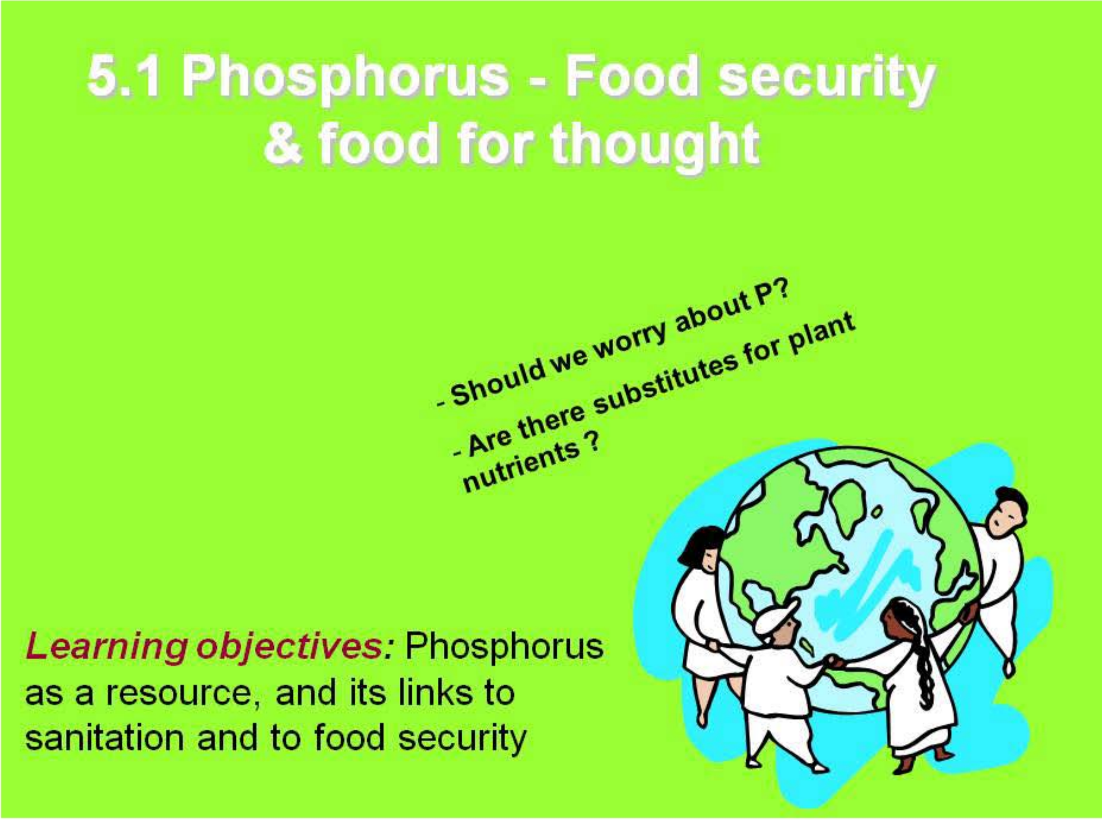


There are almost seven billion people on earth, and so our combined daily activities have a significant impact on the world's limited resources. If, for example, many people acquire and drive cars, oil reserves will eventually become scarce. As we continue to pump large amounts of groundwater for irrigation water tables recede. If we harvest too many fish from the oceans, fish stocks will dwindle. The same applies for nutrients – if we all use mineral fertilisers to grow crops, the source of those fertilisers may become scarce. Further, if most humans move to cities where organic waste (such as excreta and food waste) is no longer returned to agricultural soils, we will face a shortage of nutrients (fertiliser) for crop production sooner rather than later.

This chapter focuses on a particularly important nutrient, phosphorus, or P for short. Phosphorus is an essential mineral building block for all living organisms, including plants, animals and humans. Therefore, the future availability of P is as critical as energy and water resources for meeting the food demands of a growing global population. Up to now, global environmental challenges related to phosphorus have typically been associated with water pollution and eutrophication. Today we are on the brink of a new global understanding: phosphorus scarcity and the serious threat that this poses to future food security (Cordell, Drangert & White, 2009a).

This chapter outlines the challenge of increasing global scarcity of high quality and easily accessible phosphate rock. The chapter first discusses the important characteristics of phosphorus, its role in food production in the past, the present and the future, including how humanity became dependent on phosphate rock. The increasing political power of countries controlling the world's phosphate rock reserves is highlighted. A simplified substance flow analysis and future scenarios analysis helps to identify potential measures and strategies to secure enough mineral and renewable phosphorus for food for present and future generations.

The good news is that a crisis due to phosphorus scarcity can be avoided with a concerted effort by the world community. Since P cannot be destroyed there will not be a scarcity unless P is managed in a wasteful manner and is disposed of in places where it is difficult to access. A world with an increasing population and growing per capita demand will require innovative strategies to use resources more efficiently and ensure their recovery and re-use. Re-using resources also reduces pollution. Recovery and re-use is particularly critical for resources for which there is no substitute, such as phosphorus and water. Strategies to recover and re-use phosphorus from human excreta, food waste and animal waste are likely to provide a major source of phosphorus in the near future.

If all phosphorus were used efficiently in food production and recirculated after use, much less additional phosphate rock would be required and phosphate rock scarcity would be of little concern. However, achieving this will require substantial changes to the way we think about and manage our resources. Today there is a scarcity of good management of phosphorus resources rather than simply a physical scarcity of phosphate rock. If this is borne in mind, institutional and other constraints can be approached with a better understanding.

5.5 - 2

A global view can illustrate the human impact on the globe and the earth's responses. From a satellite, the globe looks blue, green, and generally hospitable in the daytime (left picture). However, the collective impacts of all our individual activities can be more readily seen and understood by looking at the night-time view (right). At night, large parts of the globe are illuminated by street, building and house lights. We can no longer tell ourselves that '*what I do has no effect on the globe'*, because the combined effect of what everyone does will '*light the globe*'. In addition, the emissions from the energy sources required to produce all this light have a great impact on the thin layer of atmosphere surrounding the globe – causing global warming.

A recent estimate by McMichael et al. (2007) tells us that 35% of global greenhouse gas emissions come from agriculture and land use. Livestock production alone accounts for about 18% of global greenhouse gas emissions. Livestock-related emissions are caused by: deforestation to clear land for grazing land and soya-feed production; soil carbon loss in grazing lands; the energy used in growing feed-grains and in processing and transporting grains and meat; nitrous oxide releases from the nitrogenous fertilisers; gases from animal manure (especially methane); and enteric fermentation. The greenhouse gases from these sources make up an estimated 9% of global emissions of carbon dioxide, 35–40% of methane emissions, and 65% of nitrous oxide emissions. Although they have shorter half-lives in the atmosphere, the near-term warming potential of methane and nitrous oxide, per unit of volume, is much greater than it is for carbon dioxide.

There is little doubt today that the earth is experiencing unprecedented global environmental changes due to human activity – from climate change, widespread eutrophication, deforestation, loss of biodiversity, water scarcity and more (WWF 2004). Human impact has increased dramatically in the last 50 years, driven mainly by rapid population growth, and even faster increases in the production of goods. We now begin to comprehend that the hydrosphere, biosphere, lithosphere, and atmosphere are directly or indirectly interlinked and that the impact of human activity on one component can have far-reaching effects on the others. We adversely affect the very same components that we depend on. Without vital 'ecosystem services', human society could not exist – it would have no energy, no clean water and no food. The following presentation deals with the global impacts of phosphorus usage on food security. Sustainable sanitation will be highlighted as one way to ease P scarcity problems.

