Phosphorus resource economics - A review

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BIOP Working Paper, 2016-1

Abstract

P 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 P" similar to the dispute on the oil peak back in the 1970ies. The processing use of phosphate rock to P fertilizers fed the Green Revolution and therefore was seen a chance to overcome the hunger on Earth. Thus, the expansive use of P had serious negative impacts to the reserve stock of P. However, if and only if business sees a certain price margin as a threshold beyond P cannot be explored with benefit for agricultural use only in this case P really gets a scarce resource. The peak price shock in P had almost other reasons than a real physical shortcoming in the reserve stocks. Moreover, if that threshold would be exceeded recycling technologies and better management practices in the field will serve the agriculture with enough P to support food production. Along with this other strategies may lower the pressure on P reserves and the resource stock as a whole.

1. The P stock and flows

P is the number 11 in the elements composition of the Earth. The P stock constitutes of various elementary composition depending on its regional, biological or geobiochemical origin. The geobiochemical cycle of P lasts million of years whereas the biological stock “in flow” may regenerate in years.

In addition, a serious part of the stock is permanently in flow in the biological web and thus organically bound. This flow part is almost always in move. The timescales of assimilation and dissimilation processes varies from parts of second to lifelong processes as the spatial scales vary from intra-cellular to regional scales. Life depends on P since it is part of all living cells and tissues. The P cycle inside organisms serve the organism with the ATP/ADP energy pump. However, the most of the P stock is inorganic, of marine origin and rests in the deep sea layers thus not exploitable to recent technology or market prices (Smil, 2000).

However, the extraction prices of P from apatites or the enrichment processes for uranium in the atomic energy generation are only part of the market prices observed at the world markets during the peak P. The prices consist only to a minor extend of the costs of extraction and processing but the more from logistic and trading margins. There were similar “price making” mechanisms at work seen in the peak oil periods before (Cordell 2010, Childers et al. 2011, Heckenmüller et al. 2014).

The exploitable stock constitutes the world reserves of P (fig. 1, https://www.mineralseducationcoalition.org/minerals/phosphate-rock). The economic P reserve is a minor portion of the World´s resource stock (Smil 2000). However, one has to add to these mineral stocks the biological stocks that are accumulated along the food web in the oceans annually. Some of the biological recycled P still is of importance to the human food since the main biological collector for P is pelagial fish from the upwelling regions along the Peruvian coast used as fishmeal to feed livestock all over the world. If the livestock manure is used to fertilize arable land the P cycle is closed in a short loop this way.

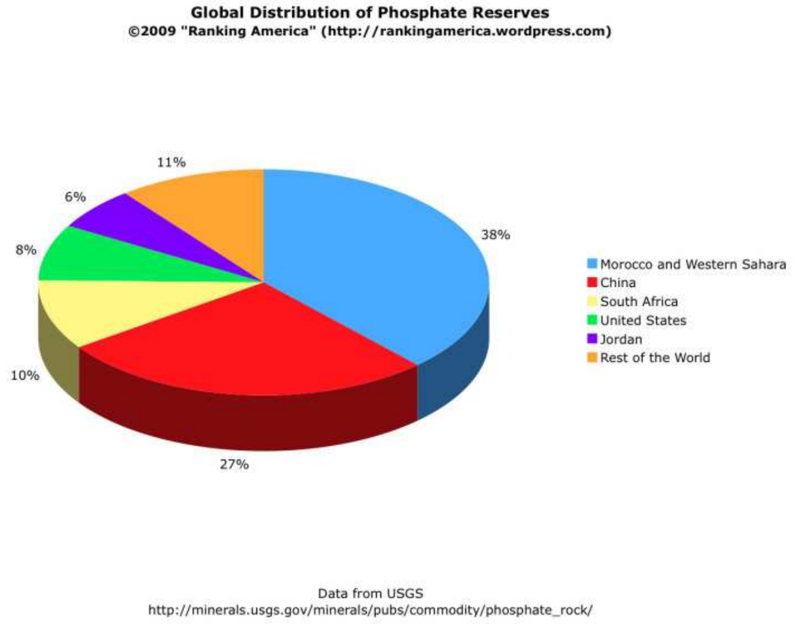

Figure 1. The distribution of global phosphate reserves.

