Phosphorus economics - A review

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Abstract

Phosphorus is not a physically scarce resource but more than 90 per cent of the stock is not technically extractable. Economic scarcity takes this and other aspects into consideration. The price spike in 2007/8 induced a scientific debate on a "peak phosphorus" similar to the dispute on the oil peak back in the 1970ies. The processing use of phosphate rock to phosphorus fertilizers fed the Green Revolution and therefore was seen a chance to overcome the hunger on Earth. Hence the expansive use of phosphorus also had serious negative impacts to the environment and also on human health. Thus, the phosphorus dispute needs to be opened for other aspects besides the economic scarcity. The present day phosphorus technologies and economics are unsustainable threatening food safety, food and feed security, human health and many environmental resources. The paper, therefore, focuses on some main aspects of the phosphorus economics. (1) Phosphorus as an essential resource, (2) (economic) phosphorus scarcity that may harm food security, (3) external effects the main use path of phosphorus extraction towards the application in agriculture - mine to food or feed - has, and options to improve the efficiency along this path, (4) strategies to abate the phosphorus losses to the environment, (5) measures to recover phosphorus from various wastes including decontamination strategies, (6) changes in the phosphorus economy from rock to fertilizer if accompanying trace elements will be used, (7) the role of human consumption modes in phosphorus demand, and (8) a better agro-economy that improve phosphorus use efficiency. Each and any of the aspects dealt with in this paper only highlight some aspects of these rather complex topics. In conclusion, the phosphorus puzzle is very complex and cannot be reduced to economic scarcity since it also includes "political, quality, innovation, technology, chain versus cycle management and good governance" aspects. To really cope with the phosphorus scarcity, environmental impacts, food/feed security and health issues an institutional framework that assures a good governance policy practice needs to be evolved.

1. Phosphorus - a resource

Non-substitutable but essential

Life without phosphorus will not survive on Earth. DNA, RNA, fatty acids, teeth, bones and on the cellular scale the mitochondrial energy system converting ADP into ADP and vice versa require phosphorus and thus phosphorus is non-substitutable and essential for all life (e.g., Ashley et al. 2011, Childers et al. 2011, Smil 2000).

Almost non-renewable?

Originally phosphorus was solved from rocks by "acid rain", transported into the ocean, being accumulated in sediments along with other - trace - elements (Chen et al 2015).

Some of the phosphorus, however, entered and accumulated in the biological cycle. Algae "filtered" phosphorus from the sea water, nourishing zooplankton, fish and birds. Birds are one vector bringing phosphorus back to land. Birds excrements were and still are covering (coral) islands such as Nauru in the Pacific ocean. The guano on Nauru created wealth on this island by exporting the "biological" phosphorus throughout the world in the last century.

Phosphorus is one of the most valuable part of bird excrements (guano). Renewable or "biological" phosphate resources as guano were always relatively rare due to the phosphorus hunger in the last century and therefore almost extinct. It does not even compare to the huge demand of industrial agriculture nowadays (Heffer et al 2014). Therefore, the Nauru guano as the one and only source of the islands´ welfare was gone within a mining period of just 50 to 70 years. Nauru was a paradise for sale (Gowdy et al, 2000), provided high quality "clean" organic phosphorus fertilizer (Weikard et al 2009) and may picture a thread of the world´s food security when phosphate rock once is gone (Schröder et al. 2010). Nowadays, Western Sahara seems to share the fate of Nauru (Lewis 2014).

Most of the phosphorus was deposited on the sea floor. It formed phosphate rock and consists of calcium phosphate mainly. Phosphate rock was deposited in extensive layers covering thousands of square miles. Due to geological processes the seafloor phosphate rock up-lifted above sea level. Phosphate rock is unevenly located at some places around the world (Fig. 1, https://www.mineralseducationcoalition.org/minerals/phosphate-rock). Hence the most of the phosphorus reserves still sit in the deep oceans and are unavailable for human usage (Smil 2000).

Thus, one may distinct two types of phosphorus resources, first a biological one that may be renewed within times of ecosystem cycles (guano and animal bones respectively), and second a mineral deposit type mainly consisting of calcium phosphate rock being part of long-time geochemical and geophysical cycles (Cordell 2010, Filippelli 2011). This geo-cycle has been accelerated by humans activity in particular by industrial agriculture measures that have increased the phosphorus run-off to the coastal seas by factor three within the last 50 years (Moss 1998, Smil 2000). The eutrophication process induced by additional phosphorus loads is well documented especially for the drainage basins of the Chesapeake Bay, the North Sea or the Baltic Sea (e.g. BEACON 2014, Costanza et al 1995, Köhn 1999, Laane et al. 2005, Smil 2000, Turner et al. 1999).

Production of inorganic fertilizers began during the 1840s with the treatment of phosphate rocks with dilute sulphuric acid. The resulting ordinary superphosphate (OSP) contains 7–10% phosphorus, ten times as much as recycled phosphorus-rich manures. Huge phosphate deposits were discovered in Florida (1870ies), in Morocco (1910ies) and Russia (1930ies) and laid the foundation for the rapid post-World War II expansion of the fertilizer industry (Smil 2002). The agricultural demand on phosphorus fertilizers is greater than the biological renewal rate, thus, the high consumption rate can only be met by mining and converting the mineral and non-renewable phosphate rock into phosphorus fertilizers. The global annual production of phosphate rock almost doubled from 1970 to 2010 (Prud´homme 2010).

The mineral Phosphorus stock

The worlds reserves of phosphate rock are located in Western Sahara (Morocco), China, South Africa, the US and Jordan mainly (Fig. 1). These countries host about 85% of the world reserves (Schröder et al. 2010). Mineral phosphorus is a nonrenewable resource, although phosphogenesis takes place in the oceans also on a low rate at present (Filipilli 2011), the phosphorus resources will be exhausted one day. Meanwhile, (1) the phosphorus content in the phosphate rock is decreasing, (2) the costs for exploration, mining and processing per ton phosphorus fertilizers and the amount of waste of the fertilizers processing are exploding (Zhan et al. 2008), (3) the number and amount of contaminants in the rock and in the finished fertilizer is increasing (Chen et al 2015), thus (4) the loads of unwanted substances such as cadmium and uranium to the environment (and consequently to feed and food) grow (Schnug et al 2014) whereas (5) the demand on phosphorus still increases (by about 1.4 percent annually, Heffer et al 2014) due to a growing world population and an increasing popularity of meat and dairy in human food (Schröder et al. 2010).

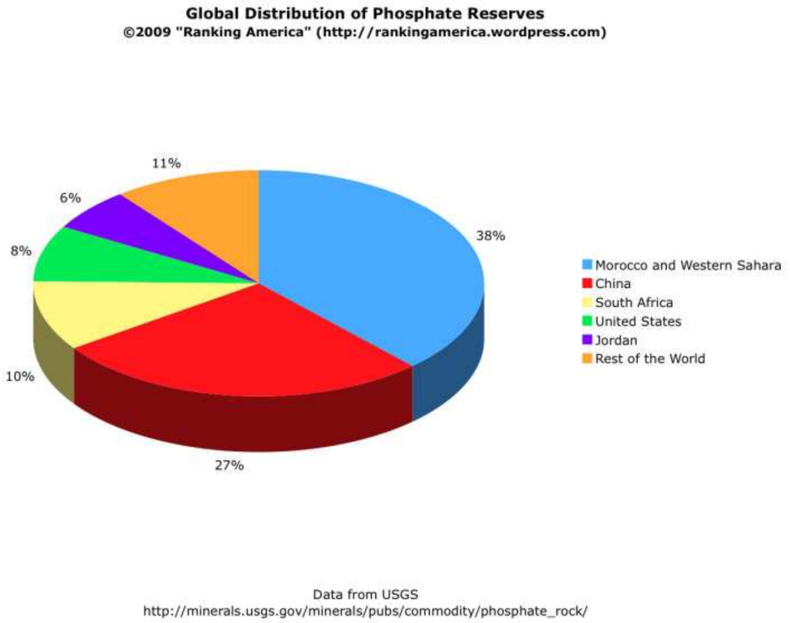

Figure 1. The distribution of global phosphate reserves (http://rankingamerica.wordpress.com)

Mineral Phosphorus - the only source of agricultural wealth?