Comparing water and phosphorus for food security

5.5 - 3

Water	Phosphorus
• Water molecules cannot be manufactured or destroyed	• Phosphorus (P) cannot be manufactured or destroyed
• Water is renewable (sun-driven cycle)	• P is essentially immobile and is mined in only a few countries
• Water is available in soil and replenished annually by rain	• P is naturally available in soil and depleted by crops
• 70% of global water use is for crop production	• 90% of global P extraction is for crop production
• A balanced diet results in the **loan** of 1300 m^3/yr to each person on the planet based on current practice. This is 70 times greater than the 50 l/d per person for basic water needs.	• A balanced diet results in the **depletion** of 22.5 kg/yr of phosphate rock (=3.2 kg/yr of P) per person based on current practice. 0.5 kg of this reaches the average person's food.

Source: Cordell, Drangert & White (2009a)

Both are critical to food production, but need to be managed differently

Two molecules that are particularly vital for food production are water (H_20) and phosphorus (P_2O_5). The table above compares and contrasts them, and shows that while many similarities exist, the contrasting circulation properties of P and water mean that they require different approaches to manage them sustainably.

A feature common to phosphorus and water is that humans cannot manufacture or destroy them – they can only alter their location and affect their quality as they cycle naturally or anthropogenically on the earth (see 1.2-4). Another common feature is that neither water nor phosphorus can be substituted in plant production. Plants require water to circulate nutrients and for photochemical processes to build cells, while phosphorus is required to build cells and enzymes, and to form fruits and seeds. Hence, deficiencies in plant-available phosphorus and water can severely reduce crop yields and fruit/seed development. An average human body contains about 650 grams of phosphorus. Most of this P is in our bones, and the rest is in our DNA, cellular membranes and the molecule adenosine triphosphate, or ATP, which the body uses to process energy. We need an intake of 1 gram of P every day to maintain body functions (Vaccari, 2009).

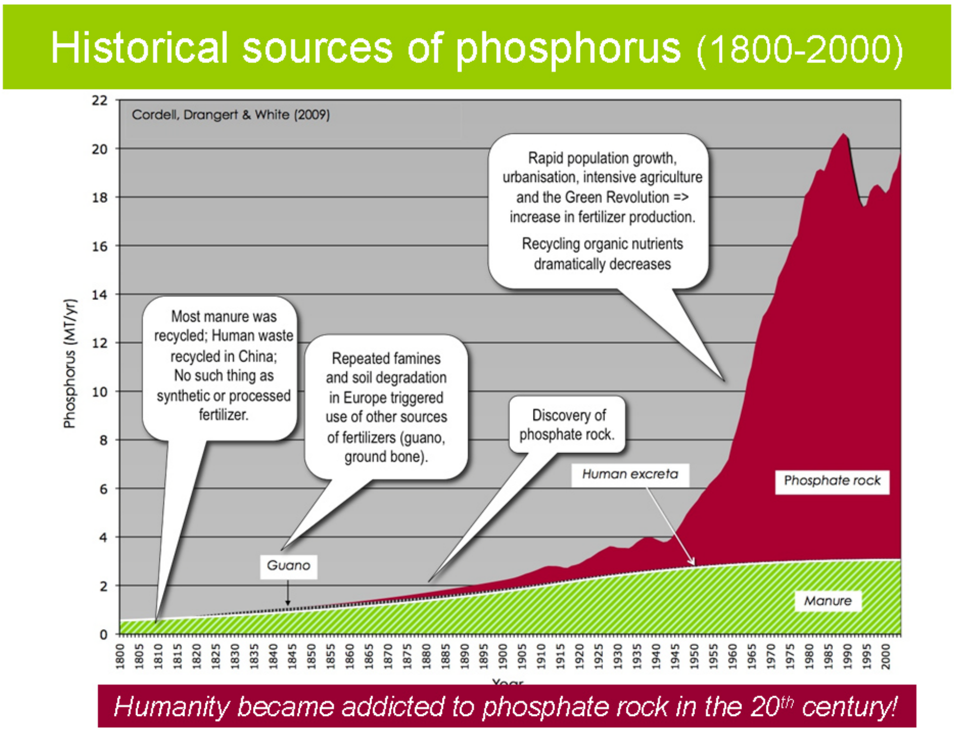
Soils naturally contain water and phosphorus to varying degrees and, depending on the form it takes, this P may be accessible to plants (P_2O_5). Water and P molecules differ when it comes to their natural cycles and mobility in the soil and the atmosphere. The sun drives the water cycle and makes water a renewable resource which is partly cleaned through soil filtration and evaporation and condensation. While water is renewable, the rain may not appear when and where farmers would prefer. Therefore, crops are increasingly irrigated by surface water or groundwater.

Unlike the water cycle, the phosphorus cycle has essentially no atmospheric phase and only cycles between the lithosphere, biosphere and surface and groundwater. It is practically immobile in soils unless washed away by stormwater or groundwater flow. In the biosphere P can stay in one place for periods which range from one day to many years. Phosphorus in mineral fertilisers comes from phosphate rock (PO_4), which is a non-renewable geological resource that has taken around 10 million years to form. Rock phosphate is made from the remains of aquatic life on the bed of the sea and tectonic uplift has moved it onto land (White, 2000). The phosphorus in soils originates from long-term weathering and erosion of the parent rock. The mineral, through further weathering and runoff, makes its way into the ocean, where marine organisms may recycle it some 800 times before it passes into sediments (Vaccari, 2009). After tens of millions of years of tectonic uplift it may return to dry land.

The major human use of both water and phosphorus is in agriculture. Seventy per cent of the water used by humans goes to agriculture while the remainder is used for household and industrial activities (see 1.2-5). Based on current practice it is estimated that the agricultural sector will need to double the amount of water it uses, to feed humanity in 2025. However, this quantity of water is not available and thus innovative strategies to achieve '*more nutrition per drop*' will be required (SIWI-IWMI, 2004). Similarly, almost all (90 %) of mined phosphate rock is for food production, mainly as fertiliser, animal feed and food supplements. The remainder is used for detergents and industrial applications. It is estimated that the agricultural sector's need for phosphate rock will increase by at least 50% by 2025 compared to the mid-90s (5.5-10). The same goes for the other essential macro-nutrients, nitrogen and potassium. Plants take up the nutrients via their roots, and once plants are harvested, the phosphorus leaves the topsoil for good – unless it is returned as fertiliser or organic waste. The non-renewable phosphate rock reserves are likely to be depleted in 50 to100 years. Meanwhile, demand continues to increase.

An important difference between phosphorus and water use is that the water is returned to the water cycle (**renewable**) whereas the phosphorus from mined phosphate rock is usually immobilised in the sediments of rivers, lakes and oceans (or in landfills) and will take millions of years to cycle naturally back to the soil (**non-renewable**). Therefore, different strategies are needed for sustainable use of these two resources. Water used by humans is essentially a '*loan*' from nature's hydrological cycle. While the used water may not return to the same water catchment when it falls again as precipitation, it will reappear sooner or later through the water cycle. On average, a person requires some 1300 m^3/yr of water to produce her food, and this water can come in the form of rain or irrigation (SIWI-IWMI, 2004). Phosphorus fertiliser, on the other hand, is mined. A balanced diet requires mining approx. 22.5 kg/yr of phosphate rock (PO_4) per person per year. This rock is converted to 3.2 kg of elemental P. About 0.5 kg of this phosphorus is contained in the food we eat and excrete.

5.5 - 4



The graph shows the world's usage of phosphorus fertilisers over the past 200 years, comprising manure, human excreta, guano and phosphate rock (in million tonnes of P per year). The graph indicates the world's growing dependency on phosphate rock (dark red) over the past 60 years, since the Green Revolution in the 1950s.