Moreover, the "peak P dispute" initiated an increasing number of studies that show that the human induced acceleration of P use also bear chances for modes of recycling. Calculations show that humanity may act almost independent from a further exploitation of the reserve stock if recycling is paid more attention and the market prices say the ecological truth. The internalization of all the external effects the present day use of P causes into the market prices the peak P prices only showed a shadow of real environmental and social costs.

Moreover, the present day stocks of P are shifted to arable land, landfills for sewage, freshwater reservoirs and coastal zone ecosystems. The main reasons are over-fertilization in the last 60 years and the reserves fixed to the soil, unlimited growth of livestock, non-recycling of sewer sludge and unbalanced exports of P into cities, the runoff of untreated sewer and from treatment plants, and runoff from fields into lakes, rivers and the coastal zone.

In conclusion, the flow cycle of P can be managed for human purposes almost without a further cut of the P reserves. The barriers are price expectation of the market players and the lack of political will to cope with the P issue.

1.1 P an essential, un-substitutable and almost non-renewable element

Life will not survive on Earth without P. DNA, RNA, fatty acids, teeth, bones and on the (intra)cellular scale the mitochondrial energy system converting ADP into ATP and vice versa require P and thus P is non-substitutable and essential for all life (e.g., Ashley et al. 2011, Childers et al. 2011, Smil 2000). P also shows leverage effects on the dynamics of biological processes in ecosystems and can be seen as the main limiting factor to processes like eutrophication in aquatic and coastal marine ecosystems (Vezjak et al. 1998, Gustafson et al. 2012). The role P plays in all biological processes makes it essential and non-substitutable.

1.2 P an almost non-renewable resource

Geologically, phosphates exist as apatites, different calcium phosphates with different accompanying elements such as Fluor, Chlorine, Cadmium and Uranium. Almost all stable Earth elements are found along P ore. They can originate from marine-sedimentary, magmatic or biological processes. 90 % of the phosphate is of marine-sedimentary origin. The P content in marine sediments is higher than in the magmatic ores as well as the portion of contaminants is (Killiches 2013).

Originally P was solved from rocks by "acid rain", transported into the ocean, being accumulated in sediments along with other especially trace elements (Chen et al 2015). Mineral P is an almost non-renewable resource, although phosphogenesis takes place in the oceans also on a low rate at present (Filipilli 2011).

Some of the P, however, entered and accumulated in the biological cycle. Algae accumulated in the photosynthesis P from the sea water, nourishing zooplankton, fish and birds. Birds are a vector bringing P 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 accumulated and mineralized" P for agricultural purposes throughout the world. P is one of the most valuable part of bird excrements (guano) Renewable or "biological" phosphate reserves as guano were always relatively rare compared to the P hunger in the world. It accounts only to 0.3 per cent to the worldwide phosphate resources (Killiches 2013). This amount does not even compare to the huge demand of industrial agriculture nowadays (Heffer et al 2014).

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 P 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 P was deposited on the sea floor. Phosphate rock was deposited in extensive layers covering thousands of square miles. Geological processes up-lifted the seafloor phosphate rock above sea level. Phosphate rock is unevenly located at some places around the world (fig. 1). Moreover, the most of the P resources can not contribute to the P reserves still sit in the deep ocean are unavailable for human usage because of lacking technologies and unaffordable prices (Smil 2000).

