and WHRC 2007), while phosphorus seems to contribute to eutrophication especially in freshwaters. However, this distinction is not clear-cut and in many cases nitrogen and phosphorus pollution interact, so that the integrated management of both is needed in addressing environmental impacts (UNEP and WHRC 2007). The amount of phosphorus entering the environment in streams, rivers, lakes and oceans depends in the balance of phosphorus entering and leaving any particular system. A positive surplus occurs when the phosphorus inputs (mineral fertiliser, manure, atmospheric phosphorus and phosphorus in seeds) are higher than the outputs (phosphate in harvested crops and grazed vegetation). However, due to the relative immobility of phosphorus in soils, a surplus of phosphorus might not represent an immediate loss into rivers or streams because phosphorus can remain stored in the soil pool. In the same way a negative balance is not guarantee of zero losses since dissolved or particulate phosphorus can have left the soil pool through leaching or run off. The latest estimates of surplus phosphorus in Europe record losses of about 7 kg phosphorus per hectare, and ranges from close to zero in Eastern Europe to about 20 kg phosphorus per hectare in Belgium, the Netherlands and Portugal (Schröder et al, 2011 based on OECD data for 2004).

Phosphate surpluses and deficits have been estimated for many regions of the world, but there is a limited understanding at the global level. Global studies of phosphorus imbalances found that phosphorus deficits covered 29% of the global cropland area and 71% had overall phosphorus surpluses (McDonald et al, 2011). On average, developing countries had phosphorus deficits during the mid-20th century, but MacDonald et al, (2011) showed that current phosphate fertiliser use may be contributing to soil phosphorus accumulation in some rapidly developing areas, like China together with relatively low phosphorus use efficiency.

High use of chemical fertilisers resulted in a greater proportion of intense phosphorus surpluses globally than manure application. Where there were high concentrations of livestock, there were typically some phosphorus surpluses, while phosphorus deficits were apparent in areas producing forage crops used as livestock feed. The disconnection between livestock and land is behind some of these imbalances in phosphorus use (Naylor et al, 2005). Optimising the use of land for food and livestock in ecological farming systems will help in using nutrients efficiently and avoiding massive losses of phosphorus into the environment (see section 5).

As some of the surplus phosphate accumulates in soil after the crop have been harvested, accounting for this residual soil phosphorus in calculating phosphorus demands for crops will optimise fertilisation rates and projections on future phosphorus demands. Recent research concluded that food production in 2050 will probably require 40% less phosphate than was previously assumed if this residual phosphorus is taking into account by farmers when fertilising crops, especially in regions with a long history of fertiliser surplus (Sattari et al, 2012).

4.3.1 Europe

For Europe, there has been a much more intensive use of phosphate fertilisers and, for a longer time period in the western countries than the central and eastern European (CEE) countries. This has led to higher phosphate surpluses in soils in the western countries compared with the CEE countries. Given the importance of phosphate from fertilisers in causing eutrophication of water bodies, in the majority of EU countries, it has been suggested that a Phosphate Directive should be urgently compiled (Csathó and Radimszky 2009). This should include stopping phosphate fertiliser overuse in the whole of the EU. The European Commission is expected to publish a report on the status of phosphorus issues within Europe in July 2012.

A recent European study attempted to quantify the phosphorus discharged into the European seas for the period 1985 to 2005 (Grizzetti et al, 2011). The study found that the phosphorus exported to coastal waters is significant (0.2-0.3 Tg phosphorus/year) with higher loads located in more intensively farmed agricultural regions. Although there has been a decline in the input of phosphate to agricultural soils in Europe during this time, this was not always reflected by significant reductions in the load of phosphate to the sea, partly because of stocks of nutrients previously accumulated in soils and aquifers.

North-west Europe

A review of phosphorus losses from agriculture and eutrophication in north-west Europe was undertaken for Norway, Sweden, the UK and Ireland by Ulén et al, (2007). Despite a reduction of use of phosphate fertilisers, phosphorus levels in soils remain at a constant and relatively high level. It is known that agriculture is a major contributor of phosphorus to inland and coastal waters in all four countries. Due to intensive agriculture, several lake systems in these countries have become eutrophic. For example, Lake Vansjø in Norway, Lake Ringsjön in Sweden and Lough Neagh in Northern Ireland.

Sweden: Levels of phosphorus in soils in Sweden have been increasing in the 20th century according to soil testing although presently no trends can be detected for the soil surplus. Generally inputs of mineral phosphate fertiliser are low in Sweden. The average total phosphorus loss from agricultural land is estimated to be 0.4 kg per hectare per year. In rivers adjacent to agricultural land, slight decreases in phosphorus (amount 2% per year) were found in streams in the south of the country. Grassed buffer strips along rivers are being tested to improve water quality.

Regulations on livestock densities and phosphate application rates are used to reduce phosphorus inputs in Sweden. However, agriculture in the south of Sweden is a still a significant source (40%) of phosphorus entering the Baltic Sea and the input is enough to be a cause for concern (Ulén et al, 2007).

Norway: Levels of phosphorus in soils in Norway have been increasing in the 20th century according to soil testing. For arable farms in Norway, current phosphorus applications generate a surplus of 8 kg per hectare per year. For intensive livestock farming, the surplus is 20 kg per hectare per year. At present the phosphorus surplus is stable. Losses from agricultural land are 0.3 to 2.6 kg per hectare per year. Losses for potato and vegetable growing areas can be high. There have been decreases in phosphorus loss to streams and rivers in some areas as a result of measures implemented to reduce phosphorus loss from agriculture. Several economic incentives related to phosphate application in fertiliser and manure have been introduced. The main focus has been on reducing erosion rather than on nutrient application rate (Ulén et al, 2007).

UK: In England, there has been a reduction in soil surplus phosphorus since 1975 as a result of increasing crop yields and phosphate off takes, while fertiliser and manure inputs have remained fairly constant. In addition, over the last 20–25 years, phosphorus surpluses in the UK have declined further by about 50% due to reductions in phosphate fertiliser use due to falling farm incomes and increasing fertiliser costs. Studies of river catchments show total phosphorus losses from agricultural areas in the UK are around 0.2 to 6 kg per hectare per year. In 2004 there was a major government initiative in the UK that aimed to reduce agricultural inputs of phosphate to waters in England and Wales. It does not use blanket reductions in emissions to achieve its ends but instead focuses on high risk areas and the ecological sensitivity of receiving waters (Ulén et al, 2007).

