Chapter 2
Exploration: What Reserves and Resources?

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Abstract The Exploration Node focuses on the search for assessment and quantification of phosphate reserves and resources in relation to the geopotential (i.e., the undiscovered reserves and resources). The Exploration Node encompasses all aspects of the predevelopment stages of phosphate deposits from initial discovery of deposits to the involved feasibility studies required to obtain funding for the development of a mine. The feasibility of producing phosphate rock (PR) can be broadly defined in terms of technical feasibility and economic feasibility. In order for potential ores to be classified as *reserves*, consideration must be given to issues of grade, quality, operating, and investment costs which include studies of the accessibility and availability of financing. Details about these considerations are often proprietary, making it difficult to publically assess the resource picture. Phosphorus is the eleventh most abundant element. P is essential for life and cannot be substituted by other elements in food production. The given knowledge

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about *reserves* and *resources*, the *accessibility*, and *scarcity* of phosphorus and phosphate rock may depend on available technologies and is finally an economic question. We discuss a number of parameters which may indicate whether scarcity of a resource may be an increasing concern. These include the resource/consumption ratio, Hubbert-curve-based peak predictions, trends in ore grade, new resource discovery rates, and resource pricing as they are important for understanding exploration efforts. We further discuss estimates of reserves and the trends in actual estimates of phosphate reserves. P reserve estimates are dynamic and will increase for some time. Nevertheless, at some time in the long-term future, there will be a peak such as there will be a point in time that mined P becomes less economical than conservation and recovery.

Keywords Phosphorus reserves · Indicators for resources scarcity · Uneven distribution of reserves · Supply–demand dynamics

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1 Introduction

The Exploration Node focuses on the search for assessment and quantification of phosphate reserves and resources. The key question to be assessed is: What knowledge is available about the nature, location, quality, quantity, and accessibility of P deposits in various world regions? As we will show, the answer to this question is often depending on economic issues.

At the present time, for the purpose of this study, *phosphorus reserves* are considered phosphate rock (PR) that can be economically produced at the time of the determination using existing technology, reported as (metric) tons of recoverable P_2O_5 concentrate (which includes 43.6 % pure P). Resources are considered PR of any grade, including reserves that may be produced at some time in the future, reported as tonnage and grade (in terms of the mean percentage of P_2O_5 contained in that rock which is assigned to phosphate processing) in situ. The Exploration Node covers sedimentary and igneous deposits and includes the assessment of all forms of mining as exploitation methods, in particular surface, underground, and offshore mining for establishing the viability of a deposit from a geophysical accessibility and projecting perspective. The exploitation itself is part of the "Mining Node." These deposits may be "conventional" deposits containing the mineral apatite, or nonconventional containing P in some other mineral forms.

The Exploration Node encompasses all aspects of the predevelopmental stages of phosphate deposits from initial evaluations to the involved feasibility studies required to obtain funding for the development of a mine. This generally includes a detailed geologic, mining engineering, and economic studies to quantify reserves, production and investment costs, and consequently optimal capacity. This would also include preliminary viability and prefeasibility studies to the final feasibility study including a market assessment. If positive, an investment decision normally follows. The Mining Node picks up from that point on. However, as P is an essential element, from a sustainable development perspective, also the (real) long-term availability of P is of interest. As we will show, this asks for comprehensive considerations on supply–demand dynamics.

The feasibility of producing PR and other mineral deposits can be broadly defined in terms of *technical feasibility* and *economic feasibility*. Determination of technical feasibility includes geologic, chemical, mineralogical, textural, and other studies of the potential ore, beneficiation studies, processing studies of raw ore or concentrates, and mining studies. Determination of economic feasibility is performed at increasing levels of complexity and cost data from opportunity studies to very detailed bankable feasibility studies. Engineering cost estimations are performed at varying levels of expense and accuracy, and these analyses rely heavily on supporting technical studies. Associated technical studies often have to be performed at higher levels of complexity and cost. Economic and financial analyses further depend heavily on the comparative cost of raw materials or fertilizer products on the world market delivered to a production facility or distribution point, the grade, quality, characteristics of potential products, and the cost of borrowing money.

To enable a financial analysis, not only does the cost side have to be investigated but also the potential financing and revenue aspects must be assessed. Therefore, assumptions about realistic future price levels and price developments have to be made. All of these factors, and others, must be addressed before potential ores can be called reserves, i.e., they should address that part of the total resources that can be economically extracted with available technology under environmentally and socioeconomically acceptable conditions (the modifying factors according to JORC or CIMM codes, which today are the worldwide standards; JORC 2004). The Canadian National Instrument 43-101 standard is even more restrictive, requiring technical disclosure.

The phosphate Exploration Node is a supply chain node, wherein the body of knowledge is largely contained in mining companies (often integrated with fertilizer companies), consulting companies, and independent consultants specialized in such studies. Other organizations that may have an in-depth understanding of the issues associated with geological exploration and mining are geological surveys and mining bureaus (often at the national level; e.g., the US Geological Survey (USGS), the German Geological Survey (BGR), the French Geological Survey (BRGM)) and international organizations (IFA, IFDC). Universities with mining schools (University of Nevada's MacKay School of Mines, McGill University, etc.) may have general knowledge, but there are only few special exploration programs on a national scale, which focused exclusively on phosphorus (Tilton 1977). It should be noted that large international mining companies that are primarily interested in large, long-lived deposits with prospectively low costs—so-called tier-1 projects—show growing interest in the fertilizer minerals potash and phosphate (Crowson 2012).