Thus, one may distinct different types of P resources, first a biological flow-stock one that may be renewed within times of ecosystem cycles (guano, fish meal and animal bones respectively), second apatite ore of magmatic origin, and third, a marine sedimentary phosphate ore. The later both are resulting from long-time geochemical and geophysical cycles (Cordell 2010, Filippelli 2011, Killiches 2013).

The geo-cycle for marine sedimentary ore has been accelerated by humans´ activity in particular by industrial agriculture measures that have increased the P run-off to the coastal seas by factor three within the last 50 years (Moss 1998, Smil 2000). The second main source of P run-off is untreated and treated waste water from municipalities in the drainage basins. The eutrophication process induced by additional P 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). Hence, these huge amounts of P cannot be recycled to human uses, add to the recipient systems´ entropy and may stress the ecosystem manifold since the sedimentary process itself depends on various factors especially the redox milieu at the seafloor (Ekeroth et al. 2016, Gustafson et al. 2012).

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% P, ten times as much as recycled P-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 2002a).

Today, the agricultural demand on P 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 P fertilizers. The global annual production of phosphate rock almost doubled from 1970 to 2010 (Prud´homme 2010).

Two additional aspects need to be taken into consideration to that conclusion: First, the efficiency of the use of P from mine, to field, to fork can be improved substantially (Scholz et al 2015 a, b), and second, various technologies to recycle P from municipal sewer or waste are at hand to lower the demand of mineral P in total. Hence, the pricing from mine to farm are too low to make those measures work (Cordell et al. 2009, Drangert 2012, Shakhramanyan et al. 2012).

1.3 The mineral P stock

The mineral P stock consists of mainly two parts, the un-exploitable and the today known exploitable P reserves. As in other resource stocks too, the amount of reserves may increase if new technologies allow for exploitation and the society is willing to pay higher market prices. In the later case, the present day production chain of mineral P fertilizers will increasingly compete with recycling technologies and the reserve stock may last forever (Drangert 2012).

The worlds´ known 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). Thus the supply market is an oligopolistic one.

The economists´ fear is that the mineral P reserves will be exhausted one day as the “peak P” dispute shows (for instance, Cordell et al. 2011). Meanwhile,

(1) the P content in the phosphate rock is decreasing,

(2) the costs for exploration, mining and processing per ton P fertilizers and the amount of waste of the fertilizers processing are exploding (Smil 2000, Zhang et al. 2008, Scholz et al 2015a),

(3) the number and amount of contaminants in the rock and in the finished fertilizer is also 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 P still increases (by about 1.4 percent annually, Heffer et al 2014).

P fertilizer is the main (see Gustafson et al. 2012) driver of the Green Revolution (Munson et al 1959) and therefore is still seen the solution to fight hunger in the world. The negative external effects of the extensive use of mineral P are underestimated and are not reflected in the market prices (see for instance Shakhramanyan et al. 2012).

The pressure on P reserves reason in

(1) a growing world population and

(2) an increasing popularity of meat and dairy in human food

(Schröder et al. 2010).

Whereas, the growing worlds´ population is a non deniable fact, the hunger for more dairy and meat as a mean of wealth and an accelerator of the P use to produce feed and fodder to livestock can be defeated. Moreover, some fodder plants like soya demand more P input than human food plants (Smil 2002b, 2014, Schröder et al. 2010, Neset et al 2012, Cordell et al. 2015).

2. Mineral P - 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 P 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, P 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 P 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 P as fertilizer is still of paramount importance in agricultural industry. More than 90 per cent globally mined and processed 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 P per hectare and year, 6 in Europe, and 2 in Africa. About 3 kg P per hectare and year are harvested for instance per ton grain. P shortage in feed may harm substantially the livestock health, especially dairy in the lactation phase (Grünberg et al. 2015).

Only four countries count for 64 per cent P 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 P fertilizer (25 - 30 kg per hectare and year, Schröder et al. 2010). However, some 80 per cent of the P gets lost along the path from mine to fork to plate. Eventually only about one-fifth of the pure P extracted from phosphate rock is consumed as food (Cordell et al. 2009, Neset et al 2012).