Ireland: In Ireland, levels of phosphorus in soils have increased tenfold over the past 50 years as a result of the intensive use of fertilisers. There is still a soil surplus input of 8.3 kg per hectare per year although the mineral phosphate input has decreased. High phosphorus losses are associated with a history of fertiliser inputs combined with intensive grazing. Total phosphorus loss to waterways from agricultural land in Ireland is estimated to be 0.5 kg per hectare per year. There has been an increase in pollution of rivers in Ireland and this is mainly attributed to eutrophication.

Since 1997, there has been a target to reduce phosphate fertiliser use and good progress has been made, especially since 2000 the situation has improved (Ulén et al, 2007).

Southern Europe

Torrent et al (2007) undertook a review of phosphorus losses from agriculture and of eutrophication in southern Europe (including Portugal, Spain, France, Italy, Former Yugoslavia, Albania, and Greece). The inputs of fertiliser into agricultural soils of southern European countries are less than those in other European countries. However, inputs of phosphorus are higher than the amount of phosphorus taken out by crops and grazing, which results in high amounts of phosphorus accumulating in some areas. Surplus phosphorus inputs are approximately 5kg phosphorus per hectare per year for Greece, 10 kg phosphorus per hectare per year for Portugal, Spain and former Yugoslavia, and 15–20 kg phosphorus per hectare per year for France and Italy. These are average figures and do not reflect the true picture. In intensive horticulture and where animal production is concentrated greater phosphate surpluses occur. For example, for intensive animal production in the Po Valley, Italy, a 2003 study reported surplus phosphorus inputs of 112 kg phosphorus per hectare per year. Conversely areas of extensive grazing or cereal dry-farming have a modest phosphorus surplus or are in balance.

In general, phosphate losses via erosion and surface runoff are the most prevalent losses and by far outweigh losses by drainage. After the dry summer season, with little crop and vegetative cover remaining, the autumn rains, often intense showers, fall on unprotected soil and cause runoff and soil erosion. In addition, croplands are often on sloping areas where the risk of erosion is high. The most extreme autumn rainfall occurs in Italy. Extreme rainfall events in some countries are limited but can be responsible for high nutrient losses from soil. In north-east Spain in 2000, an extreme rainfall event caused losses of 109 kg phosphorus per hectare. Losses can also be substantial in autumn rains on arable land because phosphate mineral fertilisers are often applied in autumn. Soil loss rates are highly variable. Soil management can greatly influence losses. Research shows that using conservative tillage systems in which the soil surface is protected by at least 30% residue cover limits soil and phosphorus losses. Such systems are gradually now gaining acceptance in some Southern European countries (Torrent et al, 2007).

Available data on the quality of water in rivers, lakes and reservoirs suggests that eutrophication caused by agricultural phosphorus is common. In some rivers, industrial effluent is dominant such as the river Ebro in Spain, but where the river runs mainly in agricultural areas, for example, in Galicia in north-west Spain, phosphorus pollution is mainly from arable land and pasture (50–60%) and intensive livestock production (20–30%). In the river Po in northern Italy, greater than 90% of the phosphorus is due to agricultural inputs, 50,000 tonnes phosphate per year from animal husbandry and 90,000 tonnes phosphate per year from arable land (Torrent et al, 2007).

Implementation and adoption of soil conservation measures and other good agricultural practices by farmers are crucial if an agricultural loss to surface waters is to be reduced. To date, adoption of such measures has been slow or non-existent in many vulnerable areas, even though farmers, planners and the public know the problem.

<u>Central and eastern Europe (CEE)</u>

Phosphate fertiliser use in CEE did not start until the 1960s. By the 1980s, phosphate balances were positive, ranging from 4 to 31 kg per hectare. But in 1990 there was a rapid decline in fertiliser use and phosphate balances in soil fell such that they now ranged from -7 to +7 kg per hectare phosphorus (Csathó and Radimszky 2009). This can be partly attributed to the fact that the substantial phosphate carry-over effects still make it possible for the crops to extract large quantities of phosphorus, resulting in relatively high yields (Csathó and Radimszky 2009).

CEE countries typically have low amounts of applied mineral fertilisers and manure (5 kg phosphate per hectare) compared with western European countries. The only exception is Slovenia, which is higher than other CEE countries (20 kg phosphate per hectare). The phosphate balance in western European countries is generally much higher than that in CEE countries. Due to a decline in fertiliser use since the 1990s, the balance of phosphorus in soils in CEE countries declined from 1980 peak values. Generally it can be concluded that the potential for losses of phosphate to water is much less in CEE countries than in western Europe because of lower reserves of phosphorus in soils (Csathó et al, 2007).

The Danube river system is the heartland of CEE. It crosses Germany, Austria, Slovakia, Hungary, Croatia, Serbia, Kosovo, Ukraine, Moldova, Romania and Bulgaria. The phosphorus load going into the Danube has reduced considerably since the late 1980s but levels are still higher than values recorded in the 1960s. Research shows that the amount of phosphorus going into the Danube from agriculture in Slovakia, Croatia and Hungary is small (9-10% of the total phosphorus load). Research shows that the water quality in most small rivers in CEE countries is good. There are a few exceptions that are more polluted: the Morava, the Dyjein in Slovakia and the Hungarian rivers, Tisza and Sió. For most CEE rivers, point sources account for the majority of the phosphorus load, but the load from diffuse agricultural sources has become relatively more significant due mainly to improved purification of urban wastewater (Csathó et al, 2007).

For lakes, the average eutrophication status is worse than that of rivers in CEE countries. This may be because the lakes are relatively small and even small phosphorus losses to the lakes become significant. Work to reduce phosphorus losses to lakes has been successful in several countries. Measures of eutrophication status in the Baltic Sea for Baltic CEE countries are moderate. The Mediterranean is prone to eutrophication events some of them severe. The study by Csathó et al (2007) concludes that if declining levels of phosphorus in soils continues, this will lead to lower crop yields and economic decline in rural areas of CEE.

4.3.2 China

China encourages fertiliser production and use, under the assumption that this will help raise food production in the country. As a result of economic incentives, fertiliser production in China has increased dramatically over the past two decades and there has been excessive fertiliser use in many areas of China. The efficiency of fertiliser use has been low and accumulation in soils and pollution in water has been high (Ma et al, 2011).

Ma et al (2011) looked at phosphorus flows in China's main crops in 2004. About 80% of phosphorus inputs originated from chemical fertilisers. The study calculated that the surplus of phosphate fertiliser for wheat, rice and maize crops was 29.4, 13.6 and 21.3 kg phosphorus per hectare, respectively. These amounts are an order of magnitude higher than average losses in Western Europe, for example (Schroder et al, 2011, although crops-specific comparisons will be needed to assess the real differences). Recycling via animal manures has not been efficient since using animal manures is no longer considered vital for satisfactory crop yields.