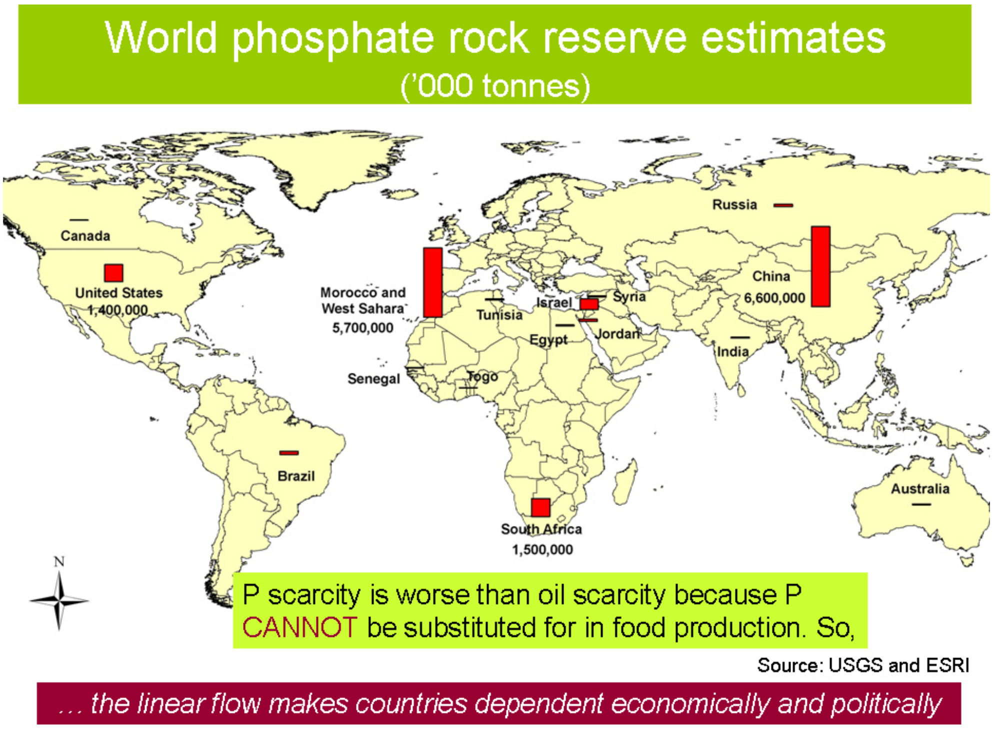
Historically, crop production relied on natural levels of soil phosphorus, which comes from erosion of bedrock, with the addition of organic matter like crop residues and manure (shaded green) and, in parts of Asia and Europe, human excreta ('nightsoil'). Repeated famines and gradual soil exhaustion in Europe triggered the search for other sources of fertilisers, such as ground bone and guano (bird and bat droppings). Island caves and land rich in guano were mined off the Peruvian coast and in the Pacific Islands. However, the obviously limited supply of high quality guano was depleted within decades and other sources of phosphorus were again sought. Already in 1840 the chemist Liebig had discovered that phosphorus deficiency limits plant growth. But, phosphate rock was not mined before the late 19th century. The first half of 20th century saw moderate use of phosphate-based fertilisers, and crop yields increased. There were still recurrent famines in many countries. The launch of the Green Revolution in the 1950s with large-scale irrigation farming using new varieties of rice and the application of chemical fertilisers improved yields tremendously (IFPRI, 2002b). Phosphate rock mining expanded rapidly to keep up with increased P demand due to rapid population growth and urbanisation (Smil, 2000b). Famines due to natural causes were substantially reduced and food security improved.

Thus, a dependence on phosphate rock for global food production was established. By 1990 the demand and production of phosphate rock and mineral fertilisers dropped somewhat, due to a number of factors. One was an increasing awareness in Europe and the US that overfertilisation was leading to phosphorus leakage which was causing algal blooms in lakes and estuarine waters. Another was that the Soviet Union collapsed, resulting in a sudden reduction in the phosphate demand from a previously high fertiliser-consuming region. While demand has receded in the developed world, the rising demand in developing and emerging economies has resulted in an overall increase in the global demand for phosphorus fertilisers. This has occurred despite many poor farmers not gaining access to world phosphate fertiliser markets (Cordell et al., 2009a).

Urbanisation, sewered sanitation and global trade affected the flow of phosphorus in the 20th century. In the past, most people lived in rural areas where phosphorus was typically returned to soil in a closed loop (Drangert, 1998). Today, however, agricultural products are transported long distances to feed consumers in cities and in other countries. The organic ‘wastes’ generated from food consumption (mainly food waste and excreta), therefore, end up far away from where the plants they came from grew. Also, the fertilisers used to grow the plants are shipped around the world since the phosphate rock is only being mined in a few countries. The average distance a phosphorus molecule moves in the food system from source (such as a mine) to sink (such as lakes or oceans) has thus increased dramatically since the mid-20th century.

Cities are fast becoming ‘phosphorus hotspots’ in two senses – as centres of demand for phosphorus (to produce food consumed in cities) and as locations of large amounts of phosphorus (in excreta and food waste). For example, urine is the largest single source of phosphorus emerging from cities (Jönsson, 2001). However most nutrients in urban waste are not recovered and re-used. Many urban councils collect and transport organic waste to landfills, where the nutrients will remain for uncounted years unless leached to groundwater. The situation is similar for toilet waste, which in the best of cases ends up as sludge in a wastewater treatment plant. However, sludge is also often sent to landfills due to its perceived or real toxicity. The more the flow of phosphorus from mine to field to fork is linear and in one direction only, the greater our dependence on mined phosphate rock and the faster high-grade phosphate rock resources will be depleted. Recirculating urban nutrients such as urine back to agriculture therefore presents an enormous opportunity for the future.