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

Comparing to the figures given in Smil (2000) that annually 5-10 kg of organic P were applied at the beginning of the 20ies century those figures of applied mineral P in Europe (6 kg per hectare) appear very low. Whether the present day P fertilizer stocks in farmland soils are as high that they may support the low rates of annual application or the rates are high enough to stabilize the annual yields due to a better management and thus reduce unwanted losses to the environment. On the other hand, if the rates are really so low manure from livestock and recycling of P from waste, sewer sludge or other sources might already substitute mineral P imports at least in Europe?

3. P scarcity

3.1 Peak P

P is 11th frequent element on Earth lithosphere, essential for life but rather scarce in the biosphere (organically bound P, Smil 2000, Killiches 2013). Most of the mineral P reserves 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 P 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 P is about 200 $/t on average. Farm gate prices are higher (at least double in America and Europe or fourfold in Africa) and depend from many other aspects.

The 2008 price shock called economists to study P markets and to assess how long P still can be used (Cordell et al. 2009, 2011, Heckenmüller et al. 2014, Schröder et al. 2010). Since P 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 P in 1974-5 occurred always simultaneously in between the two oil price shocks. The oil and the P markets show many similar economic properties (Heckenmüller et al. 2014).

Cordell et al. (2009) introduced the “peak P” concept illustrating the shortage of the P reserves. Their model bases on the presently known stock, today´s exploitation rates and expectations on future demand. They estimated that the global peak for P production is likely to occur as early as 2033. They defined the term “peak P” a point at which the production of P from phosphate rock reaches its maximum due to the decreasing availability rock deposits, the declining P content of the rock, assuming a steadily high or growing demand. Cordell et al. (2009) used the a Hubbert styled resource model to assess the longevity of the reserves assuming that P might be behave similar to oil reserves in markets (Hubbert 1979). Cordell et al. (2011, 2015a) corrected their estimates, according to their calculations, peak P may occur some years later - in 2070 or after 2300. If the demand of a non-substitutable, essential and non-renewable resource 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 - P - can be eaten up only once. By the end the resource, the cake, is gone completely. In case of P that model might not apply since the reserves are only a minor part of the overall resource stock. In addition, one may influence the rate of consumption by various political or economic measures. Thus, different models show the impact of those measures on the rate of consumption, the remaining resource stock at a particular time and its longevity and P for fertilization purposes is recyclable at least in part (Drangert 2012).

Models such as the “cake eating” one illustrating the scarcity of a resource use prices as indicators for an economic scarcity. Prices may reflect the economic scarcity of a commodity. In theory, the higher the prices of a (normal) good the more scarce the resource is. Hence, economic scarcity includes not only the physical shortness of a resource but also if it is worth or economically feasible and viable to continue extracting P from the rock. One has to acknowledge that there are some problems involved that make the "cake eating model" not applicable to the P market.

Heckenmüller et al. (2014) concluded in their economic analysis of the peak P 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 influenced the pricing of P fertilizers as well as some environmental conditions and the financial crisis in 2008 caused the price shock in P rather than the price set a physical scarcity signal. Clift et al (2012) assumed that policy induced the price jump in the P market. The political target substituting as much as possible fossil fuel by biological ones growing on fields for climate change reasons may have caused market players speculating on increasing P demands. The uncertainty in such assessments is high and requirements inherent in the model are not met in P, since

(1) P is not a homogeneous resource. The phosphate rock species worldwide contain different amounts of P (and along with it different elements that go along with it) depending on the mine and therefore would need different technologies to process (decontaminate) it to clean fertilizers.

(2) Since P is distributed in clusters around the world there are political issues involved in the pricing of P 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 processing of uranium or rare Earth elements).

There are enormous losses along the mining, processing and application line that can be avoided. "Peak P" thus rather is a concept to draw attention and awareness on the reserve stock.