High usage of phosphate fertiliser and resulting high levels of phosphorus in soils leads to high amounts being lost from fields to waterways. In China, this has led to immense threats to the environment, as in widespread eutrophication of water bodies (Ma et al, 2011).

The Yangtze floodplain in China accounts for 44% of the total paddy area and total rice production in China. Application rates of phosphorus to the soils are high and excessive nutrients in the paddy fields are discharged into surrounding water, which results in pollution of Yangtze floodplain lakes. Application of chemical fertilisers in this region should decrease in order to reduce pollution. In addition, vegetative buffer strips between crops and surrounding water bodies are a way to trapping nutrients that could be used (Liu et al, 2011, Le et al, 2010).

Pollution of the many inland lakes in China became serious in the 1980s when the national economy underwent rapid development (Le et al, 2010). Since then, there have been frequent algal blooms in the lakes. Of the 67 main inland lakes in China, 49 or roughly three quarters are now severely eutrophied according to a 2006 study (Le et al, 2010). Another survey of 50 lakes in the middle to lower reaches of the Yangtze River reported that the majority of them were seriously eutrophied. In recent years, there has been emphasis on dealing with point source pollution to the lakes from industrial wastewater. However, nutrients of nitrogen and phosphorus from agricultural fields and also from untreated sewage have now become the main contributors to lake eutrophication.

For example, for Lake Tai, phosphorus from agricultural practices accounts for 39% of the total phosphorus entering the lake according to a 2003 study (Hu 2003, as cited in Le et al, 2010). For Lake Dian, surface run off and agricultural production contribute over 70% of the nitrogen and phosphorus entering the lake according to a 2002 study (Guo and Sun, 2002). Le et al (2010) concluded that controlling non-point sources of phosphorus to the land, including agricultural nutrients, needed to be tackled to prevent lake eutrophication. Additionally, construction of wetland protection zones around lakes to absorb residual nitrogen and phosphorus could help in the short term.

Gerber et al (2005) investigated phosphate balances from animal farming in Asia. The study found typically high concentrations of animal farming around urban centres. Manure from animals represented more than half the phosphate surplus on the land in north-eastern and south-eastern China and was high at the periphery of some urban centres.

This study suggested that there is a great potential for better integration of crop and livestock activities, like substituting chemical fertilisers by animal manure, thereby decreasing the environmental impacts on land and surface waters. This would require adequate policy frameworks and technological packages to help implement practically.

4.3.3 India

India was mostly reliant on organic manure as fertiliser until the middle of the 20th century. After the introduction of high yielding crop varieties and the development of irrigation facilities during the 1960s, the consumption of chemical fertilisers increased significantly. A recent study looked at nutrient budgets for India for the first time, using figures from 2000-2001 (Pathak et al, 2010). The study found that addition of phosphorus in the form of manure is small in most of the states and inorganic mineral phosphate fertiliser accounted for 78% of the phosphorus inputs. Annual removal of phosphorus through crop uptake was estimated to be 1.27 Mt and there was an overall positive balance of 1.02 Mt phosphorus in agricultural soils of India, so that we can roughly estimate that only 0.25 Mt of phosphorus, or 20% of the phosphorus applied, is recovered in the crop. The majority of states had a positive phosphorus balance (surplus), while a few small states had slightly negative balance, and the state of Madhya Pradesh was the most negative (balance of 0.05 Mt phosphorus). The study predicted, however, that consumption of phosphorus fertiliser will increase in the future and use efficiency will have to improve in order to feed a growing population. It was also suggested that increased use of manures would help and for this, there is a need to "promote a more dynamic manure market". Presently, the manure market in India is unorganized and localised manure price has been higher than chemical fertiliser in terms of nutrients. At the same time, the chemical fertiliser market is state-supported (subsidised prices).

A few studies have looked at contamination of groundwater from agricultural practices in India and Sri Lanka:

- A study on groundwater quality from wells in Palar and Cheyyar River basin, Tamil Nadu, India, investigated possible contamination of groundwater in this intensive agricultural area (Rajmohan and Elango, 2005). Results showed that 35% of the 43 samples taken exceeded the phosphate limit of drinking water standards and were deemed unfit for human consumption. The contamination was assigned to agricultural activities in the region and recommended efforts should be made to advise the use of efficiency of fertilisers.
- A study of nutrients in groundwater was carried out in the agricultural region of north-central and north-western areas of Sri Lanka (Young et al, 2010). The study noted that information from government and individual farmers indicates that the use of fertiliser application rates may be six to ten times higher than levels recommended by government. Despite excessive use of phosphate fertilisers the groundwater was not found to be contaminated above drinking water standards. However, high levels (>21.7 mg/l) were found in some lakes where eutrophication was evident. These high values are likely due to excessive fertiliser use and possibly also due to livestock using the lakes (Young et al, 2010).
- Another study in Sri Lanka looked at nutrient contamination of water from aquifers of Kalpitiya peninsula where agricultural activities are intense (Jayasingha et al, 2011). Low phosphate concentrations were found in the groundwater and surface soils indicating that phosphate was probably adsorbed in clayey deep soils, or that there was less use of fertiliser in the regions.

In 2007–8 the extreme price increases for phosphate mineral fertiliser took the world by surprise. In India, which is totally dependent on phosphate imports, there were farmers' riots and deaths due to the severe national shortage of phosphorus fertilisers.

05

Solutions for a broken phosphorus cycle

Ensuring phosphorus remains available for food production by future generations and preventing pollution with phosphorus in water systems requires actions in two main areas: reducing phosphorus losses, especially from agriculture lands, and increasing phosphorus recovery and reuse to agriculture lands. As illustrated in Figure 4, to close the broken phosphorus cycle, major actions are needed both in arable land and livestock systems (and in smaller magnitude, in the industrial, food and sewage sectors).

Actions required could be outlined as:

Reduce losses of phosphorus (increasing efficiency of phosphorus use)

1. Reduce phosphorus losses in arable land
   a) Stop overuse of phosphorus fertiliser: minimise mineral phosphorus use and optimise land use (optimise the trade-off between yield and ecological services)
   b) Avoid phosphorus losses from cropland soils: avoid erosion by improving soil management (cover crops, buffer strips) and improve soil quality
2. Reduce phosphorus losses in livestock systems
   a) Maximise use of phosphorus in manure for soil fertility in croplands and pastures
   b) Adjust livestock diets

Increase recovery and reuse of phosphorus

1. Recover phosphorus currently lost in livestock manure
2. Recover phosphorus currently lost in human excreta and other organic wastes

5.1 Reduce losses of phosphorus (increasing efficiency of phosphorus use)

5.1.1 Reduce phosphorus losses in arable land

a) Stop over use of phosphorus fertiliser, minimise mineral phosphorus use and optimise land use (maximise trade-off and synergies between yield and ecological services)

Losses of phosphorus are often larger when soils are enriched with phosphorus than when phosphorus levels are kept at levels just sufficient to give optimum crop yields (Johnston and Steén 2001). This is the “critical value” of phosphorus, above which phosphorus is lost, and thus it becomes a waste of money for farmers now and a waste of this scarce resource for the future.