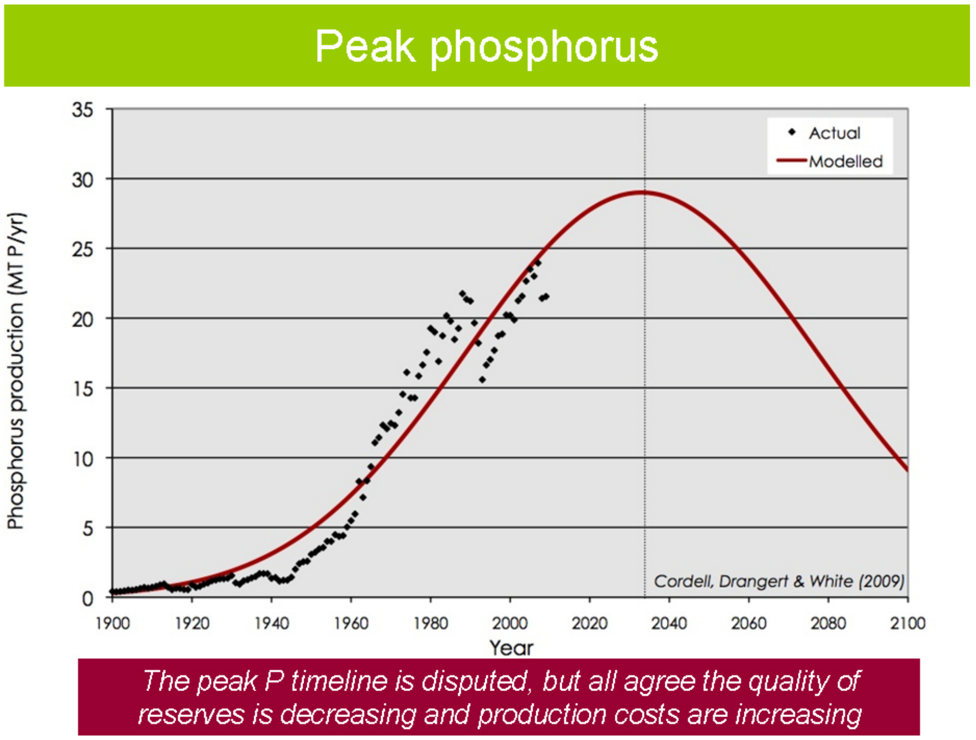
5.5 - 5



While all farmers need access to phosphorus fertilisers, just six countries, China, South Africa, Morocco with its occupied Western Sahara, the US and Jordan hold 90 % of the world's reserves and account for more than two thirds of annual production (Vaccari, 2009). This uneven geographical distribution of phosphate rock resources should concern countries that rely on imports of mineral fertilisers for food production. Imagine if all the world's freshwater resources were controlled by just a handful of countries – national leaders would be much more concerned with securing water from alternative sources to avoid such dependence on imports. Other important global resources subject to geographical concentration, such as oil, can be substituted by other forms of energy, such as hydropower, natural and biogas, nuclear power, wind power, water-current power, or biofuels. However, there is no substitute for plant nutrients such as phosphorus, nitrogen, potash, and sulphur. Yet there are no widespread political discussions about phosphate rock dependency.

In 2006, China surpassed the United States as the world's leading producer of phosphate rock, and China produces 30.7 Mt (million tonnes), the United States 30.1 Mt, and Morocco/Western Sahara 27.0 Mt (USGS, 2007). U.S. marketable phosphate rock production and reported usage dropped to their lowest point since 1965. However, the United States remained the world's leading consumer and importer of phosphate rock and also the leading producer and supplier of phosphate fertilisers, accounting for about 37% of world P_2O_5 exports. Most of the phosphate shipments from Morocco/West Sahara were used by three phosphoric acid producers located in the US along the Gulf of Mexico (USGS, 2007). This is geopolitically sensitive as Morocco currently occupies Western Sahara in violation of international law and controls its vast phosphate rock reserves. Trading with Moroccan authorities for Western Sahara's phosphate rock is condemned by the UN, and importing phosphate rock via Morocco has been boycotted by several Scandinavian firms due to corporate social responsibility (Hagen 2008). Western Sahara's P reserve is, in per capita terms, infinitely bigger than the reserves of any other country. However, the world community has not been able to ensure that the people of Western Sahara gain their rightful income from this resource. Instead, a portion of the population is in refugee camps.

5.5 - 6



According to peak minerals theory, first formulated by Hubbert (1949) in relation to US oil reserves, the important point regarding mineral availability is not when the resource is depleted, but when production peaks. In this case – peak phosphorus – is the point at which supply starts decreasing year upon year, due to lower accessibility and economic and energy factors, while demand for phosphorus fertilisers continues to increase. A peak phosphorus analysis (Cordell et al, 2009a) based on US Geological Survey and industry data suggests that production of phosphate rock could peak by 2035.

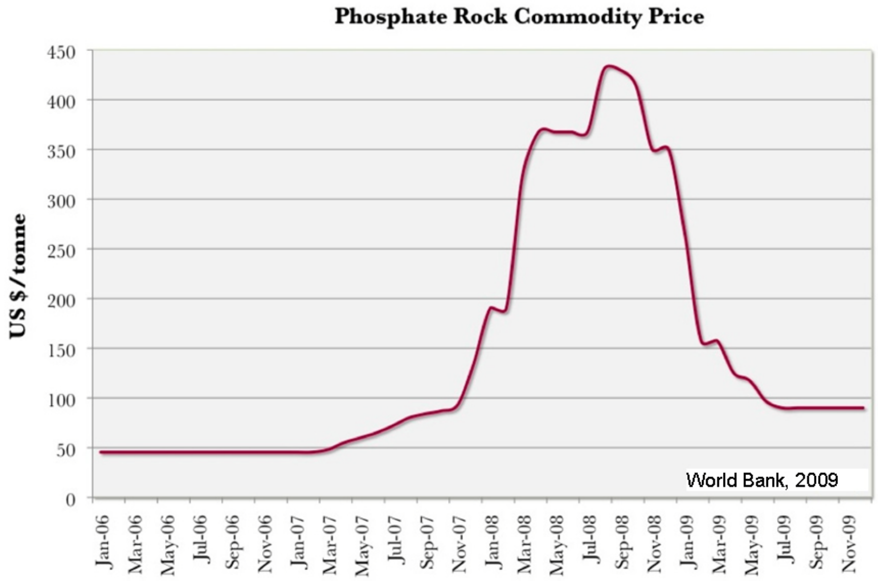
The exact timeline of the peak is currently disputed. The fertiliser industry, on one hand, claims that USGS reserve data is unreliable, and that more phosphate reserves exist (Prud'Homme, 2010). Other scientists dispute the timeline because they believe peak phosphorus occurred in 1989 (Dery and Anderson, 2007). Regardless of the exact timeline, there is general consensus that in the remaining reserves, P concentrations (expressed as P_2O_5) are declining, that the presence of contaminants such as cadmium, uranium and thorium is increasing, and that these remaining reserves are physically more difficult to access.

Each tonne of phosphate (P_2O_5) produced from phosphate rock generates 5 tonnes of phosphor-gypsum (11.5 tonnes per tonne P) waste which must be stockpiled because its radioactivity levels are considered too high for use. Global phosphogypsum stockpiles are growing by over 110 million tonnes each year. Workers, as well as the ecosystem, are seriously affected and the local groundwater is likely to be contaminated (Wissa, 2003).

Worldwide, there has been a gradual shift to manufacture high-purity phosphoric acid from wet-process acid, which has lower operating costs than the older thermal process which requires large amounts of energy. The wet process also produces less hazardous waste. However, thermal acid still accounts for 65% of annual world production of high-purity phosphoric acid (EFMA 2000). New phosphoric acid and fertiliser plants have been built in Brazil, China, Morocco, and Saudi Arabia. Exports to Latin America are expected to continue to grow, and sales to Asia are expected to gradually decrease.

Access to phosphate markets

5.5 - 7



Future fertilizer price spikes are also possible

Farmers around the world demand 135 million tonnes of phosphate fertiliser for their crops each year. While the quantity and quality of existing high-grade phosphate rock reserves are decreasing, the cost of extracting this resource is increasing. Economic theory of demand and supply predicts an increase in the market price. In 2008 the world had a first wake-up call when the price of phosphate rock rose dramatically from about US$50/tonne to US$430/tonne – an 800% increase from previous years (World Bank, 2009).

Analysts indicated the price spike was due to a number of global demand-side factors, including the rising demand for food, increasing trends towards more meat-based diets (particularly in emerging economies such as China and India), and the expansion of the biofuel industry (biofuel crops compete with food crops for fertilisers). On the supply side, the International Fertilizer Industry Association suggested the price rise was partly due to an under-investment in new capacity which created a short-term scarcity. Also, unfavourable exchange rates (resulting in the value of the US dollar pushing up quoted prices) contributed to the price spike (IFA, 2008). China imposed a 135% export tariff on phosphate in 2008 to secure domestic supply for food production, which essentially stopped exports overnight (*Fertilizer Week*, 2008). This is thought to have exacerbated the 2008 phosphate price spike.