A coupling of fertilizers application and agricultural wealth has only been observed since the second half of the 20ies century. Before World War Two the use of mineral fertilizers was almost to neglect. Organic fertilizers were used in an almost closed cycle, among them manure, guano, teeth and bone meal - corresponding to 5-10 kg organic phosphorus supply per hectare and year in Europe and Asia limiting the amount of crop yields (Smil 2000).

The Green Revolution in the agriculture in the developed countries led to a threefold growth in food production in the last 50 to 75 years. Along with those increases in yields the demand of fertilizers (nitrogen, phosphorus and potassium) grew concurrently. The growth was exponentially mainly in the US, Canada and (Western) Europe from the 1960ies to the 1990ies when soils were over-supplied and the application rate of phosphorus especially in Europe stagnated (Munson et al 1959, Childers et al. 2011, Jat et al. 2012, Schröder et al. 2010, Smil 2000).

However, the application of inorganic phosphorus as fertilizer is of paramount importance in agricultural industry still. More than 90 percent of the globally mined phosphate rocks is used in the agricultural sector, 82 per cent to fertilize farm land and 9 per cent as an additive to animal feed. It is considered indispensable for food production and thus to sustain food security (Shakhramanyan et al. 2012). Schröder et al. (2010) report on application rate on arable land in Asia and Northern America of 10 to 13 kg per hectare and year, 6 in Europe, and 2 in Africa. About 3 kg phosphorus per hectare and year are harvested for instance per ton grain. Phosphorus shortage in feed may harm substantially the livestock health, especially dairy (Grünberg et al. 2015).

Only four countries count for 64 per cent phosphorus consumption worldwide: China, India, USA and Brazil. The EU consumes another 10 per cent. Special crops such as soya or oil plants demand even higher application rates of phosphorus fertilizer (25 - 30 kg per hectare and year, Schröder et al. 2010). However, some 80 per cent of the phosphorus get lost along the path from mine to fork to plate. Eventually only about one-fifth of the pure phosphorus extracted from phosphate rock is consumed as food (Neset et al 2012).

The demand of phosphate fertilizers shifts from the developed world towards the developing regions such as SE Asia or Africa now (Amanullah 2011, Jat et al. 2012, Motsara 2002, Ryan et al. 2012, Sanchez et al. 1997). It is still increasing globally at about 1.4 per cent per year (Heffner et al 2014, Zhang et al. 2008).

2. Phosphorus scarcity - peak phosphorus?

Phosphorus is 11th frequent element on Earth lithosphere, essential for life but rather scarce in the biosphere (Smil 2000). Most of the phosphorus resources are unevenly spread around the world and therefore form oligopols on the supply side of the market. Only a handful (in some cases state owned) suppliers may override the market, dictate prices or shorten quantities. The situation makes the prices for phosphorus very volatile as seen between 1974-5 (peak prices were above 1.800 $/t) and in 2008, when prices jumped of 800 to 900 per cent (peak prices 1.200 $/t). The market price for phosphorus is about 200 $/t on average (farm gate prices are higher and depend from many other aspects). The 2008 price shock called economists to study phosphorus markets and to assess how long phosphorus still can be used (Cordell et al. 2009, 2011, Heckenmüller et al. 2014, Schröder et al. 2010). Since phosphorus prices are very volatile and oil crops require considerably high amounts of the fertilizer to achieve and sustain high yields this impact can be seen reasonable for the price spike in the early 2000ies (e.g., Smil 2000). The more the first price jump in phosphorus in 1974-5 occurred always simultaneously between the two oil price shocks. A market that shows very similar economic properties (Heckenmüller et al. 2014).

Cordell et al. (2009) introduced the peak phosphorus concept illustrating the shortage of the phosphorus resource. Their model bases on the presently known stock, today´s exploitation rates and expectations on future demand growth. They estimated that the global peak for phosphorus production is likely to occur as early as 2033. They defined the term “peak phosphorus” a point at which the production of phosphorus from phosphate rock reaches its maximum due to the decreasing availability rock deposits, the declining phosphorus content of the rock, assuming a steadily high or growing demand on the resource. Cordell et al. (2009) used the a Hubbert styled resource model to assess the longevity of the resource assuming that phosphorus might be behave similar to the oil resources (Hubbert 1979). Cordell et al. (2011, 2015a) corrected their estimates, according to their calculations, peak phosphorus may occur some years later - in 2070 or after 2300. If the demand of a non-substitutable, essential and non-renewable resource clearly is larger than its supply in the long run we are faced with a phenomenon economists call a "cake eating problem" (Hotelling 1931).

The cake - phosphorus - can be eaten up only once. By the end the resource, the cake, is gone completely. However, one may influence the rate of consumption by various political or economic measures. Thus, different models show the impact of those measures on the consumption rate, the remaining resource stock at a particular time and its longevity (Drangert 2012) and phosphorus is recyclable at least in part. However, models such as the cake eating one illustrating the scarcity of a resource use prices as indicators for an economic scarcity. Prices reflect the economic scarcity of a commodity. The higher the prices of a (normal) good the more scarce the resource. Hence, economic scarcity includes not only the physical shortness of a resource but also is it worth or economically feasible and viable to continue extracting phosphorus from the rock. One has to acknowledge that there are some problems involved that make the "cake eating model" not applicable to the phosphorus market. Heckenmüller at al. (2014) state after their economic analysis of the peak phosphorus model that the peak unlikely will occur in this century. The price peaks in 1974-5 and 2007-8 based on other reasons. They and others assumed that food prices (feed back mechanisms), some environmental conditions and the financial crisis in 2008 caused the price shock in phosphorus rather than the price set a physical scarcity signal. Clift et al (2012) assumed that policy induced the price jump in the phosphorus market. The political target to substitute as much as possible fossil fuel by biological ones for climate change reasons may have caused that market players speculated on increasing phosphorus demands. The uncertainty in such assessments is high and the model requirements are not met in phosphorus: (1) Phosphor is not a homogeneous resource. The phosphate rock species worldwide contain different amounts of phosphorus (and along with it different elements that gores along with it) depending on the mine and therefore would need different technologies to process (decontaminate) it to clean fertilizers. (2) Since phosphorus is distributed in clusters around the world there are political issues involved in the pricing of phosphorus resources that make a prediction almost impossible. (3) As in other mineral resources too low grade stocks that are not even known at present and, therefore, might become exploited later because of improved technologies (innovation aspects) or as a by-product to other resources (maybe uranium).

There are enormous losses along the mining, processing and application line that can be avoided. "Peak phosphorus" thus rather is a concept to draw attention and awareness on this resource. Hence phosphorus it is by no means a finite physical resource (Smil 2002a, Scholz et al 2013) and if handled efficiently it may last almost for ever (Drangert 2012). But, from the economic point of view if taking into account the production costs, political interference and properties of non-open access markets one may declare phosphorus an economically scarce resource (Cordell et al. 2009).

Giraud (2011) argued for some reason that a Hubbert-style analysis, the tool used by Cordell et al. (various papers), depend on a set of specific conditions that are not apply to phosphorus. He argued that there are two important qualitative differences between phosphorus and carbon-based fossil fuels: (1) phosphorus is in principle recoverable after use but (2) is not substitutable by any other resource because it is an essential element for almost all life-forms (quoted in Clift et al 2012). Vaccari et al (2011) show that a Hubbert analysis cannot be used in this case since there is no substitute for phosphorus.

More dynamic models contradict at least in part the peak phosphorus model and shift the awareness of the phosphorus scarcity discussion to other important aspects of the issue. Scholz et al (2013) show in their analysis that the phosphorus resources are underestimated, that many aspects a Hubbert analysis requires are not fulfilled in the case of phosphorus (such as innovations, various markets, many stakeholders etc.) and that the reserve consumption ration in phosphorus is rather high compared to other resources.

However, beside the quantity and longevity dispute on phosphorus the peak phosphorus model increased the awareness on this particular resource and caused scientific interest that up to date generated several thousand publications on the topic since. Whereas natural scientists focused on phosphorus from the environmental impact aspect since the 1970ies as the main cause for eutrophication and (environmental) economists take a stake in this discussion seeing the pollution effect (see for instance Costanza et al 1995, Köhn 1986, 1999, Turner et al. 1999), the discussion got enriched by many transdisciplinary aspects of the phosphorus problem from mine to fork (and human health) and back to the oceans. Almost 90 per cent of phosphorus is lost along the application line to the environment (Clift et al 2012). The phosphorus cycle is an open one at present. There are no or only little economic incentives to change this chain into a close cycle for a sustainable use of phosphorus (Molinos-Senante et al. 2011).