Hence P it is by no means a finite physical resource (Smil 2002a, Scholz et al 2013) and if handled efficiently it may last almost forever (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 P 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 P. He argued that there are two important qualitative differences between P and carbon-based fossil fuels

(1) P is in principle recoverable after use but

(2) P 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).

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

However, beside the quantity and longevity dispute on P the peak P 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 P 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 1999, 1999, Turner et al. 1999), the discussion got enriched by many transdisciplinary aspects of the P problem from mine to fork (and human health) and back to the oceans. Almost 90 per cent of P is lost along the application line to the environment (Clift et al 2012). The P 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 P (Molinos-Senante et al. 2011).

The main shortage of the “peak phosphorus” model is that: Within the concept real prices including social and environmental costs the exploitation of mineral P reserves exploitation and the use of fertilizer cause are neglected. If these prices would be known one may compare them with technological and economic (pricing) options for recycling of P. At a certain level prices for recycling will make mining of apatite or using P from other industrial processes where P is a byproduct superfluous. Maybe the future P fertilizer will be also cleaner and free of other minerals that may harm environmental and human health.

Moreover, the dispute of "peak P" is a model that bases on expectations on prices for mineral P for instance assuming that prices should not exceed 200-400 $/t for mining or 1.000-1.200 $/t at farm gate.

P is a kind of an inferior commodity rather than a normal good. It is non-substitutable and essential for life and thus for human nutrition also. Prices of inferior goods increase with the amount of supply. They do contrarily to normal goods. In normal goods the greater the amount of supply is the lower the prices will be.

However, the mineral P can be substituted by other sources of P – biological or recycling ones. Assuming P is an inferior good if the prices get paramount they will still be paid before starving for hunger. However, at a certain price level at latest new recycling technologies and a better resource management will prevent humankind for those prices. At that point new technology options will successfully compete with the costs of the mining and processing technologies. Therefore, prices cannot explode without limits as one may expect in real inferior goods.

The P resource market behaves almost similar to the oil market. The longevity of the oil reserves steadily increased over time for several reasons. Oil shell exploration may serve as an example. For transportation means oil can be substituted in part by other sources of power, hydrogen generated from renewable energy or electricity respectively.

3.2 Properties of P as a resource in markets

The following list demonstrates properties of the P resource and may explain why the P problem is a very complex one. Various markets interfere in the P markets and make predictions highly uncertain.

(1) Most of the P 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 P markets being observed in 2008 (Schröder et al. 2010).

(2) 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.

(3) Phosphate rock is not a uniform but multi-resource commodity. The P content within phosphate rock varies from region to region and within one region even from mine to mine. Technologies and costs for mining and refining may vary substantially for this reason as the prices of the "final" product will (Zhang et al. 2008).

(4) The extraction technologies differ from region to region also because of environmental standards set by governments. P gypsum is excluded from further use and produces huge piles of landfill waste in the US respectively (Smil 2000).

(5) The economic viability of resource exploitation may also be influenced by rare trace elements accompanying P in the phosphate rock. If extracted before or simultaneously from P rock trace element may drive the market and thus will interfere in the P mar-

kets. P may sustain in those markets only as a byproduct (or waste to use) to a more attractive market for trace elements making P less worth (El-Ramady 2008, Chen et al 2015, Kratz et al. 2015).

(6) Uranium extraction from the rock may serve as another example (Habashi 1960, Nomura 1961, Shakir et al. 1992, Heshmati-Rafsanjani 2009, Knolle 2008, Schnug et al 2014). P in those extraction processes is a by-product only and may be dumped at lower prices into fertilizer markets if uranium is ranked higher than P in markets. In these cases, the power generation market interferes or competes with the agricultural markets.

(7) Mineral P is substitutable at least in part. One may recycle P 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 P resource stock and, being part of a more sustainable P strategy.