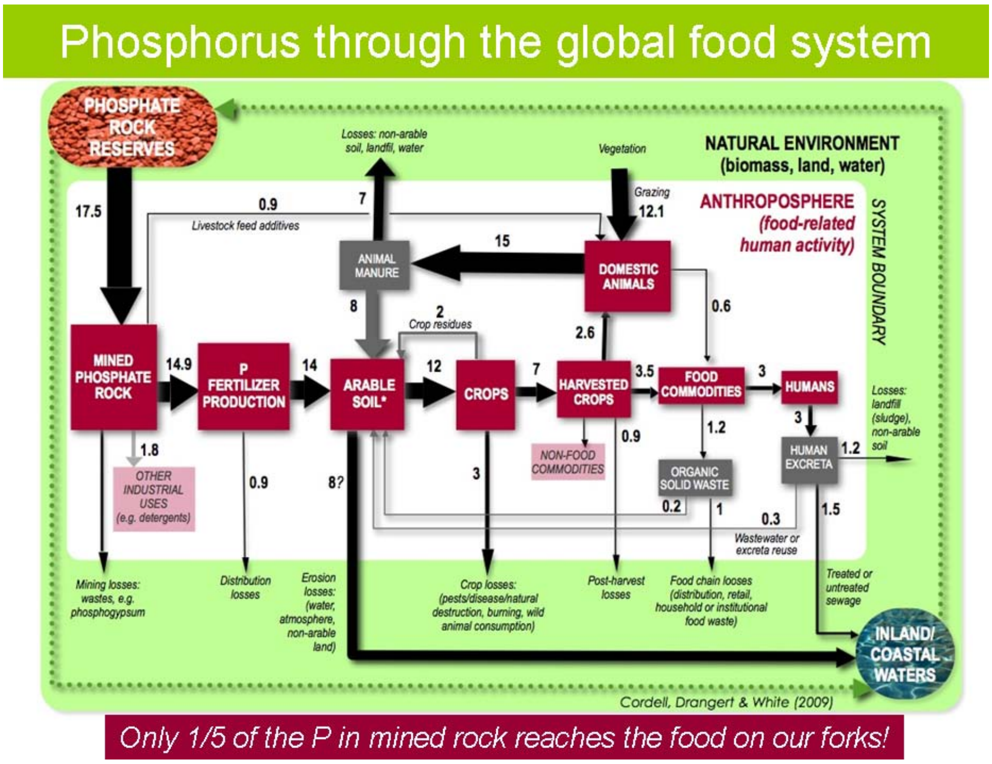
The global financial crisis later in 2008 led many commodity prices, including phosphate prices, to crash (graph). Farmers were also holding off purchasing fertilisers, in the hope that prices would come down, and this further reduced the price (Heffer and Prud'homme, 2009).

The lack of reliable global phosphorus statistics and analysis prevents farmers, policy makers and urban planners from making informed decisions. Unlike many other mineral commodities, no standard domestic or world price for phosphate rock exists. Average ranges of world prices are published in World Bank Commodity Price pink sheets (e.g. World Bank, 2009) and various industry trade journals (such as *Fertilizer Week*) based on a sample of transactions. But the US Census Bureau withholds tonnage and value information for some phosphate rock and fertiliser product shipments, which necessitates the use of other sources of data.

The fertiliser companies that mine ore and produce phosphate rock from Morocco and Western Sahara will be able to influence the market prices as other countries run out of high grade phosphate rock or decide to use it for their own consumption. This means that countries that are dependent on imports, and who continue wasting phosphorus in landfills and water bodies, will be increasingly economically and politically dependent on Moroccan and US fertiliser companies. However, P-deficient countries can improve the efficiency of their phosphorus usage and make use of recirculated phosphorus. An illustration of this is that conventional sanitation dumps 50 million tons of fertiliser equivalents into our water bodies including erosion losses. The market value of these nutrients is around US$15 billion (Werner, 2004). Less dumping would increase the supply and dampen market price increases.

An on-line tool, the US Minerals Databrowser, allows users to create a variety of plots based on data from the USGS dataset: Historical Statistics for Mineral and Material Commodities in the United States. The databrowser includes both phosphate and potash as well as 84 other minerals.

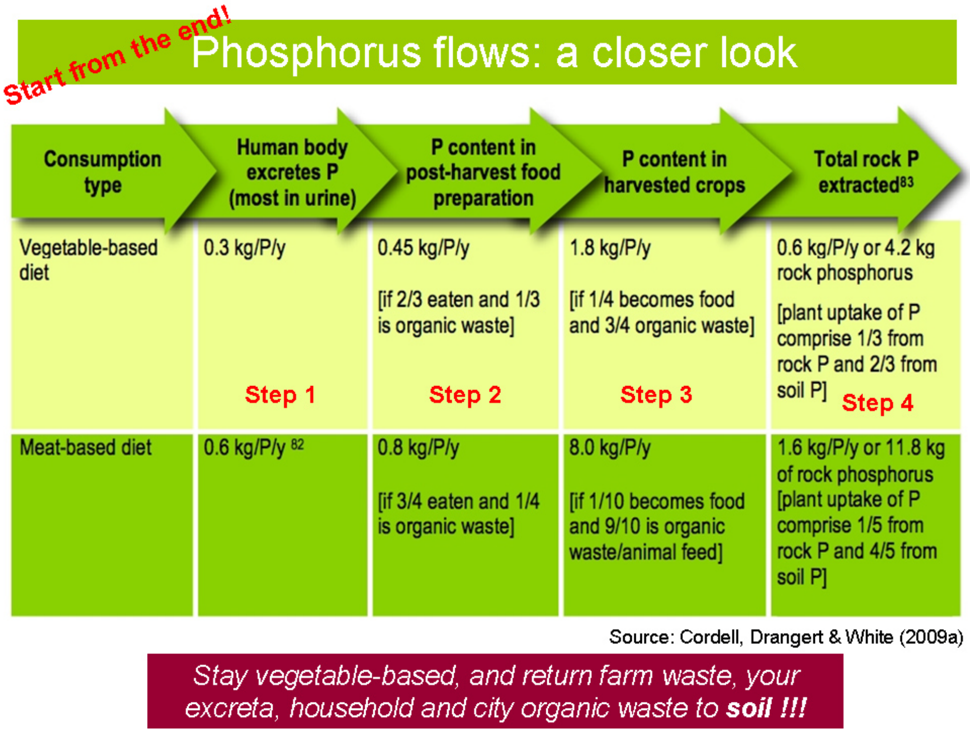
5.5 - 8



A simplified Substance Flows Analysis (see Ch. 1.3) can help us estimate the flow of phosphorus in the global food system. It traces the flow of P from mined phosphate rock via fertiliser and crop production to human and animal consumption (Cordell et al., 2009a). The quantities of phosphorus (in millions of tonnes per year) between these major stages and the losses on the way are shown above.

While some 14.9 million tonnes of phosphorus is used in fertiliser production, only 3 million tonnes end up in human excreta some of which originates from soil P. The flow analysis indicates that there are substantial phosphorus losses that occur throughout the food production and consumption system – from mine to field to fork to toilet. Most of these losses, such as the losses due to the wastage of edible food and loss of P in animal manure, are avoidable (see 5.5-12). Other losses, such as the loss of P through soil erosion, can potentially be reduced if the P is managed wisely. The graph shows that more phosphorus ends up washed away by erosion than ends up in food. In the Illinois River basin, for example, about 1.2 kg of soil is eroded for each kilogram of corn produced (Vaccari, 2009).