Properties of phosphorus as a resource in markets

Many aspects make the phosphorus "problem" a very complex one.

(1) Most of the phosphorus resources are unevenly spread around the world. This situation restricts market forces. Suppliers may form market cartels. Those entities may dictate prices or shortening supply quantities. The oil market may serve as an example for those markets. One may see the market power of the cartel reasoning the price volatility in phosphorus markets being observed in 2008 (Schröder et al. 2010). Moreover, the resources of the world largest supplier Morocco are still due to dispute about the Western Sahara political status (Lewis 2014). Thus, political conflict may interfere in the phosphate rock market too.

(2) Phosphate rock is not a uniform but multi-resource commodity. The phosphorus content within phosphate rock varies from region to region and within one region even from mine to mine (Zhan et al. 2008). The economic viability of resource exploitation may also be influenced by trace elements accompanying phosphorus in the phosphate rock. If extracted before or simultaneously the drivers in trace element markets may interfere in the phosphorus markets (Chen et al 2015, Kratz et al. 2015).

(3) Thus, the extraction technologies differ for the reason what else could be extracted for economic or environmental reasons. Uranium extraction from the rock may serve as an example (Habashi 1960, Nomura 1961, Shakir et al. 1992, Schnug et al 2014). Phosphorus in those extraction processes is a by-product only and may be dumped at lower prices into agricultural markets if uranium is in the market focus rather than phosphorus.

(4) One may recycle phosphorus from various animal, human, municipal and industrial wastes. It may be recovered from ecosystem restoration processes too. That slows down the rate of depletion, pre-longing the lifetime of phosphorus resource stock and, being part of a more sustainable phosphorus strategy. Hence, such a strategy would demand also that recycled phosphorus must be free of adjuvant contaminants at least meeting the valid legal limit values defined by the German Fertilizer Ordinance respectively. Additional costs for the required decontamination have to be included in the costs functions in recycling processes.

(5) One may assume that the shorter the resource phosphorus will be for economic reasons the more attractive are any option to recover it from waste or the environment. Various economic instruments such as taxes have been already proposed to induce this process during the peak phosphorus debate.

It is obvious that are many uncertainties involved in the complex phosphorus market that do not allow for precise predictions (Johnson et al. 2013). The main barrier to understand the phosphorus market is that phosphorus rock has been always treated a one resource market neglecting that the ore itself is a collection of (trace) elements. Some of them are of increasing economic interest that may make phosphorus a by-product of the extraction process if they are of economic interest, other elements harm the environment and consequently livestock and human health. This requires to extract these elements from the ore before the phosphate fertilizer is spread to the farmland. However, the only thing we know for sure is that the mode we treat and use phosphorus as a resource has accelerated the natural geological process of phosphorus erosion to coastal and open sea sediments along with human caused processes of eutrophication and soil contamination (e.g., Smil 2002a).

Phosphorus scarcity and food security

The peak phosphorus concept and the economic interest in the life time of phosphorus resources was instantly linked to the food security issue. Hence, the interpretation of economic scarcity of phosphorus was limited to the quantity of the stock only. But, if food security is at stake there are other aspects to be considered:

(1) A steadily growing world population need food (Cordell et al. 2009, Schröder et al. 2010). But food consumption modes had changed many times in human evolution. Nowadays, food consumption closely linked to urbanization and the economic situation of the families. An increasing income shifts the nutrition mode towards more meat and dairy products. This, however, ends in an inverse U-shaped function: the shift towards meat and dairy stops at a certain point and get inverse. However, at first the shift to meat and dairy demands more phosphorus in food production and may create additional losses along the fertilizer to fork chain (Ma et al. 2014, Metson et al. 2015, Ryan et al. 2012). Hence this aspect is only one part of the truth since it makes the phosphorus part of the food concentrated in urban systems and thus easier to recycle from human excreta (Drangert 2012).

(2) The downslide of the U-shaped curve is related to a decreasing demand in meat and diary in the developed countries (Mathijs 2015, Vranken et al. 2014). Smil (2002) showed that the data on phosphorus fertilizers application went down in developed countries according to this trend, especially in Europe, where the oversupply of phosphorus in the 1980-90ies (Harenz 1991) is almost over. This may also result from changing legal obligations and new farming technologies such as precision farming using GIS in Europe and Northern America (Iho et al 2012).

(3) A vegetarian nutrition demands only about half of the phosphorus to produce the caloric value of daily food (Schröder et al. 2010). Hence vegetarian food does not contain all trace elements and vitamins humans need for their health. Humans are not made for vegetarian food alone (Döll 2005).

(4) Food security also requires that the food we eat and drink does not harm humans health. The loads of phosphorus in the food itself and the adjuvant contaminants within the phosphorus fertilizers may cause sever diseases that are like epidemics contradict the term food security (Burlingame et al 2014, Döll 2005, Huffmann 2015, Kratz et al. 2015, Reijnders 2014).

(5) Food security implies that humans get food from healthy environments otherwise they need part of their food (or additives) to cure the effects of diseases that stem from polluted environments (e.g., allergies, Huffmann 2015). Livestock health counts as well in this aspect (Grünberg et al. 2015).

3. External effects

A short introduction into the theoretical concept

External effects occur if not all aspects resulting from the production and consumption process are included in the products prices. Positive external effects increases the overall value of a commodity or service but nobody pays for these extras. For example, a forest used for timber production also improves the (micro-)climate, host songbirds or serves as recreation ground but the owner of the forest get not paid from users, e.g. vacationers, birdwatchers or hunters, for the ecosystem services he delivers. Thus, the positive external aspects increase or sustain local, regional, national or even global welfare but are usually not measured in monetary terms, get compensated and therefore are not calculated in the GDP. To the contrary, negative external affects are almost all unwanted but are hardly paid/compensated from the polluter. If so, polluters have not to pay for damages related to their doing and thus the damage will not be compensate to the victims, the environment or other. Since the polluter does not acknowledge the impacts to the environmental or social system they are outside - external - to his private costs and price calculations. Thus, those costs are shifted to the society.

Both positive or negative external effects occur along the whole life-line or life-cycle of a certain product, service or commodity. To assess all the positive and the negative aspects along the life of a product or commodity the concept of life-cycle assessments (LCA) has been introduced in the 1990ies. One may earmark all known aspects with prices and create comprehensive Cost-Benefit-Assessments (CBA) along the cradle-to-grave lifetime of a good, service or commodity (Köhn et al 1996).

Thus, prices hardly tell the truth regarding and acknowledging social, cultural, ethical, or environmental aspects. To overcome this shortage in the price building process some measures and methods have been developed in the last hundred years starting with the Pigouvian tax in the 1920ies (Pigou 1920). Economic theory have paid a steadily increasing attention in those especially environmental aspects for about fifty years now. They all target on valuations of these affects in economic terms. Once costs are known they can be internalized in prices of the goods. According to the economic theory this integration into the product price will support to mitigate unwanted affects to the environment whether while the product gets out the market because its price is no longer competitive or part of the sales price is used for compensation. Methods developed in this context are for instance Transferable Pollution Rights (TPR, e.g. Kampas et al 2006), Production Costs Method (PCM) for the product itself (see LCA, e.g. Hasler et al. 2015, Wu et al. 2015) or the costs to mitigate the negative external effects e.g. in a sewage plant, the Contingent Valuation Method (CVM, e.g. Nelson et al. 2015), Travel Costs Method (TCM), Willingness-to-Accept (WTA) or Willingness-to-Pay (WTP) assessments (Bromley 1995).

A sustainable use of phosphorus demands an internalization of all external costs into the phosphorus price (Innes 2013, Shakhramanyan et al. 2012) for both closing the phosphorus cycle encouraging recovery technologies of uncontaminated phosphorus fertilizers for instance in Europe, having no natural phosphorus resources but consuming about 3 kg per capita a year, and to compensate unwanted effects to the environment in full (Schröder et al. 2010). Hence, an economic system that assures the full integration of social costs into the private calculations of all suppliers requires conditions that are not fulfilled whether in the supply nor in the demand side - phosphorus markets are not really open markets. That is one source of uncertainties in the phosphorus markets and makes predictions quite hard.