(8) Moreover, such a strategy may also inhere that recycled P is free of adjuvant contaminants meeting at least the valid legal limit values defined by the German Fertilizer Ordinance respectively. Costs for decontamination of soils may therefore decrease. Thus the environmental value of recycled clean (?) P fertilizer has to be ranked higher than the mineral P fertilizers with accompanying contaminants.

(9) The pressure on technology to recycle clean P for agricultural purposes, the timing for the necessary change and the social will to accept and include all external effects that go along with the use (and the pollution of the environment especially soils, ground and surface water) in prices depend on many circumstances. All of the scales for the named systems and actions are highly uncertain (Scholz et al, 2015 a, b).

(10) Neglecting all the shortcomings from the dispute and the models applied, the "peak P" debate put the risk of P reserves depletion on the agenda. Hence, science as well as the public need to acknowledge that the P problem addresses more to them than an economic or an environmental problem.

It is obvious that are many uncertainties involved in the complex P market that do not allow for precise predictions and expectations (Johnson et al. 2013, Scholz et al 2015 a). The main barrier to understand the P market is that P rock has been always treated as a one resource market neglecting that the ore itself is a collection of almost all stable Earth elements (Schnug et al 2014). Some of the accompanying elements are of increasing economic interest more than P is. The interest on those elements may drive the technological development of mining, extracting and refining processes into a more "clean" P fertilizers production.

Other elements pollute and harm the environment, consequently livestock and human health. This requires extracting these elements in the refining process before the phosphate fertilizer is spread to the farmland. On the one hand, the refining processes will increase costs for P fertilizers on the other hand side it will substantially reduce the costs of external effects for human/livestock health, environmental integrity and the society in whole. The plea is on "clean" P fertilizers.

4. P scarcity and food security

The peak P concept and the economic interest in the life time of P resources were instantly linked to the food security issue. Hence, the interpretation of economic scarcity of P was limited to the quantity of the stock only as the term of food security in this dispute is. But, if food security is at stake quantitative as well as qualitative aspects of clean P need to be considered:

(1) A steadily growing world population needs food (Alexandratos et al 1995, 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. The quantitative aspect of food security is that every human is served with enough water and food a day. The term “enough” is disputable. Whereas people in the industrial countries are oversaturated (Schatalova 2002) and a substantial part of the produced food is damped to waste (FAO 2011) people in the developing countries starve for hunger. An aggregated figure how much is enough is the needed daily uptake of calories from food. This figure does not say anything about the composition or other quality parameters for the food. However, the figure allows for calculate the worlds´ population at least demand for food, and the theoretically estimated demand for P transferred from soil (or water) into the food. This calculated demand on P is much lower than real demand expressed in P market reports.

(2) Vegetarian nourishment requires less P than nutrition based on dairy products and meat only about half of the P to produce the caloric value of daily food (Schröder et al. 2010). However, humans are not accumulating P in their bodies. Typically an average human body (45 kg) contains about 400 g P. Daily consumption and excreta almost equal. Smil (2000) reports a typical daily consumption - meat and dairy foods are rich in P - of 1.5 g, while the recommend daily allowances are 1.2 g for children and young adults, 800 mg for adults older than 24 years. Cordell et al. (2009) report a significant influence of human diet on the P demand. A vegetarian diet would correspond to about 0.3 kg P 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 P demand substantially (Hallström et al. 2014, Machovina et al. 2015, Schröder et al 2010, Shimokawa, 2015, Vranken et al. 2014).

(3) However, along with an increasing income one may observe a shift of 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 gets reverse. However, at first the shift to meat and dairy demands more P 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).

(4) The downslide of the U-shaped curve is related to a decreasing demand in meat and dairy in the developed countries (Mathijs 2015, Vranken et al. 2014). Smil (2002) showed that the data on P fertilizers application went down in developed countries according to this trend, especially in Europe, where the oversupply of P in the 1980-90ies is almost over (Harenz 1991, Gustafson et al. 2012).