A substantial amount of phosphorus is lost as phosphogypsum waste in the fertiliser production. Transport, storage and other production losses also occur between the mine and the farm gate Phosphorus must be in solution in the soil for plants to be able to take up the nutrient. Once applied to agricultural soils, phosphorus in fertilisers can quickly adsorb to other particles, making phosphorus unavailable for use by plant roots (FAO, 2008). It has been estimated that plants only take up around 15–25% of phosphorus in fertilisers applied that year (FAO, 2006). The remaining phosphorus is either temporarily locked up in soils, or lost to water bodies via erosion and runoff. Once harvested, crops are either processed for food, feed, fibre or fuels - or traded globally. A substantial amount of phosphorus is lost in this stage, for example through conversion to feed which is then consumed by animals, and only a fraction is returned to the food system as animal protein products (Cordell, et al, 2009a). The waste created in the processing, preparation and consumption of agricultural products, such as foo proportion of the organic waste from households, restaurants and d disposed of in supermarket dumpsters and household bins, can also be large (Smil, 2000a). Only a small institutions is recovered and re-used.



5.5 -9

Phosphorus travels from mine to field to fork – and is finally excreted unless lost on the way. A scenario of phosphorus losses is presented in this picture. We start from the end (excreta) and work backwards in order to understand what impact our diet has on phosphorus usage. This exercise could look as follows:

Step 1: A vegetarian excretes approximately 0.3 kg P per year, and a meat-eater around 0.6 kg per year. The reason is that there is more P in meat and milk products and the body does not need all of it (Drangert 1998). The body extracts energy from food, about 2,500 K calories per day, but adult bodies do not accumulate any nutrients only replace some. This means that almost all the phosphorus (98% according to Jönsson, 2001) consumed with food is excreted in urine and faeces.

Step 2: A surprisingly large portion of food is not eaten but ends up as organic waste from leftovers after eating and from food preparation, Other losses occur during transport to shops and from past expiry date. The amount wasted ranges from 10% to 50% in the North according to the Swedish National Food Administration (2008). In the above picture we conservatively assume that 1/3 of P in vegetarian food is lost in this way and 1/4 of P in meat-based food. Therefore, farmers provide food products that contain 0.45 kg/yr and 0.8 kg/yr of P for vegetarians and meat-eaters respectively.

Step 3: The part of the crop that is edible is often small (e.g. the maize on a stem or the banana on a banana tree) and we have assumed ¼ to be the edible part (therefore containing 1.8 kg of P), while the rest remains on the farm. Producing meat and dairy products involves the production of animal feed and we assume that 10% is converted into food output and 90% is feed and organic waste which remains on the farm. The edible meat therefore would require an input of about 8 kg P.

Step 4: Fertiliser application rates differ depending on a number of factors such as soil type, farm practice, economics and soil composition. If the soil phosphorus stock provides 2/3 of the needed P, 0.6 kg/vegetarian/y needs to be added as fertiliser or 4.2 kg of phosphate rock. Similarly, for meat-eaters some 11.8 kg/p/y of rock P has to be applied, if we assume that 1/5 of the P is coming from the fertiliser and 4/5 from the soil phosphorus stock. However, as soil P is depleted P has to be added.

This simple kind of calculation by hand using guestimates of phosphorus losses can be done with real local data. It is likely to highlight that a vegetarian diet demands significantly less phosphate fertiliser than a meat-based diet. It also shows that returning biomass from plants and manure from animals to the soil is by far the most important measure to retain soil phosphorus in a meat-based diet. This also requires little or no transport back to the field. For the vegetarian diet, the recovery of human excreta is the most important measure, but this involves collection and transport back to the field.

A simple check can be done to find out if the results are plausible. If we assume that 80 % of the food intake is from plants and 20 % from meat and milk products, an average diet would require 0.8 times 4.2 kg + 0.2 times 11.8 kg = 5.72 kg phosphate rock per person and year. With 6 billion people that would mean some 34 Mt of phosphate rock. This is twice as much as the 17.5 Mt in the previous global calculation. This could be a possible outcome in a given community or country, and at least the magnitude seems right. The scenario can be refined by manipulating assumptions and reiterate the calculations.

We may also consider an extreme case where all food is produced in the garden and all organic waste including excreta is returned to the soil. A small household with a garden of a few hundred square meters could be almost self-sufficient in food (Drangert, 1998). Sanitised human urine and composted faecal and other organic matter would return almost all the nutrients required for the next crop of maize, tomatoes etc. These fertilisers only have to be transported a few metres and the work required to prepare them for the garden (storage) is easy. The household could also raise a few chicken and possibly a pig if they so desire. Almost all nutrient losses can be avoided – in the household setting all organic waste can be composted and returned to the soil. Precision farming will also reduce emissions of greenhouse gases.

This situation is very different in the global food market which involves huge losses in all stages. For countries with large agricultural exports such as Australia, the recovery and recycling of human excreta would make up only a small percentage of the required application of fertiliser (Cordell et al. 2009a). See also slide 1.3 - 11 with the proportion of recycling over time in a Swedish town.

Energy savings and reductions in carbon dioxide emissions are substantial when food is grown using local inputs only. Indeed, recycled P compares favourably with phosphate rock, one of the most highly traded commodities in the world (over 30 million tonnes per year), and its transport currently relies on cheap fossil fuel energy (IFA, 2006a).

5.5 - 10

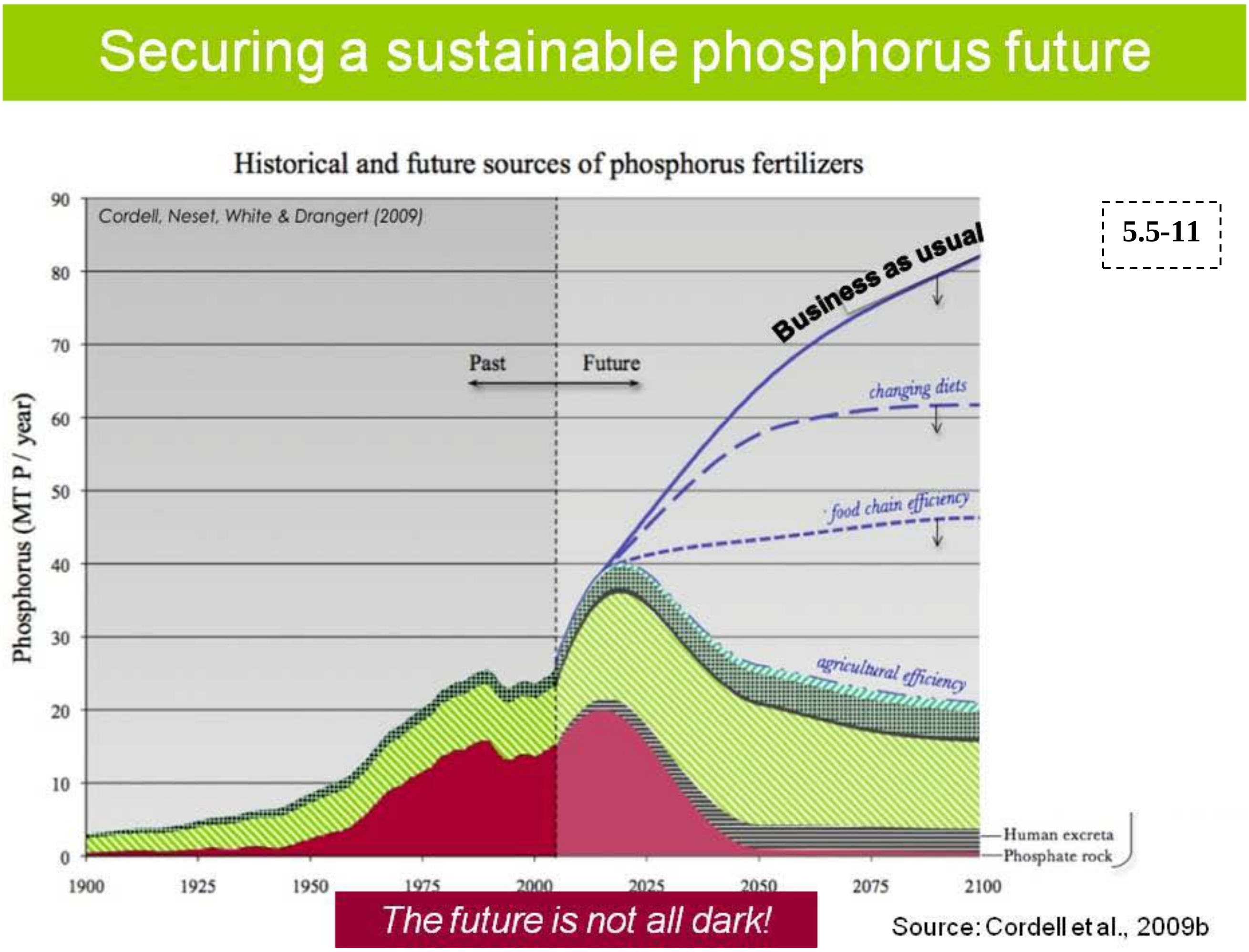
Feeding humanity is a serious global challenge both today and for the future. Today, an unprecedented 1 billion people are hungry – one sixth of all humanity. Global food security is now considered a global priority (UN, 2000). The UN's Food and Agriculture Organization (FAO) states that food security "*exists when all people, at all times, have access to sufficient, safe and nutritious food to meet their dietary needs for an active and healthy life*" (FAO, 2005). This definition does not address the emerging health hazard of eating too much. Obesity will soon become as common as malnourishment. The EU estimates that every citizen accounts for 11 tons of greenhouse gas emissions a year. A fat person is responsible for about one tonne more of carbon dioxide emission than a thin person (Edwards and Roberts, 2009).