According to FAO, identifying the critical level of plant-available phosphorus that a crop needs is one of the most effective ways to increase the efficiency of fertiliser use (Syers et al, 2008). “Below the critical value yield is lost. Above the critical value there is no justification for applying more phosphorus and such applications use phosphorus inefficiently.” Farmers should aim at maintaining phosphorus levels in the soil that ensure economically optimal yields while diminishing risk of phosphorus losses to surface water. For that aim, policies and capacity building that enables farmers to decide in critical values of phosphorus soil nutrition are needed. Depending on the specific situation, this might include periodical testing of soils and closely monitoring phosphorus inputs and outputs in the farm, plus accepting a time-lag in achieving high phosphorus-use efficiency (Syers et al, 2008). Supporting farmers in any interventions to reduce phosphorus overuse is a first necessary step.

In some regions, especially developing countries, phosphorus levels in soils are low, and for optimal yield farmers need to increase phosphorus in the soil. However, in the majority of farming regions many soils are at or near the critical level (Syers et al, 2008). A recent global average estimated surpluses of phosphorus in 70% of global agriculture lands, while 30% showed phosphorus deficits (MacDonald et al, 2011). Surprisingly, phosphorus deficits in Africa are lower than previously assumed, and in some cases there is high phosphorus overuse, especially along West Africa (see figures in MacDonald et al, 2011).

Avoiding the overuse of phosphorus in the 70% of the world's agriculture land with phosphorus surpluses will save million of tonnes of phosphorus that will not need to be mined and applied. This will obviously benefit the farmer's finances, the sustainability of phosphorus reserves and prevent losses to water bodies worldwide.

A 2009 study estimated that 70-80% of soils in European countries showed an average high-level phosphorus status and at these locations it would be possible to maintain yields for several years even without phosphorus application (Schröder et al, 2011). In Western Europe, in spite of recent increases in efficiency, generally more phosphorus is added in agriculture than exported from farms (Schröder et al, 2011).

b) Avoid phosphorus losses from cropland soils, avoid erosion by improving soil management (cover crops, buffer strips) and improve soil quality

Phosphorus is lost from arable lands mostly by soil erosion; both by wind and water (see section 4). There are a number of farming practices that serve to prevent soil erosion and subsequent losses of phosphorus to water bodies. But the first priority is maintaining a low phosphorus level in soils, as losses are more extensive when the phosphorus content of the soils is higher. Indeed, the most effective long-term solution to preventing phosphorus losses and water pollution with phosphoprus is to decrease the enrichment of erodible soil (Carpenter and Bennett 2011).

Measures to prevent losses by soil erosion include reduced tillage without removal of crop residues (like the herbicide-free mulching developed for organic systems); terracing on sloping land; cultivation and planting along the contour; and, maintaining a soil cover of actively-growing vegetation or plant residues (Schröder et al, 2011, Soil Association 2010, Syers et al, 2008).

These practices also have benefits for overall soil fertility, nitrogen status and increased soil carbon, all of which benefits the long-term sustainability and resilience of the farm soil (Mäder et al, 2002, Kibblewhite et al, 2008).

Practices that minimise losses of phosphorus by run off include applying phosphorus when soil is best able to capture it, thus avoiding applying phosphate fertilisers or manures to frozen or snow covered land or to soils that are dry and hard or waterlogged (Schröder et al, 2011, Syers et al, 2008). These practices also include placement of fertiliser as close as possible to where the roots of the crop plants are growing (Schröder et al, 2011). In addition, in many places the replanting and restoration of hedgerows, small woodlands, and buffer vegetation around water courses will avoid erosion and offer further synergies with biodiversity restoration.

Adoption of these best practices described above such as precise timing and placement of fertilisers and reduced tillage cultivation urgently need to become more widespread to help reduce losses of phosphate to surface waters (Elser and Bennett, 2011).

Application of manures can also be a source of phosphorus loss, especially because they tend to be applied in large quantities and at inappropriate times to minimal areas of land. Farmers tend to underestimate the potential of phosphorus pollution from manure, as there is a tendency to apply too much increasing the risk of loss to surface waters via runoff and erosion. Practices to avoid phosphorus losses from manure should aim for a low-enough rate, and, for example, "application during heavy rainfall should be avoided and soil cultural practices aimed at improving and maintaining good soil structure should be employed" (Johnston and Dawson, 2005). As with mineral phosphorus fertilisers, farmers need support in implementing policies and practices aimed to avoiding any phosphorus losses from farm soils. With regards to manure, below we address further measures to increase re-use of phosphorus in livestock manure.

Maintaining good soil quality and soil fertility are necessary to assure that phosphorus is available to the crops and that it can be efficiently utilised once it is taken up. Maintaining high soil organic matter, good structure and high biodiversity are all conditions that preclude the best use of phosphorus or any other nutrient added to the soil. Phosphorus stored in organic form is made available to plants by the activity of micro-organisms.

Thus enhancing micro-organism activity by regularly returning organic material (crop residues, composts, manures, etc.) to the soil, increases the cycling and best use of phosphorus (Soil Association 2010).

Phosphorus-solubilising bacteria and mycorrhizas are worthy of further scrutiny in relation to the development of inoculants for use as a mechanism to increase phosphorus availability in pastures and cropland soils from reserves in the soil and/or applied rock phosphate.

Plant root length and root distribution are very important in determining how much phosphate from the soil is available to plants. Maintaining good soil structure to encourage good root development is important especially avoiding compaction of soils that impedes growth. Some crops have particularly deep rooting systems such as chicory and clover and using these crops in rotation can help gain access to phosphorus from deeper in the soil. Also, some crops (e.g. buckwheat, lupin) release chemicals from their roots that make insoluble phosphorus more available to plants and, using such crops in rotation, can make more phosphorus available in soluble form (Soil Association, 2011). It has been suggested that breeding plants with root characteristics that enable efficient uptake of phosphate and, plants that use phosphate efficiently, could be a helpful strategy for agriculture. However, it was noted that finding plants with both traits could be difficult and expensive in breeding programs, and investments may be more effective if aimed at soil and crop management (Schröder et al, 2011).