(5) Hence this aspect is only one part of the truth since it makes the P part of the food concentrated in urban systems and thus easier to recycle from human excreta respectively (Drangert 2012). In addition, it makes cities a future source of (recycled) P since the import to the cities exceed manifolds the export of P back to the countryside (Cui et al. 2015, Ma et al. 2014, Metson et al. 2015, Schmid-Neset et al. 2008, Thitanuwat et al. 2015, Wu et al. 2015).

(6) This, however, 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). In consequence, the demand of P decreases while food security is still provided and the livestock populations are still as high as before?

(7) However, vegetarian food does not contain all trace elements and vitamins humans need for their health. Vegetarians suffer a lot of diseases than humans balancing their

meat consumption do not experience. Humans are not made for vegetarian food alone (Döll 2005, Nawroth 2016).

(8) Food security also requires that the food we eat and drink does not harm humans´ health. The loads of P in the food itself and the adjuvant contaminants within the P fertilizers may cause serious diseases contradicting the term food security (Burlingame et al 2014, Döll 2005, Huffmann 2015, Kratz et al. 2015, Reijnders 2014).

(9) P fertilizers contain many contaminants that pollute the water reservoirs used for human and livestock as drinking water. Cadmium and Uranium may serve as examples (Schnug et al 2014) that P application may harm food security.

(10) 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 caused by polluted environments (e.g., allergies, Huffmann 2015). Livestock health counts as well in this aspect (Grünberg et al. 2015).

Summarizing, linking P scarcity with food security is at the first glance obvious on the second this conclusion neglects many aspects inherent to the “food security” concept as research reports especially from medicine. Since humans as all life on Earth are only through flow systems for P having an almost equal in- and output of P a day a change in nutrition to no meat rather harms human health than it solve the P problem. Reducing, however, the meat and dairy consumption is a task that should rank high in agricultural production regimes as well as for ethical reasons (Allievi et al. 2015).

Nevertheless, the consumption of dairy products and meat can be reduced substantially since the losses of P from mine to fork are too high. Less meat and dairy may do for human nourishment, thus adapting the number of livestock population to farmland and grassland area of a region should determine agrarian policy. The production mode of meat and dairy should base on resources that the region itself can provide in an extensive way avoiding any imports of feed and fodder and along with them also the inherent P.

5. Summary

Cordell (2010) explored the P resource problem in deep. She and co-authors introduced the peak phosphorus concept similar to peak oil as a warn mark for the perpetuation of a steadily increasing market demand. Both markets show similarities not only reflecting physical scarcity. Both resources fuel markets and are essential for present day human life. P is non-substitutable in food production in the present day mode of industrial agriculture. P enabled the Green Revolution to nourish World´s population. The increasing demand for P continuously eat up the P reserves worth to be exploited for technological options and economic feasibility. Only a minor part of the World´s P resources are exploitable for these reasons. Technological options and pricing mechanisms may make a resource scarce. The excessive use of P however caused negative impacts to the environment but also formed new stocks of P that can be used for agricultural purposes or only simply pollute and transform environmental systems. Some of these stocks can be recycled (manure, food waste etc., Seyhan et al. 2012, Gibbons et al. 2014) or reactivated in arable soils by new types of agricultural management (Kucey et al. 1989, Gholamhoseini et al. 2013, Battini et al. 2014). Thus, more supply markets for P fertilizers come into the play, after the initial P reserves of organically grown guano stocks were exploited at first, the apatite stocks become the second and the main source still, third, P (as a waste?) from Uranium enrichment compete the prices of P from apatite, and now the recycling and soil stocks will set limits for pricing and may open at a certain price level the floor for closing the P use chain into a more and more closed cycle. However, this process bears many uncertainties and there are a lot of impacts of the social system to acknowledge until a wise P management happens (Scholz et al 2015b).

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