A century ago, most people lived on farms and produced their own food nearby with the help of easily recycled organic matter. Today, the conditions are totally different. More than half the world's population lives in urban areas, and there will be another two billion new urban mouths to feed by 2035. Future food security can only be achieved by addressing a number of interlinked social, economic and environmental issues. Innovative ways are needed to meet the food requirements of undernourished urban populations, not least those living in peri-urban areas of mega-cities. Existing decentralised urban food production could be developed further by sustainable communities which recycle nutrients and water. We will have to stop the wasteful linear one-way flow of nutrients from farms to lake sediment.

The kind of food we eat on a daily basis has a dramatic impact on the environment. An illustration is the strong link between diet and land use. The production of meat-based food occupies almost a third of the world's land surface. This consists mostly of permanent pasture but also the third of the world's arable land that is cultivated to provide livestock feed (McMichael et al., 2007). A meat-based diet requires a much larger area of land than a diet of cereals and vegetables. A serious challenge is to keep crop-based diets and not to switch to meat-based diets for status reasons.

Averting future phosphorus and food crises is possible, but it will require substantial changes to our behaviour, and to our society's physical infrastructure and institutional frameworks. Sanitation systems of the future, for example, will need to ensure that close to all phosphorus in excreta is recovered for re-use in fertilisers. Hence the sanitation sector will play a vital role in achieving phosphorus security and food security, in addition to enhancing environmental protection and public health.

5.5-11



This graph combines both past and expected future sources of phosphorus fertilizers for meeting global food demand. The graph for the future presents results from a 'preferred' scenario generated from a futures scenario analysis (Cordell et al., 2009b). The '*business-as-usual*' scenario takes into account factors such as population growth, likely changes in preferred diets, and improved efficiencies. The result is a demand that grossly exceeds anticipated supply.

The situation is not as grim for food security as it may first appear. Due to the substantial mis-management and inefficient use of phosphorus in the current food system, there are numerous opportunities to change current practices in order to avert a crisis. However, there is no single quick-fix solution for ending the dependency on phosphate rock. The above scenarios analysis shows that a number of different supply- and demand-side measures can together close the growing gap between supply and demand for phosphorus.

The graph shows that ***demand-side measures*** are crucial. The almost universal trend towards eating more meat- and milk-based food doubles the demand for P for the same nutrient intake. At the same time the beef industry releases 18% of the global greenhouse gas emission (5.5-2). These are two reasons for society to advocate a more cereal-based diet. The demand for P can also be substantially reduced through minimising losses of edible food through wastage during transport, storage, food processing and disposal (slide 10). The third important demand-side measure is to improve efficiency in agriculture which would contribute to a substantial reduction in demand for fertiliser. Stalks and stems should be returned to the soil to prevent erosion.

The collection and return of animal manure and human excreta to the soil reduces the need for chemical fertilisers. Incentives to change agricultural practices are likely to be more effective than incentives to change diets.

The main ***supply-side improvements*** are recycling measures, since the peak phosphorus may occur around 2035 (5.5-7 and 12) and the static reserve life of phosphorus is 107 years (USGS, 2007). More efficient mining processes would prolong the lifetime of rock phosphate reserves, and a higher market price would make more sources economical to exploit. Implementing these measures will require substantial changes in behaviour in industry, in agriculture, and among individuals, in addition to new physical and institutional infrastructure.

Can I eat climate-smart and phosphorus-smart?

5.5-12

- ***Think twice when shopping***
  Don't buy more food than you have time to eat
- ***Eat up the food you cook***
  Serve reasonable portions and use the leftovers
- ***Use your senses***
  Look, smell, taste and feel the food. Most foodstuffs last longer than their 'use-by' date if they are stored properly
- ***If you want to eat meat***
  Choose local produce and try to eat fish, chicken and no beef
- ***Eat more vegetarian food***
  Especially root crops and legumes
- ***Choose fruits and vegetables of the season***
  Preferably local products

Source: Sweden's National Food Adminstration Report 2008:9

The previous presentation talks about what households and individuals can do to enhance the availability of phosphorus fertilisers and reduce emissions of greenhouse gases. Such climate and phosphorus smart activities are in the hands of all individuals. The following individual activities will have a tremendous positive impact on the globe if most of mankind adheres to them:

Measures to reduce demand include not buying more than what will be eaten up. Expiry dates for products are quite short and can be extended with proper storage. However, milk, meat, fruit, juice, etc are often flushed away. Most of the damage has already been done during production, but flushing away organic matter in the sewer will cause eutrophication and algal blooms in water bodies. This may result in dead zones on lake floors and less aquatic fauna.
Eating a diet with less meat and diary products will reduce the number of animals on the earth, and cut down inefficiencies in food production and emissions of carbon dioxide and methane gas. If you want to eat meat, chicken, fish and pork require less phosphorus per kilogram than beef.

Measures to increase supply: Measures that reduce the environmental impacts include returning sanitised human excreta to the soil. The short loop of using urine and composted organic matter in the garden is sustainable, whereas treating and using sludge from wastewater treatment plants is more risky and difficult to monitor (see Module 4.5).
Sweeping away food remains and fat/grease from plates and cutlery into the organic waste bin makes it possible to compost the material and use it as a soil conditioner in the garden or to collect it and use it in agriculture. The alternative is that this fat/oil/grease will eventually clog the sewer pipes, and cause costly maintenance.

All these measures also reduce transport and thus save energy. An energy balance is required for each product. For instance, because of the heating required, growing paprikas in a greenhouse in the Netherlands uses vastly more energy than if they were produced under the sun in Libya and transported to Europe.

Epilogue

5.5 -13

The green revolution in the 1950s saved the world from hunger - by using irrigation water, new crop varieties and chemical fertilisers

Next revolution must be to recycle the nutrients used in food production !