Ulrich et al (2014) show in their analysis that the world market price may only reflect a fourth of the farm-gate-price, thus along the supply chain are many other aspects to acknowledge that makes it difficult to see the price a real indicator for the scarcity. Moreover this makes it almost impossible to see any effect of market instruments like taxes since they will be always only a little compound of the final product price in relation to other aspects (Shakhramanyan et al. 2012).

From mine to fork or plate and back to the ocean

Phosphorus, nitrogen and potassium together form the so called macronutrients and thus are in a certain stochastic relation essential for all life - microbial and macroscopic. All biotopes need to be nourished by macro- and micronutrients. If nutrients get short in specific environments they need to be added or applied on at least plants demand. The higher the energy and material turn-over or productivity of a certain system the more of these nutrients are required or if exhausted need to be added. Thus, adding phosphorus to plant growth enabling agro-industrial production a doubling or tripling of yields is a positive effect. However, not all of the applied nutrients are instantly transferred into plant growth (Larney et al. 1997). They are stored or transformed in soils depending on soil properties and conditions, some of them among these phosphorous can be immobilized in soils. Others are transported by soil erosion into neighboring or adjacent ecosystems and may cause unwanted environmental effects such as eutrophication in surface waters or may along with other elements also pollute or contaminate groundwater (Ashley et al. 2011, Schröder et al. 2010). Those effects are negative and mostly external to the crop price calculation by farmers (or traders) and, thus, not be compensated by the price of the final good by the consumer. External effects are observed in each and every step along the life chain from phosphorus mining to the final consumption of food. Only one fifth of the mined phosphorus is eventually been eaten in the best case, the rest is lost along the use chain from mine to plate (see e.g. Schröder et al. 2010). We grouped the externalities along the phosphorus use chain into six groups: (1) externalities and inefficiencies in the production process of phosphorus fertilizers, (2) externalities occurring due to the specific behavior of phosphorus in soils after application, (3) contaminants that accompany phosphorus fertilizers causing environmental and maybe also health effects, (4) phosphorus losses from fields and pastures to the environment causing environmental effects such as eutrophication of water ecosystems, (5) increasing phosphorus demand due to human food preferences that changes with increasing income, and (6) excrements discharge to the environment from municipalities and staples but providing options to recycle phosphorus from this wastes.

(1) In 2008, respectively, about 180 Mt phosphate rock were mined and 17.8 Mt - one tenth (!) - applied as fertilizer phosphorus to fields globally (Prud´homme 2010). Already phosphate rock mining and processing to phosphorus fertilizers causes drastic environmental burdens and counts for huge losses. In China respectively, from every 10 kg phosphorus in ore, only 3.9 kg P were used to produce fertilizer, 5.6 kg of the residues were discarded at the mining site, and 0.5 kg get manufacturing waste (Zhang et al. 2008). Smil (2000) reports a 12 t phosphogypsum waste pile resulting from processing 1 ton phosphorus in the US. The Environmental Protection Agency banned phosphogypsum from any use because it contains radium. Thus, along with the low rate of phosphorus used from the rock, a huge and still increasing waste problem arise. Energy costs are also high in extracting and processing ore to fertilizer (Zan et al. 2008). They are as high as 16 per cent of the product price (Schröder et al. 2010).

(2) Phosphorus losses continue to appear on the field. Depending on soil properties some of the phosphorus instantly might be stored in the soil, almost unattainable for the crop plant, or washed out to surface waters (Smil 2000, Ryan et al. 2012). Clift et al (2012) reported on almost 90 per cent losses of phosphorus after application according to leaching from soils and animal excreta in relation to inputs. Leakage may be avoided by better management practices and losses can be compensated by recovery technologies. Phosphates in soils rapidly transform into insoluble forms no longer contributing to yields. Smil 2002a reports on recovery rates of 50–60% of the initially fixed phosphorus in the following years. This effect is caused by changing physical or chemical soil conditions but also symbiontic impacts of ekto- or endo-mycorrhizal fungi and bacteria. Thus, after decades of relatively high phosphorus applications and the gradual release of the initially fixed nutrient of the "old" applications add to considerable surpluses of available phosphorus in many agro–ecosystems.

(3) Not only phosphorus is accumulated in soils. Along with phosphorus other (unwanted) components of the fertilizer are found enriched in fields and pastures, e.g., radioactivity due to the content of uranium and thorium in the fertilizer depending on the mine the rock was extracted from (Ulrich et al. 2014). Other contaminants are respectively, cadmium accumulation (McLaughlin 2014, Smil 2000) or fluorine emissions (Schröder et al. 2010).

Along the losses of phosphorus in the environment contaminants in the phosphorus fertilizers accumulate in crops or hidden plant growth (Kratz et al. 2015). Cadmium is the most enriched element in phosphate rocks, occurring in concentrations almost 70 times higher than in average shale. The global average of cadmium levels in phosphates is about 21 mg cadmium per kg of rock, but some Moroccan rocks have up to 40 mg, and phosphates from Togo and Tunisia contain up to 50–55 mg cadmium per kg. The lowest cadmium concentrations are found in Florida phosphate rock. Cadmium is enriched in the food web and add to the cadmium in fields (Smil 2000). Since cadmium is not stable if the ore would be heated up to more than 400^{o}C it could be removed from the fertilizer easily by "cooking" the milled phosphate rock. This procedure is energy intensive and increases costs for the fertilizer, but according to the pre-cautional principle the procedure should be mandated from policy to avoid a further enrichment and contamination of arable soils. The process would be similar to the cement production or the clinoptilolith activation, thus, approved in the industry. Moreover, if the demand for phosphorus decreases due to a high recycling rate from waste along with clean-up processes the contamination risk may be reduced too (e.g., Haneklaus et al. 2014).

(4) In addition, the use of phosphorus in agriculture is not balanced. The import of phosphorus to any agricultural entity exceeds the export to feed, food, meat or dairy products. Thus, we are faced with a phosphorus surplus that correspond with losses to the environment or an accumulation in the soil (Innes 2013, Schröder et al. 2010, Smil 2000).The main environmental concern is on leakage of phosphorus from arable land and pastures. Whereas phosphates in soils rapidly transform into insoluble forms making the element commonly the growth-limiting nutrient, in aquatic ecosystems it stimulates algae growth. Since nitrogen may cause eutrophication through biological and airborne pollution processes, phosphorus seems to be the only responsible factor for eutrophication that can be managed in point-pollution and at drainage basins scales. Although, many crops use the nutrient with relatively high efficiency, lost phosphorus to surface waters is commonly the main cause of eutrophication (Moss 1998, Vezjak 1998). The phosphorus content in the open water exposed to light is the key factor enabling and stimulating phytoplankton growth in aquatic systems. Redfield (1958) set the average C:N:S:P atomic ratio for marine phytoplankton at 106:16:1.7:1. This ratio has been proven right in many ecosystem studies in the coastal zone. The eutrophication process may alter the whole aquatic ecosystem, harm the ecosystems resilience and cause shifts towards unwanted states of the ecosystem (e.g. Duckstein et al. 1978, Gunderson et al 1995, Smil 2000). Phosphorus leakage from farmlands is seen the most unwanted thread to the environment (BEACON 2014, Laane et al. 2005, Rao et al. 2009, Schreiber et al. 2003, The Wisconsin Department of Natural Resources 2012). But not in all cases the phosphorus surplus on fields correspond with the erosion load to rivers and consequently to the coastal zone (De Wit et al 1999). Smil (2000) calculated about 10 kg phosphorus losses per hectare and year in average worldwide. Schröder et al. (2010) estimate the losses from farm to plate as 75 to 80 kg phosphorus per 100 kg fertilizer phosphorus. The main problem with phosphorus pollution from farmland is that the leakage is non-point and diffuse. There are many studies on the amount of phosphorus losses in watersheds calculated with GIS models. The papers show that GIS models allow for specification on field bases where leakage is likely to occur and on which sites is not (Meals et al. 2008, Kovacs et al. 2008, 2012). Losses of phosphorus through drainage systems to surface waters is the main bulk and might by as high as almost 70 per cent of input (Tetzlaff et al. 2009). The measured and calculated data on phosphorus losses often exceed the phosphorus reference values in European waters at some locations by factor three or more. European standards set by the Water Directive are hardly met and might never by met if the mode of agricultural production will not change (Bowes et al. 2010). The European rivers and coastal seas are over-loaded with phosphorus that stimulates especially in the coastal zones phytoplankton growth, subsequently resulting in high sedimentation rates that may cause oxygen deficiency destroying the seafloor biotopes (Köhn 1986, 1999). Whereas point source pollution can be managed technologically and phosphorus can be recovered almost complete (Drangert 2012), leakage and runoff from farmland require systems holding