5.1.2 Reduce phosphorus losses in livestock systems

a) Maximise use of phosphorus in manure for soil fertility in croplands and pastures

The current intensification of livestock systems translate into an increasing decouple between animals and land: animals are grown mostly in confinement in highly concentrated areas while their feed is grown in faraway large expanses of croplands, often continents apart (Naylor et al, 2005). This decoupling creates a large imbalance in nutrients: animals concentrate nutrients in areas far away from the land where these nutrients will be essential to crop production, including their own feed production. Manure is bulky and high in water content, so that is long-distance transport is often unfeasible.

This intensive livestock system brings along large losses of valuable nutrients, including large losses of phosphorus (Figure 4). As summarised in Figure 4, it is estimated that about 45% of the phosphorus entering the livestock system is lost to the environment. Measures to avoid these losses from animal operations should aim for re-linking livestock and land towards a more even distribution of livestock over the area where feed is produced (Naylor et al, 2005). Returning manure to the land where the feed originates is thus very important (Schröder et al, 2011). This goal might need drastic changes in current agriculture systems, including a shift towards mixed livestock-crop farming where manure can be utilised for food production to its maximum. Given that animal production already uses directly or indirectly a shocking 75% of available agricultural land (Foley et al, 2011), and additional high share of all nutrients needed for food production, reducing average global levels of industrial animal production and consumption will be needed.

b) Adjust livestock diets

Livestock farmers usually supply extra mineral phosphorus in the animal's diet as "cheap productivity insurance" and very often this represents overfeeding beyond levels that could be utilised by the animals. However, there is evidence that overfeeding with extra phosphorus has no positive effect on animal productivity (Knowlton et al, 2004). Thus, adjusting phosphorus requirements in diets to the animal real needs is the first imperative in reducing phosphorus losses in livestock systems .

Monogastric animals have a limited capacity to take up phosphorus from their diet, especially when their feed consists mostly on grain, as it is the case in current industrial poultry and pork systems. In order to increase production in these industrial pork systems, farmers often select feedstocks with naturally high phosphate or add phosphate salts to feed. In the EU, particularly high amounts of phosphate are added to feed and this result in high amounts of phosphate in pig manure being discharged (Schröder et al, 2011).

This reflects an unsustainable chain of events. For example in pork factory farms, pigs are fed an inefficient diet high in unavailable phosphorus that results in very inefficient flow of phosphorus out of the livestock system, (in turn resulting in massive problems for pork farmers and the environment). There are some proposals on technical fixes to reduce this loss of phosphorus in manure (see below), but they are just addressing the symptoms and not the cause of the problem. To really reduce the massive environmental problem of high phosphorus losses in pig manure, policies should aim at fixing the industrial meat factory system, including encouraging a sustainable diet that animals can utilise efficiently. In that sense, feeding pigs a diet high in phosphorus from alternative sources, as an omnivore, that could for example feed on vegetable and animal scraps (ensuring this is done safely), will be a move in the right direction (Fairlie 2010). However, this will need changes in current regulations and precautionary measures, i.e. in the EU after the tragedy of mad cow disease.

Techno-fixes for pig factory farms include the widespread practices of adding the enzyme phytase to the pigs' diet. Phytase is an enzyme that allows pigs to utilise some of the excess phosphorus in their concentrated feed, thus reducing the amount of phosphorus in their manure. However, as phosphorus is still entering the system, this is just exporting the problem somewhere away from the pork factory farm.

Another highly publicised solution to factory pork systems is the so-called "Enviropig", a genetically engineered pig with bacteria and mouse genes that express the enzyme

Why adding organic matter to soils is crucial for soil fertility and food production

Practices that make soils richer in organic matter are essential for making food production more resilient and stable. There are four main reasons why addition of organic matter, including crop residues, to soils is vital for food security:

1. **A soil rich in organic matter is needed for the efficient cycling of nutrients and for avoiding nutrient losses.** Major losses in soil nutrients occur from soils low in organic matter. For phosphorus, for example, about half of all the phosphorus applied to farm soils is lost due to wind and water erosion. Maintaining high organic matter in soils, by for example retaining crop residues, is crucial in avoiding erosion and holding nutrients needed for crop's growth (Blanco-Canqui et al, 2009).
2. **A soil rich in organic matter is better able to resist drought and other erratic climatic conditions**, predicted to be more frequent in the future. A soil rich in organic matter needs less water to grow a crop than a soil poor in organic matter. In addition, a soil rich in organic matter is better able to resist floods and torrential rain.

   Crop residues that protect soil from wind and water erosion, and legume intercrops, manure and composts that build soil rich in organic matter help increase water infiltration and greatly increase the ability of soils to store water. Healthy soils rich in organic matter are also less prone to wind or water erosion. A large amount of scientific evidence shows that organic matter is the most important trait in making soils more resistant to drought and able to cope better with less and more erratic rainfall (for a scientific review on drought-resistant soils, see (Tirado & Cotter, 2010).
3. **A soil that sequesters and conserves organic carbon contributes to climate change mitigation**. Improving agriculture soils management and restoring degraded soils by increasing soil organic matter, by for example retaining crop residues, has the potential to take up more than 3,300 Mt CO_2 a year by 2050 (Greenpeace, 2009).
4. **Soil organic matter is needed to support soil life and biodiversity**. Soils managed with ecological farming practices are richer in micro-organisms, earthworms and fungi, which makes the soil less dense, less compacted and with gives it better physical properties for storing water and cycling nutrients (Fließbach et al, 2007; Mäder et al, 2002).

phytase "naturally". Expressing the bacterial enzyme in the pig's saliva enables the pig to utilise more of the phosphorus in the concentrated feed, thus metabolising more phosphorus into its body instead of excreting it in its manure. In addition, of all the uncertainties and risks associated with genetically engineered organisms, this techno-fix does not address the real cause of phosphorus pollution with manure: the concentration of pig confinement facilities and the number of animals in them, and not the pigs themselves. Recently this project to genetically engineer the pig as "Enviropig" has been cancelled as key investors withdrew their support .

Recycling of phosphorus from organic sources in organic agriculture

Most of the practices given above that aim to reduce the use of chemical fertilisers are already employed by farmers who follow organic agriculture practices. The aim in organic agriculture is for sufficient phosphorus to be returned to the soil by the use of farmyard manure and greenwaste composts from organic farming sources. The maintenance of ground cover also reduces the loss of phosphorus from soils. Note that the short-term availability of phosphorus from animal manures is greater than that from rock sources. Management of livestock organic manures and crop residues should aim to achieve maximum recycling of nutrients with minimum losses (Soil Association 2010).