"Two major opportunities for increasing the life of expectancy of the world's phosphorus resources lie in recycling by recovery from municipal and other waste products and in the efficient use in agriculture of both phosphatic mineral fertilizer and animal manure" European Fertilizer Manufacturers Association (2006)

Jan-Olof Drangert, Linköping university, Sweden

Today we are faced with numerous interlinked global sustainability challenges, from climate change, peak oil, water scarcity and poor sanitation to food security. Global phosphorus scarcity presents yet another such globally significant challenge. The good news is that opportunities exist to integrate innovative responses to this new challenge with responses to other challenges in order to create a sustainable, safe and food-secure future. Countries with no phosphate rock reserves can, through recycling strategies from farm to toilet, reduce the demand for rock phosphate to a minimum. Poor countries can prevent price shocks and limit high costs for subsidies by subsidising recycling measures.

Given the dire consequences of phosphorus scarcity for food production, it is surprising that the role of future phosphorus scarcity is not well recognised in the food security debate. For example, the director of FAO, as recently as World Food Day on November 2009, said that food security can be achieved if the rich countries provide subsidies to poor countries so that they can buy chemical fertilisers. The missing debate could be due to a 'lack of fit' between the natural phosphorus cycle and existing institutions and social arrangements. For example, while almost all phosphorus flows from consumed food to excreta in the natural phosphorus cycle, there is little institutional connection between the food sector and the sanitation sector. Phosphorus is perceived quite differently by different sectors. For example, it is perceived as an 'environmental pollutant' by freshwater ecologists, or an 'agricultural commodity' by resource economists, and so on. Up to now, phosphorus scarcity has been a priority to none. It has essentially slipped through the institutional cracks. It is clear that the market alone cannot manage the wider system in a sustainable, equitable and timely manner

Increasing political awareness about the future of oil in recent decades has resulted in a massive restructuring of investments to reduce oil dependency. The phosphorus sector can learn from such experiences to redirect investments to plant nutrient recycling. This will at the same time reduce energy demand and greenhouse gas emissions.

The Green Revolution saved millions from starvation through the use of irrigation, fertilisers and new crop varieties. The next revolution is a rethink that will require new infrastructure, partnerships and social change to recirculate nutrients back to agriculture.

The International Fertilizer Industry Association (IFA) indicates it is committed to a sustainable fertiliser industry and the European Fertilizer Manufacturers Association states: "*Two major opportunities for increasing the life expectancy of the world's phosphorus resources lie in recycling by recovery from municipal and other waste products and in the efficient use in agriculture of both phosphatic mineral fertilizer and animal manure*" (European Fertilizer Manufacturers Association, 2000, p.9).

While dependence on mined phosphate rock increased dramatically over the second half of the 20^{th} century, reliance on non-renewable phosphate will need to decrease over the 21^{st} century due to the phosphorus peak. A sustainable phosphorus future will include a reduced reliance on phosphate rock and efficient recycling measures in all spheres of P usage.

References

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

Cordell, D., Neset, T. S., White, S., & Drangert, J.-O. 2009b. Preferred future phosphorus scenarios: a framework for meeting long-term phosphorus needs for global food demand, International Conference on Nutrient Recovery from Wastewater Streams Vancouver, 2009., Edited by Don Mavinic, Ken Ashley and Fred Koch. ISBN: 9781843392323. IWA Publishing, London, UK.

Dery P., and B., Anderson 2007. Peak phosphorus. Energy Bulletin, 08/13/2007.Available: energybulltin.net/node/33164.

Diamond, J. (2005), *Collapse: how societies choose to fail or succeed*, Allen Lane, New York.

Drangert, J.-O. 1998. Fighting the urine blindness to provide more sanitation options. *Water SA*, 24, (2) 157-64.

Edwards, P., and I., Roberts, 2009. Population and adiposity and climate change. *Int. J. Epidemiol*., 38(4):1137-1140; doi:10.1093/ije/dyp172.

EFMA 2000. *Production of Phosphoric Acid*, Booklet #4 (2000). European Fertilizer Manufacturers Association.

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

FAO 2005. *The Special Program for Food Security*, Food and Agriculture Organisation of the United Nations, Available: http://www.fao.org/spfs.

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

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

Fertilizer Week (2008). Industry ponders the impact of China's trade policy, in Thursday Markets Report, 24th April 2008, British Sulphur Consultants, CRU.

Hagen, E. 2008. The role of natural resources in the Western Sahara conflict, and the interests involved, International conference on multilateralism and international law, with Western Sahara as a case study, 4-5 December 2008, Pretoria, South Africa.

Heffer, P. & Prud'homme, M. 2007. Medium-Term Outlook for Global Fertilizer Demand, *Supply and Trade 2007-2011, Summary Report*, International Fertilizer Industry Association (IFA), Paris.

Heffer, P. & Prud'homme, M. 2009. Fertilizer Outlook 2009-2013, 77th IFA Annual Conference International Fertilizer Industry Association (IFA) Shanghai (China P.R.), 25-27 May 2009.

Hubbert, M. K. 1949. Energy from fossil fuels. *Science*, 109, 2823, 103.)

IFA 2006. Production and International Trade Statistics. International Fertilizer Industry Association. Paris. Available: www.fertilizer.org/ifa/statistics/pit_public_statistics.asp (accessed 20 August, 2007).

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

IFPRI 2002. *Reaching sustainable food security for all by 2020: getting the priorities and responsibilities right*, International Food Policy Research Institute, Washington.

Jönsson, H., Stintzing, A. R., Vinnerås, B. & Salomon, E. 2004. *Guidelines on the use of urine and faeces in crop production*, EcoSanRes, Stockholm Environment Institute, Stockholm.

McMichael, A.J., Powles, J.W., Butler, C.D., Uauy, R. 2007. Food, livestock production, energy, climate change, and health. *The Lancet*, Vol 370, October, 2007.

Prud'homme, M. 2010. *Peak phosphorus: an issue to be addressed*, Fertilizers & Agriculture, International Fertilizer Industry Association, February 2010.

SIWI-IWMI 2004. *Water – more nutrition per drop, towards sustainable food production and consumption patterns in a rapidly changing world*, Stockholm International Water Institute, Stockholm.

Smil, V. 2000a. *Feeding the world: a challenge for the 21st century,* MIT Press, Cambridge.

Smil, V. 2000b. Phosphorus in the environment: natural flows and human interferences *Annual Review of Energy and the Environment,* 25, 53-88.

Swedish National Food Administration 2008

UN 2000. Millennium Development Goals, Millennium Assembly.

UN 2007. *World population prospects: the 2006 revision*, United Nations Department of Economic and Social Affairs, Population Division, New York.

Unesco (2006) ---USGS 2006. *Phosphate rock, statistics and information*, US Geological Survey. By Jasinski, S. M.

USGS 2007. *Phosphate rock, mineral commodity summaries*, U.S. Geological Survey Jasinski, S. M. http://minerals.usgs.gov/minerals/pubs/commodity/phosphate_rock

Vaccari, D. A. 2009. Phosphorus: a looming crisis. *Scientific American*. June 2009. Vol. 300 No. 6.

Werner, C. 2004. Ecoson- principles, urban applications & challenges. Presentation at the UN Commission on Sustainable Development. 12th Session. New York, 14-30 April, 2004.

White, J. (2000), *Introduction to Biogeochemical Cycles (Ch.4)*, Department of Geological Sciences, University of Colorado, Boulder.

Wissa, A.E.Z. 2003. *Phosphogypsum disposal and the environment* Ardaman & Associates Inc., Florida. Available: http://www.fipr.state.fl.us/pondwatercd/phosphogypsum_disposal.htm

World Bank 2009. *Commodity price data (pink sheet), prospects for the global economy*, World Bank, Available: http://go.worldbank.org/5AT3JHWYU0.

WWF 2004. *Living planet report*, World Wide Fund For Nature, Cambridge. Available: http://assets.panda.org/downloads/lpr2004.pdf