back and collecting phosphorus downstream. The phosphorus loads from point sources, mainly urban from municipal or industrial waste water, or rural diffuse sources, mainly agricultural areas, tilled fields or pastures, are "registered" and quantified for many locations in Europe and Northern America on the level of drainage basins. For many of these sites also abatement strategies have been installed and the economy for these mitigation strategies have been documented. The best strategy to reduce phosphorus losses from agricultural land reported in studies is the use or the installation of wetlands in the drainage area before the loads enter the surface water (lakes, rivers) or get into groundwater aquifers. Restored or constructed wetlands are options to collect in sediments, harvest (as plants) and recycle phosphorus from soil erosion and run-off (Mitch 1992, Kladec 2006, Lu et al. 2009, Rousseau et al. 2004, Scholz et al. 2010, Wang et al. 2008).

(5) Agricultural crops are fed by about 60 to 90 per cent to livestock in developed countries (World Resource Institute 1994, Harenz 1991, Schröder et al. 2010). Meat and dairy consumption is one major driver of the increasing phosphorus demand. While the meat and dairy consumption stagnates in the developed economies in Northern America, Australia and Europe it increases due to population and income growth in developing countries espcially the BRIC states. Total meat production in the developing world tripled between 1980 and 2002, from 45 to 134 million tons (World Bank 2009). The animal-based protein consumption grew driven by economic development and urbanisation from 61g per person per day in 1961 to 80g per person a day worldwide in 2011 (Sans et al 2015). The demand for animal source foods has more than tripled over the past 50 years due to population growth and dietary change. 56 per cent of animal calories would be free to humans in terms of crop use (Davis et al. 2015). Despite this several authors dispute the effects of increasing meat and dairy consumption on health (e.g., McAfee et al. 2010, McNeill et al 2016). Säll et al (2015) propose introducing a meat and dairy tax to balance out the effects of livestock to the environment and to reduce meat and dairy consumption to a rate that may also meet human health standards.

(6) Excrements of livestock and human contains phosphorus. Excrements are collected in municipal sewer systems, in manure tanks or remain disperse on pastures adding to the run-off into rivers, lakes and coastal waters. The collected organic wastes from point sources (manure tanks near to staples, municipal sewer systems) are the main source for phosphorus recovery as "organic" fertilizers to fields. Phosphorus recycling rates from these waste stream are technically and economically feasible up to 97 per cent.

To conclude, collecting and removing phosphorus from human and livestock excrements applying it as fertilizer to arable land may reduce the demand on phosphorus, mitigate the negative (environmental) impacts along the mine-to-plate lifeline, and support making the lifeline an almost closed cycle (Burns et al 2002, Drangert 2012, Metson et al. 2015, Renman et al 2010). Thus, this strategy is supposed to avoid as much as possible negative external effects, making a sustainable phosphorus consumption and safe food production feasible and viable (Childers et al., 2011).

4. Strategies to abate the phosphorus losses to the environment

All of the listed externalities bear chances coping with the individual problem at stake, might it be through changes in technology, agricultural management or behavior of the consumers. Some aspects are interlinked and may stimulate each other synergetically. For instance, if the phosphorus cycle can be almost closed at least in the developed countries the losses during mining and processing will substantially decrease because of the shrinking demand in Europe respectively (Drangert 2012). Two paths are responsible for phosphorus losses once it has been applied to fields: (1) Phosphorus that is not used by the crop directly and cannot be stored for later uses by the crop enter the environment by soil erosion in punctuated events like storm waters or being washed down to river basins or to the groundwater on the water path (mainly non-point sources), or (2) being exported as food to cities or feed to staples (point sources). The later path opens many options to recycle phosphorus as a part of processing waste like bones and other slaughterhouse waste, human excrements (sewer) and (collected) manure. The main focus of this chapter is on the reduction the environmental impacts during the application in agriculture, thus, the losses of phosphorus from the soil to surface waters and groundwater. A high application rate for nitrogen, phosphorus and potassium started industrial farming in the developed countries in the late 1950ies early 1960ies especially in (Western) Europe, the US and Canada being the main course for the green revolution, went through a peak of application in the 1980ies and stagnating on a rather moderate level since. From an economic point of view overfertilization let the Net Present Value (NPV) of phosphorus fertilizer decreases since plant growth is stimulated only to a certain threshold point (Nyborg et al. 1999). Thus, every crop has a specific demand corresponding to environmental and soil conditions and can be applied to this threshold level. Acknowledging this level in the crop management will not only improve the environmental performance but also the economic one. However, other areas in the world are far from overfertiliziation especially Sub-Sahara, Southeast Asia and Latin America (Jat et al. 2012) and still seek for higher application rates to join the green revolution (Ryan et al. 2012). A lower application rate in the developed countries along with increasing recycling rates reduces the pressure on the phosphate rock resource worldwide. This way phosphorus fertilizers may become more available to developing countries (Weikard et al 2009) if prices permit the use in those regions too.

Concurrently to the expanded use of phosphorus the diffuse non-point source losses to the environment increased causing eutrophication (e.g. Buckley et al 2013, Harenz 1991, Smil 2000). The phosphorus "pollution" along and to waterways only can be managed both environmentally and economically on a drainage basin scale before the run-off reaches the coastal zone. Thus, numerous papers calculated critical loads for various pollutants to avoid downstream and coastal zones eutrophication (Cameron 1997, Costanza et al 1995, Folsom et al 1980, Goetz et al 2000, 2005, Hajkowicz et al. 2008, Hasler et al. 2015, Kampas et al 2006, Schreiber et al. 2003, Sohngen et al. 2015, Tetzlaff et al. 2009, Turner et al. 1999). Hence, once the phosphorus has left the field or pasture only natural or constructed wetlands may collect phosphorus before it can enter the waterways and eventually the coastal sea (Bassia et al. 2014, Dune et al. 2015, Mitch 1992, Günther 1997, Kadlec 2006, Lu et al. 2009, Scholz et al. 2010, Wang et al. 2008).

In the light of the price peak in phosphorus in 2007/8 many authors demand closing the phosphorus cycle to avoid further losses along the mine to fork or plate chain by inducing taxes (e.g. Innes 2013, Säll et al 2015, Shakhramanyan et al. 2012). The high prices at that time plus the shadow prices of negative external (environmental) effects would make almost all recycling technologies for phosphorus competitive to phosphate fertilizer processing from rock and transportation prices (Molinos-Senante et al. 2011, Seyhan et al. 2012).

5 Measures to recover phosphorus from various wastes

Phosphorus recycling is a necessity for many reason not only the application to farmland for agricultural crops. The shadow prices of ecosystem losses caused by phosphorus run-off into water, but also the external costs of the fertilizers production (Zhang et al. 2008, Schröder et al. 2010, Seyhan et al. 2012) call for phosphorus recovery also. Schröder et al. (2010) demand closing the phosphorus cycle almost at 100 per cent including an uncontaminated recovery of phosphorus from waste streams in plant-available forms (Römer 2006).

Sources or means are for instance agricultural waste (manure), municipal waste water or industrial waste or lake restoration (sludge) or wetlands that accumulate phosphorus as traps for run-off waters (Bowers et al. 2005, Cordell et al. 2011, Kaikake et al. 2009, Lamprecht et al. 2011, Lang et al. 2006, Marhual et al. 2011, Maurer et al. 2006, Renman et al. 2010, Shimamura et al. 2003, Shimamura et al. 2008, Schiemenz et al. 2010). All these studies conclude that sizable quantities of phosphorus can be recovered from wastes. Moreover, an almost closing the phosphorus cycle seems to be technologically feasible if but only if the economics fit (Molinos-Senante et al. 2010, Seyhan et al. 2011).