Nearly all organic farms will need inputs of phosphorus and in some countries mineral phosphate fertilisers are permitted as a supplement (Soil Association 2010). Nelson and Janke (2007) noted that although some organic farms have been found to be deficient in soil phosphorus, most are likely to have a phosphate surplus because they rely on manures or composts as nitrogen sources and these are also a good phosphate source. Also, organic farms have been shown in many studies to have an increase organic matter in soils, which improves soil structure and help in plant root formation and effectiveness (Carey et al, 2009, Fließbach et al, 2007).

Other studies have shown how farms relying exclusively in organic fertilisers for soil nutrition results in similar phosphorus levels in soils than farms relying in chemical fertilisers, but organic farms have higher biodiversity of microorganism in the soils (van Diepeningen et al, 2006). Organic matter decomposition increases phosphate availability acting as a phosphate source for crops. In addition, organic farms will often be using practices that promote higher levels of mycorrhizas, which in turn can help uptake of phosphorus by crops (Nelson and Janke 2007). Organic agriculture may also make use of animal bones that have been ground to form bone meal.

Several studies have reported lower total phosphate surplus per hectare in organic dairy farms than conventional dairy farms, for example, in the Netherlands (Thomassen et al, 2008) and in Australia (Gourley et al, 2010). Further, on long-term organic dairy farms in Ontario, Canada, most soils tested low to very low for available phosphate (Martin et al, 2007). An organic dairy farm in Vermont, USA had a lower positive balance of phosphate than two larger conventional dairy farms (Ghebremicheal and Watzin 2011).

Yield differences between organic and conventional agriculture are highly debated and largely dependent on the context of each farming system. The most recent meta-analysis showed, on average, lower yields for organic farms (about 25–20%), but with large variability and dependency on context. Yields range from non-significantly different between organic and conventional farms in fruit crops and oilseed crops, or when organic farms apply best management, to larger yields in conventional farms when operating under optimal conditions (Seufert et al, 2012, de Ponti et al, 2012). Remarkably, data on developing countries is scarce and it limits the ability to conclude on yield differences between organic and conventional farming precisely in the regions where food is most needed and where soil fertility needs working for a better balance. Previous analysis had shown that globally, organic farming can produce, on average, about 30% more food per hectare than conventional agriculture, and in developing countries organic farming can produce about 80% more food per hectare (Badgley et al, 2007).

Many scientists, institutions like FAO, UNEP and farmers associations are documenting remarkable success from organic agriculture in achieving high yields and fighting poverty (Scialabba, 2007; Nellemann et al, 2009; UNEP and UNCTAD, 2008; IAASTD, 2009). More research and development and further funding to develop modern organic farming technologies are needed, but nevertheless there is evidence that farming without chemical fertilisers can still produce enough food for all. This is especially true if we consider a vision aimed at farming with biodiversity, closing nutrient cycles, recycling nutrients from non-conventional sources (sewage, food waste, etc) and with more sustainable diets.

5.2 Increase recovery and reuse of phosphorus

Key to "closing the loop" on current phosphorus losses is the recovery of phosphorus from human and animal wastes, which should be used as a readily available phosphorus resource rather than treated as a waste. Cordell et al (2011) note that: "Phosphorus recovery and re-use can be defined not just as a technology, but as a socio-technical system involving collection and storage, treatment and recovery, transport, refinement and reuse".

Animal wastes that are not efficiently used as fertiliser on the land and incorporated into crops represent a huge potential for recovering phosphorus (and other nutrients) and preventing the high phosphate loss to surface waters from livestock systems (45% of the phosphorus entering the livestock system, see Figure 4).

The potential to recover the phosphorus (and also nitrogen and other nutrients) that is discharged in human sewage and sewage treatment sludge is very high, some estimates put a potential recovery of up to 90% of the nitrogen and phosphorus in human urine and faeces. Currently, about 11% of the phosphorus entering the farm system is discharged in human excreta and not recycled (see Figure 4). Ways to recover this phosphorus are discussed below.

5.2.1 Recover phosphorus currently lost in livestock manure

Animal farmyard manure and slurry are good sources of phosphorus, especially in monogastric animals, and the short-term availability of phosphorus from manure is greater than that from rock phosphate. Animal manure, and other parts of animals such as blood and bones, is widely used as a source of phosphorus fertiliser in many regions of the world (Cordell et al, 2011). Farmyard manure typically contains an estimated 2 kg/t of phosphate for sheep manure, 3.5 kg/t for cattle manure, 7kg/t for pig manure, 13kg/t for poultry layer manure and 25 kg/t from litter of laying hens (Soil Association 2010). Despite their fertiliser potential, a high share of farm animal wastes are often not recycled back to croplands and their phosphate (and other nutrients) are lost to surface waters.

One of the problems of livestock manure, if collected, is that large livestock farms mostly in developed countries with large imports of feed are now often too far away from arable land for transport of these heavy wastes to be economically viable (Elser and Bennett 2011). This presents a challenge but also an opportunity to look into policies aimed at completely redesigning the structure and volume of this damaging animal production system.

For example, the Nitrate Directive in Europe could aim at promoting the full recycling of animal manures back to farm soils and substitution of chemical fertiliser inputs, in addition to promoting the re-coupling of livestock operations and the croplands supplying the feed for them (Naylor et al, 2005). Instead, the Nitrate Directive favours inputs of synthetic fertiliser over animal manure and limits the amount of manure that can be used to reduce the risk of nitrate leaching to the environment. Manure nitrogen has a higher risk of leaching than fertiliser-nitrogen. As a result, many countries in EU have a surplus of manure, which is burnt.

In developing countries, in contrast, there are still many examples where integrated animal and crops farming are the most common farming system. However, farmers often lack incentives to make the best and most efficient use of plant nutrients in animal residues as organic fertilisers. Even in Africa, where about 40% of soils show phosphorus depletion, there are large volumes of livestock manure that end up polluting water systems instead of fertilising productive croplands (MacDonald et al, 2011).

Animal wastes typically have high concentrations of phosphorus and other nutrients together with a high concentration of organic material. Because of the high amount of phosphorus in animal wastes that are currently lost to surface waters, this makes them a prime target for capturing lost phosphorus. Cascading of animal manures into a bioenergy source plus a nutrients source through anaerobic digestion offers some opportunities to add economic value and incentives for their recycling (Rittmann et al, 2011). However, it is important to keep in mind that healthy soils also need inputs of organic carbon to maintain soil fertility and soil health. Thus, bioenergy demands and soil health need complementary, not conflicting solutions.