Smil (2002) calculated the recyclable phosphorus potentials of animal excretes. Livestock produces 2 Gt of dry waste containing up to 20 Mt P annually. Hence, only the wastes produced in confinements are recyclable but, because of their bulk, uneven distribution and excessive cost of application beyond a limited radius from the source, not all of this manure is actually applied to fields. He estimated that about 8 Mt phosphorus (40 per cent) can be returned to fields, with the highest applications exceeding 50 kg P per ha in regions with high animal density as in the US Corn Belt, in Northwestern Europe and in East Asia. The other 60 per cent of manure need to be processed to fertilizers and shipped to areas where they are applied to farm land. Prud´homme (2010) reported a 17.8 Mt fertilizer phosphorus application to fields globally. That figure almost equals that of livestock dry waste in early 2000s.

Digestate from biogas fermentation is another agro-industrial source for phosphorus removal. The biogas output can be enhanced by adding bone char or clinoptilolith to the fermentation process. Both additives bind nutrients that are plant available (on demand) after the digestate is applied to fields (Bolan et al. 2004, Siebers et al 2013).

Smil (2002) calculated the phosphorus discharge from the human population also. According to his figures from the year 2000 human excrements contain more than 4 Mt phosphorus a year now. Annually about 9 kg phosphorus per hectare a year are generated in cultivated and settled land in densely populated countries like Egypt or Japan, and more than 100 kg phosphorus per hectare a year in large cities. Most of this phosphorus is discharged to the environment (Metson et al. 2015). Many technological attempts are reported in literature to remove phosphorus from the waste water stream to protect the environment and to use the phosphorus from these processes as fertilizer (e.g. EPA 2007, Paul et al. 2001, Sartorius et al., 2011).

If the calculations on phosphorus from livestock and human excrements are right - and they have to since the daily rate per capita of each animal species and an average human are known, the annual demand of phosphorus fertilizers could by met by recycling from point source pollution alone. Hence, as in every cycle of matter one has to acknowledge at least some losses (Jeanmaire et al 2001). Bowes et al. (2010) reports that sewer treating and extraction from phosphorus from the discharged of treated water will not be sufficient to meet the standards of European Water Directive. The challenge ahead is to reduce the losses as much as economically feasible (Balana et al. 2011, Martin-Ortega et al. 2015).

However, looking on the phosphorus balance sheets for big cities especially the recycling rates from sewer treatment systems results are not very optimistic. The recycling rates from cities to agriculture are as low as 10 per cent even in cities like Stockholm (Wu et al. 2015) and thus only as high as in Beijing (Ma et al. 2014). The phosphorus import into the cities steadily increases with food but leave the cities as waste to landfills (Cui et al. 2015, Ma et al. 2015, Metson et al. 2015, Schmid-Neset et al. 2008, Thitanuwat et al. 2015, Wu et al. 2015).

Thus, the recycling from waste that is currently shipped to landfills forms the major source of phosphorus recycling from cities at present although it might be technologically easier to collect it from sewer and waste water treatment sludge directly. Anyway, landfills may become an alternative source for phosphorus if the strategy will not be changed. Meanwhile, technologies to cope with the phosphorus containing wastes are on request. These technologies have to cope not only with the phosphorus recycling but also with mitigating or eliminating contaminants.

Pyrolysis of various waste streams has been shown an option to recycle phosphorus. One example is slaughterhouse waste that has been transformed in bone char and gases. Whereas the gas contains almost all critical contaminants and can be cleaned and transferred into syngas and a waste fraction, the bone char was proofed under greenhouse and environmental conditions a reliable source for phosphorus (and other minerals), supporting and protecting plant growth. Ashes may do also but the strengths of bonechar lie in multiple functions: It stores fertilizers and minerals making them available on plants´ demand, regulates moisture, fixes contaminants, enables soil biozoenoses (plant roots, bacteria and mycorrhizal fungi) that protect plants against pests or bugs (Kleemann et al. 2014, Shepherd et al. 2014, Siebers et al 2013). Withers et al. (2015) propose a seed dressing to enable the symbiosis along with biochar application. Hence pyrolysis is not accepted in Europe than in SE-Asia respectively. Europe is in favour of incineration sludges to ash. Field and greenhouse applications in Canada, Mexico or Germany have shown that seed dressing or seed coating with bacteria and endomy corrhizal fungi reduce the phosphorus demand whereas the crop yield still increases (Wulff, pers. communication).

The myccorhizal symbioses also may decontaminate soils (Baum et al. 2013) and sludges or make phosphorus that has been fixed in soils plant available again (Kaur et al 2015, Kucey et al. 1989, Sharma et al. 2009). The bone char substrate might be combined with specific bacteria that enrich phosphorus from metal industry sludge (Marhual et al. 2011). Bone char myccorhizal symbiosis may decontaminate this sludge and can be recycled in an additional pyrolysis step (Siebers et al 2013). Myccorhizal symbiosis also decontaminate along with short rotation coppices (willow or poplar) sewer sludge from e.g. cadmium. The woodchips deliver energy in a pyrolysis process and the char can be applied almost decontaminated but rich in fertilizers and minerals (potash) to farmland (Langeveld et al. 2012).

Another option for recovery is collecting phosphorus in natural or constructed wetlands from drainage basin and stormwater run-off (Sample et al. 2012). There are various options of collecting phosphorus; in the sludge (Wauer et al. 2005), in plants (algae or reed, Gunterstam et al. 1998, Hansson et al 2004, Kadlec et al. 2006, Quilliam et al. 2015, Lu et al. 2009) or animals (Spångberg et al 2013) or by bacteria (Wang et al. 2008). The rate of phosphorus removal in those wetlands (in best cases up to 52 per cent, Rosseau et al. 2004), however, is not as high as the aquatic environment downstream demands to restore or to meet the requirements of the European Water Framework Directive (Scholz et al. 2010, Woltemade, 2000, Zamparas et al 2014). Moreover, sludge from lake or wetland restoration may contain substances in such high quantities that are far beyond the legal limit values defined by the German Fertilizer Ordinance. Thus, the sludge cannot be applied to farmland because of legal standards on critical loads of one or several substances or the already existing background load from the use of fertilizers or airborne pollution on the farmland (LUFA Teterower See xx). Obviously, there are contradictions in the legal settings fertilizers from phosphorus rock contain as much as contaminants that the fertilizer does not meet the requirements of the German Fertilizer Directive (Kratz et al. 2015, Schnug et al 2014) but sludge from lake restoration containing fertilizers such as calcium, potassium and phosphorus can not be applied to fields. Nevertheless, phosphorus recycling only makes sense if the recycled or recovered phosphorus is available to plants (Bridger et al. 1962, Römer 2006, Schröder et al. 2010).

Koopelaar et al. (2013) quantified the worldwide phosphorus flows in 2009. They showed that mining could be reduced by about one third if phosphorus fertilizer use will be improved and almost another third of the demand could be recycled from waterways and wastewater, but the later option is according to them to expansive to compete with phosphorus fertilizers processed anew from rock. Cordell (2010) draw a picture of a sustainable phosphorus cycle for the year 2100. The model refers to the business as usual case. She argued for a reduction in supply that will cut the phosphorus flow by about one third, including measures such as phosphorus recovery from manure (largest part) and human excreta, food waste and crop residues, ashes, and drastically reduced mining of phosphorus rock to fill the gap of unavoidable losses. She plead for changes in demand that will cover the other two thirds of the cycle. She see large potentials in changing diets (less meat more vegetables) and increasing efficiency in the food chain and the agricultural.

Thus, closing the phosphorus cycle is not a matter of lacking technologies but of jurisdiction and economics. The peak phosphorus dispute highlighted to economic aspects behind whereas the former dispute was more environmental aspects. High price peak in 2007/8 still has not generated prices for phosphate fertilizers high enough to make recycling technologies competitive. One aspect of the "scarcity" dispute was food security. This term includes more than only providing enough phosphorus to fertilize fields. Food security is about healthy foods also. That opens the floor for an open discussion about what goes along with the use of phosphor rock to process fertilizer? That also includes aspects such as environmental pollution (contamination of farmland and groundwater) with fertilizer application (Kratz et al. 2015, Schnug et al 2014). Those aspects need to be included in legislating and pricing mineral phosphate fertilizers.