Although phosphorus recovery from manures needs mostly holistic solutions at the farm level, there are also options for waste streams from industrial animal product operations. To be usable as a fertiliser, the organic form of phosphorus in animal waste needs to be converted to inorganic phosphorus that can then be recovered, and different processes exist to potentially recover this phosphorus in marketed products (Rittman et al, 2011). The best developed of these processes is by precipitation of solid magnesium ammonium phosphate, struvite, a valuable fertiliser. In this regard, Elser and Bennett (2011) suggested that "market incentives might help to make the struvite-recovery systems, such as those developed for municipal wastewater-treatment plants, economic for high-density livestock operations". However, these solutions only look at one side of the problem, phosphorus recovery, without considering other nutrients and organic matter in the manure, and the larger problems associated with high-density livestock operations.

Food wastes are another lost source of phosphorus. According to Dawson and Hilton (2011): "The need for phosphorus recovery must be integral in any waste management strategy. Waste streams from commercial food processing and outlets and points of consumption such as supermarkets, restaurants, hotels, hospitals, must be captured into an efficient process by which the phosphorus-containing residue is returned to farmland. A significant proportion of this material consists of animal bones discarded during processing. At present within the EU, due to BSE regulations most bone matter is incinerated and the ash taken to landfill (Ziggers, 2010; Emiel Elferink, pers. comm.). Phosphorus in bone and ash combined is estimated at some 12% of the total fertiliser and feed phosphorus import into the EU."

5.2.2 Recover phosphorus currently lost in human excreta and other organic wastes

Today, it is estimated that only 10% of human excreta finds its way either intentionally or non-intentionally back to agriculture or aquaculture (Cordell et al, 2009). Current sanitation systems in industrialised countries treat human excreta as a useless residue, wasting large quantities of clean drinking water and energy in sewage plants to manage it ("flush and forget" systems). At the same time, about half of the people living on the planet, 72% of them in Asia, do have access to sanitation facilities (Mihelcic et al, 2011).

However, historically agriculture has often relied on phosphorus input from human excreta to increase food production. In Chinese and Japanese societies, for example, it was an essential input for the high food production that enabled social development.

The increasing appreciation of mineral phosphorus (and also chemical nitrogen) as a limited and expensive input for farming is raising awareness of the potential treats to human excreta as a resource rather than a pollutant.

About 11% of phosphorus entering the Earth systems is lost in human urine and excreta (Cordell et al, 2011). If recovered, it has been estimated that it could supply 22% of the current global demand for phosphorus (Mihelcic et al, 2011). Two facts make of phosphorus recovery in human excreta a promising outlook: first, inexistent sanitation facilities in the many developing countries is an opportunity for creating real sustainable ones, and second, this is very efficient since up to 90% of the phosphorus (and nitrogen) in urine and faeces could be potentially recovered and used to fertilise agriculture lands .

The best long-term solution for recovering nutrients from human excreta is the creation of ecological sanitation systems that work simultaneously for closing nutrient cycles, saving water and energy, and improving livelihoods. This is the best option and it is immediately feasible and cost-effective in regions where sanitation facilities are not well developed. Similarly, in economically developed countries it could be initially installed in rural areas, and in newly constructed homes and public buildings. Many examples already exist (see below). It will need more investment and re-structuring of old-style sewage systems in cities and most of the developed world ("flush and forget" systems). For those, intermediate options exist that could recover nutrients while this re-design is implemented, the best developed of those being struvite recovery from sewage plants (see section below).

However, both developed and developing countries should look at the long-term solution of eco-sanitation. Many examples show that it is feasible and economical in the long-term. According to the Stockholm Environment Institute, the cost of implementing ecological sanitation systems globally could be offset by the commercial value of the phosphorus (and nitrogen) they yield (Cordell et al, 2009). Research has suggested that in the Swedish context, urine can be transported up to 100 to 200 km and remain more energy efficient than production and use of mineral fertilisers (Cordell et al, 2011b).

Small-scale decentralised ecological sanitation systems are very likely to play an important role in future sanitation systems given a future potentially challenged with energy and water scarcity, climate change and increased population growth (Cordell et al, 2011b).

Eco-sanitation to recover nutrients, save water and energy and improve livelihoods

"Ecological sanitation is one form of sustainable decentralised sanitation and refers to containment, sanitization and recycling of human excreta to arable land. While the key objectives are protection of public health and the environment, other important goals are the reduction of water use in sanitation systems, reducing the demand for mineral fertilisers in agriculture by recycling nutrients from human excreta and explicitly addresses the need to 'close the loop' on nutrients including phosphorus" (Cordell et al, 2011).

There are nowadays many examples of eco-sanitation initiatives simultaneously improving yields and public health while reducing environmental pollution by recovering nutrients in human urine and faeces. Scaling up these eco-sanitation programmes will also increase the sustainability of farm systems and the livelihood of millions of farmers in developing countries.

About 60–70% of the phosphorus in human excreta is found in the urine fraction while 30–40% is found in the faeces. Human urine is generally sterile, containing very few, if any, pathogens, but it does contain significant inorganic phosphate ions in a form that is readily available for uptake by plants (as well as nitrogen, potassium and sulphate ions making it an ideal fertiliser).

In practice, ecological sanitation relies on separating waste streams to optimise their potential for reuse. Firstly, there is a need to separate the industrial from other domestic wastes to avoid contamination with industrial pollutants. Then, domestic greywater is kept apart from urine and feces by urine-diverting toilets that separate and treat them separately. Diversion of urine keeps the moisture levels low, promoting oxygenated conditions and speeding up the destruction of pathogens through desiccation (Mihelcic et al, 2011). If urine sources are sterile and lacking chemical contaminants (i.e. pharmaceuticals, see health concerns below) it can be potentially used safely in farm soils after a precautionary wait of 6 months (Coalition Clean Baltic, 2012).

Faeces can be composted separately. In addition to nutrients, their carbon content makes them widely recognised for improving soil quality (Mihelcic et al, 2011). In the Swedish context, faeces are composted for two years or more. During that time, the microorganisms that spread diseases are killed off and the faeces are converted into a soil-like product. However, more research and development is needed before widespread recommendations can be made on how to safely use composted faeces for growing vegetables that will be consumed without cooking.

Examples

In India, at Musiri, ecosan toilets have been set up to help turn faeces into manure and to use urine as a fertiliser. A urine bank has been set up where the urine is processed into struvite for use as a fertiliser (Times of India, 2011).

In Africa, an initiative in southern Niger was set up to aid local food security using P recovery from wastes of 700 households. The system uses simple urinals and waterless toilets. The system has been successful in providing sanitation, conserving water and yields of vegetable and cereals fertilised with the excreta were equal or better than systems using equivalent amounts of chemical fertiliser. In Durban, South Africa, urine-separating latrines are now being installed on a relatively large scale funded by a grant from the Bill and Melinda Gates Foundation (Cordell et al, 2011b).

Another simple idea is the Peepoo, which is a single use, self-sanitising, biodegradable bag that captures human excreta and can be used as fertiliser two to four weeks later. It could even be sold as fertiliser and so represents a way of transforming people's own waste into a source of income for poor people .

In Sweden, two municipalities have mandated that all new toilets must be urine diverting. This involves collecting the urine in a simple storage tank under the house or to a communal storage tank. Local farmers then collect it once a year for use as liquid fertiliser (Soil Association 2010).

Health concerns

Precautionary measures are necessary to avert health risks associated with fertilising soils with urine and composted faeces. In 2006, the World Health Organisation published comprehensive guidelines on the safe reuse of wastewater in agriculture. Use of human excreta is safer where waste streams are not mixed with other waste streams such as industrial or domestic wastewater because of pollutants such as heavy metals or organic contaminants (Cordell et al, 2009). Human excreta itself may contain pollutants, primarily steroidal hormones and pharmaceuticals which can be removed to different degrees thought natural attenuation or with existing engineering treatment technologies which are energy and material intensive and thus may not be appropriate in all areas of the world (Mihelcic et al, 2011). More research is needed on how to treat hormone, pharmaceutical residues and microbes in human excreta. However, this is also true for any other type of wastewater treatment, including the "flush and forget" system.

Potential drawbacks of using sewage sludge from unseparated industrial and domestic wastewaters on agricultural land include polluting heavy metals and organic compounds. The level of heavy metals in sewage sludge has markedly declined in recent years. According to a Soil Association 2010 report, Professor Smith, who is professor of bio-resource systems at Imperial College UK, says that the levels of heavy metals in sewage sludge no longer pose a risk to the environment or human health. However, organic compounds in sewage sludge may pose a risk including pharmaceuticals, antibiotics, endogenous hormones and synthetic steroids, detergent residues, solvents, flame retardants, compounds that leach from plastics and chlorinated pesticides. This chemical contamination is minimised by separating industrial wastewater and domestic grey water from excreta (as in eco-sanitation examples).

Currently, for organic agriculture in the UK, it is not permissible to use sewage sludge on land. The Soil Association suggests that since the practice enshrines a number of principles of the organic movement, it should now be permitted to use sewage sludge on organic farms if limits are in place for heavy metals and organic compounds to ensure the practice is safe. Specifically, the Soil Association suggests: "The critical nature of peak P justifies amendments being made to EU regulation No. 889/2008 to permit the use of sewage sludge on organic certified land where that sewage sludge meets certain quality criteria and appropriate restrictions, including maximum concentrations of heavy metal and organic contaminants within the sludge".

Struvite recovery from sewage plants

A method that has been in use commercially since 2007 is the reclamation of phosphorus from sewage in the form of struvite, an inorganic salt (magnesium ammonium phosphate). Struvite can be precipitated out of some sewage sludge (Gilbert 2009, Syers et al, 2011). It has the advantage over using sewage sludge itself on the land in that it contains no heavy metals or organic contaminants. It is possible that struvite can be used as a short-term partial solution for extracting phosphorus from human excreta to use as a fertiliser. This technology is now in use in treatment plants of some major cities North America and the UK (Syers et al, 2011). The scientist (Don Mavinic), who started the process of struvite production from sewage, made a rough estimate of its potential. He estimates that if all domestic wastewater facilities in Canada were converted into biological treatment systems using his technology, Canada could produce enough fertiliser to meet about 30% of its current needs (Gilbert 2009).

Potential drawbacks of struvite are that it contains relatively low levels of nitrogen, no potassium or organic matter (Soil Association, 2010). In the longer term, the way forward is to move to decentralised ecological sanitation systems.

5.2.3 Phosphorus recovery from industrial waste streams

Although the total quantity of phosphorus in industrial waste streams is not as high as in sewage and manure, industrial waste streams often offer a good prospect for efficient phosphorus recovery, mostly because the stream is more concentrated and less variable (although it can also be problematic due to industrial contaminants). Such industrial waste streams include metal treatment/car painting, electronics, food industries, slaughterhouses, etc. Depending on circumstances (industrial contaminants, local P balance) phosphate recycled from such streams can either be reused in industry or in food production, contributing to closing local resource loops (Chris Thornton, pers. comm.).

Endnotes

1 Chinese official data on P fertiliser consumption records lower consumption totals, i.e. for 2010 it would be 8.1 Mt P (P2O5) compared to 12.8 Mt P in FAOSTAT 2012. http://www.stats.gov.cn/tjsj/qtsj/hjtjzl/hjtjsj2009/t20101208_402688506.htm

2 http://florida.sierraclub.org/phosphate.asp

3 http://www.tribuneindia.com/2012/20120219/main6.htm

4 "Crippling skeletal fluorosis, which is associated with the higher levels of exposure, can result from osteosclerosis, ligamentous and tendinous calcification and extreme bone deformity" (WHO 2006).

5 http://www.rodaleinstitute.org/no-till_revolution

6 "Large-scale, intensive operations, in which animals are raised in confinement, already account for three quarters of the world's poultry supply, 40% of its pork, and over two-thirds of all eggs" (Naylor et al, 2005).

7 "Many byproduct feeds are high in P, most notably the byproducts of corn processing and ethanol production. These are increasingly popular feed supplements for beef and dairy cattle because of the protein and energy they supply. However, inclusion of these feeds in higher amounts often increases the dietary P content beyond the animal's requirement. The popularity of these high-P byproducts will likely continue, and there is no easy solution to the problem of the resulting elevated dietary P. In the short term, producers using these feeds should at least remove unneeded supplemental inorganic P from diets. In the long run, however, the true cost of the use of these high-P feeds should be carefully considered. If the inclusion of these byproducts will cause significant nutrient imbalance in the livestock operation and lead to difficulty meeting environmental regulations, then these feeds may not be as inexpensive as they appear." Knowlton KF, Radcliffe JS, Novak CL & Emmerson DA (2004). Animal management to reduce P losses to the environment. Journal of Animal Science, 82: E173-E195.

8 http://www.reuters.com/article/2012/04/03/us-gmo-canada-pigs-idUSBRE83110320120403

9 Coalition Clean Baltic reports in http://www.ccb.se/

10 http://www.peepoople.com

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