6 Trace elements and changes in the phosphorus economy

About half of the elements on Earth are found in phosphorus ore. Among them are rare earth elements that are worth to be extracted for other economic purposes. A radical change in the "economic mind" is required. Phosphate rock must be acknowledged a multi-source, i.e. a resource that consists of many single (and compound) resources each of them can feed a specific industry. The total content of sixteen trace elements in annual phosphate rock production exceeds 10 per cent of the worldwide annual demand of these elements. Thus, extracting them from phosphate rock may (1) increase the efficiency of the mining and extraction processes, (2) minimize environmental impacts during these processes and while using phosphorus as fertilizer in the environment, for instance minimizing the cadmium or radioactivity release to the ecosystem, (3) improves the overall economy due to the simultaneous extraction of a crowed/cloud of by-products the world economy seeks for.

First, depending on the regional history of the ore several dozen trace elements present in phosphate rock could potentially be mined as by-products, reducing the contaminant load in wastes (e.g., phosphogypsum in Florida mines), and thus banned by EPA in the US for any use (Smil, 2000).

Second, the environmental impacts can be substantially reduced if the grinding and activation processes follow the procedure in the cement or zeolith industries. At least cadmium would nor "survive" the activation process by heating the grinded material up to 450 to 500^{o}C. The finally sold phosphorus fertilizers still contain many (trace) elements that are not in line with legal requirements for the fertilizers use according to the German Fertilizer Ordinance or they are accumulated in crop plants, so that crops exceed legal levels in food and feed (Kratz et al. 2015). Uranium, for example, is hosted by apatites and can be extracted from it (Habashi 1960, Nomura et al 1961, Shakir et al. 1992). Schnug et al. (2014) calculated that finalized phosphorus fertilizers applied in Germany annually contain as much as uranium that equals almost the demand on energy of 2.4 million households. Their plea is to extract the uranium from the phosphorus rock before it is processed to fertilizer and create soil and groundwater contamination.

Third, many trace elements may contribute to the global demand if they are extracted from the ore before or simultaneously to the fertilizer production process. Material flow analyses for the processing chain, potential recovery technologies, and assessments for the economic viability have been already created for scandium, hafnium, beryllium, gallium, germanium, and several other rare earth elements (Chen et al 2015).

Summarizing, splitting mining, processing and other costs between the extracted elements from phosphorus rock will reduce the overall production cost and losses along the mine to fork transformation process. The negative environmental impacts will stepwise diminish at the same time. This option will of course change the phosphorus economy completely but easies introducing a close sustainably and healthy cycle of each and any phosphorus use.

7 Food consumption modes to reduce phosphorus demand

According to Harenz (1991) every human consumes and excretes about 1.6 to 1.8 g phosphorus per day. Smil (2000) reports a typical daily consumption - meat and dairy foods are reach in phosphorus - of 1.5 g, while the recommend daily allowances are 1.2 g for children and young adults and 800 mg for adults older than 24 years. Typically an average human body (45 kg) contains about 400 g phosphorus. Daily consumption and excreta almost equal. Cordell et al. (2009) report a significant influence of human diet on the phosphorus demand. A vegetarian diet would correspond to about 0.3 kg phosphorus per year and capita in excreta, whereas a meat-based diet almost doubles this figure. Thus, a change in food consumption modes to a more vegetarian diet may slow down the rate of phosphorus demand substantially (Hallström et al. 2014, Machovina et al. 2015, Schröder et al 2010, Shimokawa, 2015, Vranken et al. 2014). In addition, phosphorus demand and therefore daily up-take in fed is especially high when livestock reproduces and lactates as well as within the growth period of the recruits (Grünberg et al. 2015). Thus, the "shadow load" of phosphorus is the highest in dairy products. However, too much phosphorus within the feed may also harm animals health (Fjelldal et al. 2012). Döll (2005) warns, vegetarian food does not contain all trace elements and vitamins humans need for their health. Humans are not made for vegetarian food alone.

Summarizing, there are at least five aspects to reconsider (Djekic 2015, Petrovic et al. 2015, Smil 2000, Thornton 2010, Vranken et al. 2014):

(1) About 70 per cent of phosphate fertilizers are used on cereals. The demand on phosphorus in some feed crops like leguminous grain is even higher than in cereals.

(2) More than 60 per cent of all grains in rich countries are used as animal feed. In the lactation period additional phosphorus is added to feed.

(3) All animals produce manure that is disperse spread on pastures and only be collected in confinements adding to the run-off of phosphorus to the drainage basin. Part of it is used in developed countries to produce biogas before the digestate is discharged to fields.

(4) The consumption rate per capita in the rich countries is about 50 kg meat and 100 kg dairy products a year. The developing countries try to attain the same rates as well as in meat and dairy product consumption even when the lack the enzymes to digest the dairies.

(5) Monogastric mammals (e.g. pork, hens but also human!) lack the requisite enzyme (phytase) to free phosphorus from the molecule and, thus, excretes about 70 per cent of the phosphorus in the grain feed unused. Since phytase is not added to pork or hen feed yet mineral phosphorus must be added. Thus, the phosphorus load in pig manure (and in sewer systems) is almost "doubled". However, phytase may also negatively influence the availability of other nutrients, including minerals and thus act as an antinutrient (Graham et al. 2014).

To conclude, meat and dairy consumption causes almost half of the agricultural phosphorus demand worldwide. It seems to be evident that this share will increase in future (Davis et al. 2015). On the one hand side, changes in consumption mode to a more vegetarian food ("sufficiency", Allievi et al. 2015) may reduce the overall phosphorus demand (Smil 2002b, 2014). On the other hand, almost the same amount of phosphorus bound in animal waste annually is required to balance out the worldwide demand from phosphorus rock. In addition, there are options to improve feed management by adding enzymes in nonruminant mammals (pork) to reduce the demand of phosphorus and therefore the Phosphor discharged to environment with the manure.

8 Towards a more efficient phosphorus agronomy

About 90 per cent of mined phosphate rock have been used to produce phosphate fertilisers for agricultural applications for the last 60 years. From that, 40 per cent of phosphorus entering the agricultural system get lost to the environment to almost similar accounts from erosion and animal waste (Rittmann et al. 2011). Phosphorus is the key driver behind the green revolution feeding a steadily growing world population. Since phosphorus is essential and unsubstitutable to plant growth, and almost all of it is used to produce food and feed agriculture is the key economic sector for the phosphorus cycle. When guano, bone meal or manure cannot longer provide farming with sufficient amounts of phosphorus fertiliser in the 1960ies phosphate rock has become a plentiful and cheap alternative since then (Syers et al. 2011). Hence, the phosphorus use efficiency is still decreasing, thus one supplies more phosphorus than the crops can afford. The phosphorus supply increases faster than the crop yields respond (Zhang et al. 2014, Li et al. 2014). Moreover, industry breed special crops that need more phosphorus to grow than the traditional races of rye respectively. The traditional breeds gain more yield at lower phosphorus supply levels than the new designer races (Suriyagoda et al. 2014).

The use of mineral phosphorus neglected that the rock might be contaminated with almost half of all earth elements until now/at first. But the excessive application to field and the accumulation of these unwanted attendees in the soil and food web caused many environmental effects. Hence, it is not only the quantity of phosphorus applied to field (and fodder) but the quality of clean, non-contaminated phosphorus that counts - independently if the fertiliser comes from phosphate rock or recycling technologies. Therefore, there are five aspects undisputable if one discusses phosphorus economics at all and in agricultural in particular:

(1) increase the efficiency of phosphorus use in agriculture - in fields and staples,

(2) apply only pure, clean phosphorus - free of contaminants that are part of phosphate rock - to fields (and as feed additives) to avoid further environmental damages,

(3) recycle only phosphorus from any former usage

 (a) if the applied technologies eliminate any risky elements that can be enriched in the food web and thus may harm at least human or farm animals health or

 (b) if the recycled phosphorus can be used from the crop plants,

(4) clean the soils from pollutants such as cadmium or radionuclides (Tirado et al 2012),

(5) avoid as much as phosphorus losses to adjacent (aquatic) environments and phosphorus use in areas especially vulnerable to phosphorus losses to surface and groundwater.

These aspects are all well known and scientifically proofed, hence the political and economic instruments to change management practices or a good governance practise is still lacking (Cordell et al. 2015, Ekardt et al. 2015, Schröder et al. 2010, Shakhramanyan et al. 2012, Ulrich et al 2015, Withers et al. 2015).

Schröder et al. (2010) demonstrated with their material flow assessments how inefficient the use of phosphorus in the chain from mine to for or plate is. High losses and environmental impacts occur already in mining, but continue to happen along the whole food and feed chain all over the world. The phosphorus use efficiency in the agricultural production system decreased over the last 50 years in China respectively. Whereas the crop yield only increased by factor 3.8 the amount of phosphorus applied by factor 20. The efficiency of phosphorus use along the food chain is as low as about 7 per cent but the losses from farmland to surface waters is about 20 kg phosphorus a hectare and year (Zhang et al. 2014). The authors conclude that a better management may help to reduce the phosphorus demand in China by one third in the coming years. This may correspond with data in Europe and Northern America where the overall phosphorus consumption decreased starting in the 1990ies by about 20 per cent due to better management practices and environmental regulations (Schröder et al. 2010). Best agricultural management practices also include to apply as much as (in small amounts) and as often as (according to the growth phases of the crop plant) phosphorus as the plants can take-up as being part of precision farming (Helyar 1998, Iho et al. 2012, Maine et al. 2007). The old thinking "if you apply more, you will harvest more" needed to rethink, since after an optimum of fertilisation yields decrease after passing a species specific threshold of optimum (Jiao et al. 2014, Nyborg et al. 1999). Thus, reducing the oversupply may be beneficial to the crop yield, farmers´ budget and the environment (Buckley et al 2013).

However, the losses to and the contamination of the environment are only two effects of a comprehensive cause - consequences web. The over-fertilization along with the contamination of the soils affect already the quality of food and feed as well as drinking water with impacts to animal and human health (e.g. Burlingame et al 2014, Döll 2005, Reijnders 2014). Some of the new grain crops demand a higher supply of phosphorus accumulating the phosphorus compounds in the grains and thus transferred to the feed and food whereas traditional local varieties require less phosphorus doing better in growth and yield - producing about 2.3 times a higher biomass with less fertilizer supply (Suriyagoda et al. 2014). Somoweera et al. (2014) showed that no losses in yield may occur if phosphorus is not supplied over some sequential years. The phosphorus use efficiency can also be improved by new crops or designing new fertilizers (Kongshaug et al 1995, Ridoutt et al. 2013, Roger et al. 2014) or combining them with symbiontic or synergetic additives or less disturbance by tillage to enhance the effect on plant growth (Gibbons et al. 2014, Karlen et al. 2013).

Secondly, the technology to produce clean phosphorus fertilizers free of cadmium and uranium, respectively, is already available. These technologies eliminate contaminants also in phosphorus recycling processes and may re-use heat energy from the process. Thus, the products are hand able such as other fertilizers and transport distances for manure from stables to field for instance, does no longer hinder this recycling option (Acelas et al. 2014, Dolman et al. 2014, Haneklaus et al. 2014, Siebers et al. 2013). Moreover, the combination of these clean phosphorus (or compound fertilizers) products along with mycorrhizal seed dressing as well as biochar or zeoliths has been proven, first, increasing plant performance (yield) with less phosphorus supply (Bahri-Esfahani et al. 2014, Ryan et al. 2012), second, improving plant health, thus, requiring less pesticides, third, decontamining soils (Baum et al. 2013, Dimitriou et al. 2012, Langeveld et al. 2012), and last but not least these technologies can also be used in phosphorus recycling from waste, sewer and manure to design new fertilizers behaving as a depot fertilizer much less leaching nutrients to the environment (Faye et al. 2014, Gholamhoseini et al. 2013, Kaur et al 2015, Kucey et al. 1989, Sharma et al. 2009, Valente et al. 1982). No new fertilizers have been formulated for more than 40 years. This business as usual strategy hinders the designing of fertilizers harming the ecosystems and human health less (McLaughlin 2014.)

Third, the technologies and in some EU countries and Northern America also the target settings to increase the recovery of phosphorus from manure and sewer systems are already installed. However, not all of the chosen technologies really fulfill sustainability premises. Phosphorus is usually bound in waste water treatment plants with calcium, iron or aluminum (Meyer et al. 2014, Müller-Stöver et al. 2014). Except the calcium compounds are the other both substrates hardly plant available. The technology of binding phosphorus in sewer, urine or manure with magnesium to struvite (Carliell-Marquet et al 2014, Campos et al. 2014, Maurer et al. 2006, Münch et al 2001, Shu et al. 2006) faces the same problem especially when the product is applied to alkaline soils (Meyer et al. 2014). However, even with the metallic additives the phosphorus elimination is not complete and thus there is still a load of phosphorus in the treatment plant run-off. Thus, several authors report on the amounts of phosphorus passing through the treatment are that high that the EU Water Directive obligations are not to meet and still add to the agricultural run-off in the drainage basins (Bowes et al. 2010).

Fourth, soils need to be cleaned from contaminants coming to the field along with phosphorus fertilizers. Phytoremidiation, using soil symbiotic systems with mycorrhizal fungi and bacteria or interim wood stages (short rotation coppices) might be options to gain this target while producing biomass for bioenergy use and let the soil recover. The yields of conventional crops may be even substantially higher after the pause (Baum et al. 2013, Dimitriou et al. 2012, Langeveld et al. 2012). Clinoptiloliths or biochars from pyrolysis of sewer sludge, bone meal or other recyclates may serve as a matrix to the soil biocoenoses or adsorb contaminants (Battini et al. 2014, Bolan et al. 2004, Faye et al. 2014, Gholamhoseini et al. 2013, Jindo et al. 2014, Kaur et al 2015, Kucey et al. 1989, Shepherd et al. 2014, Valente et al. 1982).

Fifth, the phosphorus losses from farm- and grassland are not evenly distributed. GIS modelling has shown that a "hot spot" management including the control of artificial drainage systems can avoid most of the losses to waterways (for instance Deasy et al. 2010, Gilliam 1995, Kovacs et al. 2008, 2012, McDowell 2012).

9 Conclusion

The phosphorus cycle got broken almost sixty years ago. The god news was that the use of mineral phosphorus enabled as a key fertilizer the Green Revolution to happen and to feed humans and their livestock on Earth. As every broken cycle faces the broken phosphorus one benefits and costs. Costs were detected in the environment when eutrophication occurred in surface (ground) and coastal waters harming the drinking water quality and biodiversity within these basins at first. Changes in the water quality became a predominant issue of research to environmentalists and environmental economists. Only, the price shock in 2007/8 opened the floor for economic thoughts and political fears - if the world would run out of its phosphorus resources the planet would possibly starve for hunger. Hence, the peak phosphorus dispute has drawn scientific and political attention to a nutrient that is essential for all life on Earth and human nutrition. Although, the simple model of a resource peak concept can not picture the whole complexity behind the economics of this resource it induced a wealth of scientific actions and publications. Now, scientists address to close the phosphorus cycle again to avoid a collapse. However, the quantitative scarcity aspect of a resource endowment is only one of many aspects.

Phosphorus is not a homogenous resource, almost half of the Earth elements accompany it in the mines. Phosphorus itself behaves like a chameleon in its bio-chemical and biological transformations, its properties in the soil and water environments varies depending on pH and times of bioaccumulation respectively, and even the interdependencies and feed-backs in the economic and political system are very complex. The phosphorus economics and politics are characterised by many stakeholder interests in a variety of markets. Tackling the phosphorus problem thus requires not only technological innovations for a wise use of the resource like the 5R-strategy recommended by Withers et al. (2015), a change in food modes to more vegetarian food (Schröder et al. 2010) nor a political command-control regulation as for instance taxation on some levels of the resource transaction (Ekardt et al. 2015), there is a need for a comprehensive governance process (Cordell et al 2015b, Ulrich et al 2014) involving all stakeholders (interest). Including the very aspect of clean - free of contaminants phosphorus fertilizer, thus one of many quality aspects - might be a good point to start with, for instance applying a REACH approach. Many environmental concerns and impacts to human health - negative external aspects - would evaporate as the clean phosphorus from mine would be processed in the old-fashion technology of cement or clinoptilolith activation or in technologies at hand for recycling to a plant available fertilizer. However, a clean up process of arable soils and run-off sediments is a task that need got attention too.

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