2 Indicators and Causes of Resource Scarcity

Scholz and Wellmer (2013) distinguish between *physical scarcity* and *economic scarcity*. Phosphorus is common throughout the Earth's crust. Obtaining the mineral resources that can meet the demand into the future may require a significantly increasing share of our economic resources or new technology as usually the highest grade most accessible material near the surface on the continents is consumed first and the average grade of the PR ore that is being mined is going to slowly decline (see Watson et al. 2013, this volume). This requires, in turn, that there be adequate levels of reserves that are sufficiently accessible, located in surface rock, high enough in grade, relatively free of impurities which can be removed economically and/or that recovery technology improves to compensate for changing ore characteristics.

Scarcity can also be the result of factors that are not physical or economic. Competing land use options wherein the land is more valuable for other uses may preclude development as phosphate mines. While environmental awareness and activism can have very positive results on avoiding mining in environmentally sensitive areas, missing trust in mining companies and state agencies, sometimes linked with political opposition, can result in putting meaningful mining areas off limits to exploration and development. Large prospective areas have been excluded as areas within preexisting mining areas. Examples of such areas can be found within the USA such as the Georgia coastal area or the North Slope area of Alaska. Environmental laws concerning reclamation or mitigation may make production economically infeasible, therefore excluding deposits or portions of deposits from consideration as reserves.

Phosphate producers may have to accept, or may perceive they have to accept, conditions imposed on them by importing countries imposing their environmental and socioeconomic values and standards through environmentally based trade-related laws. This would include laws concerning impurities in products and the way the materials are processed and by-products are disposed of. Naturally, sometimes these laws are motivated by other interests; they may actually be disguised trade barriers which may promote local or regional production. An example of trade restrictions based on environmental standards was the European water solubility requirements for triple superphosphate (TSP), which were launched in 1975 (EU 1976). Reduced solubility is largely caused by impurities in the precursor PR and processing conditions. The EU restrictions excluded North American TSP product from the European market for some time (this law got changed in 2004, EU 2004). Another case would be the EU cadmium laws that have been drafted (Chemicals Unit of DG Enterprise 2004). Such laws can impose thresholds for cadmium in fertilizers imported into the EU and thus affect what PR will be mined. Of course, such European laws would give companies producing phosphorus fertilizers from PR with a low cadmium contents advantage in the European market. Feasibility studies of P mines have to take these aspects into account.

Is exploration keeping up with the demand for phosphorus? Teitenberg (2003) lists several potential indicators that could signal increasing scarcity, including the resource/consumption ratio (*R*/*C* ratio), trends in resource pricing, trends in ore grade and purity, and trends in new resource discovery rates. When discussing these indicators, we will reflect both on the general trends of these indicators for minerals and metals (which may emerge after wars or economic crises) and on specifics. To this, we could also add indications of uneven distribution, such as the Herfindahl–Hirschman-Index (HHI), which is defined as the sum of the squares of the shares of the P production or P reserves.

2.1 *R/C* Ratio

The *R*/*C* ratio is sometimes called the (static) resource lifetime, as it has units of years and would represent the lifetime of the resource if no new deposits were put into production and consumption rates did not change. Given those limitations, Scholz and Wellmer (2013) point out that the appropriate use of this ratio is not to predict ultimate depletion of a resource, but as an “early warning indicator” calling for action, for instance increased exploration efforts. The *R*/*C* ratio for PR is commonly based on data maintained by the USGS.

Scholz and Wellmer compared the *R*/*C* ratio of 34 minerals and metals in 2002/2003 with that of 2010. In 2003/2003, the *R*/*C* ratio for PR was 130. In the ranking of this ratio, phosphorus was tenth of the 32 elements (which could be compared in this year). However, in 2010, the *R*/*C* ratio turned to 370, which brought it to rank 4 out of 34. On a first view, this increase has been due to an increase in the documented reserves in Morocco from 5,700 Mt PR to 50,000 Mt, which has been provided in an International Fertilizer Development Center (IFDC) report reassessing the Moroccan reserves (van Kauwenbergh 2010b). However, even if the Morocco reserves are not considered, the USGS estimates of world reserves increased from 9,300 Mt P in 2009 to 15,000 Mt P in 2011 (Jasinski 2009, 2010, 2011; USGS 2004), mainly because of increased documented reserves and reassessments of phosphate reserves from countries in the North African phosphate belt. This indicates exploration efforts in many countries though Morocco holds around three quarter of all reserves.

If the *R*/*C* ratio is best used as an "early warning indicator" calling for action, as described above, then the data indicate that society has ample time to make such efforts. This is not to argue that action should be delayed. On the contrary, it could be interpreted as a call to phase in action before criticality is approached. However, one may ask on what basis data on reserves are altered and substantiated and how valid are the USGS data. The USGS is one of the public institutions, which provides free world resource and reserve data for many commodities since more than 130 years. The 2010 change in USGS estimates was primarily based on a comprehensive secondary analysis by IFDC (van Kauwenbergh 2010a) using a 1998 report on Morocco reserves (Gharbi 1998) as well as numerous other reports and references. But it often is unclear (also for other countries in the case of phosphorus and for other minerals as well) on which geological and drilling data the conclusions are made.

Well-documented studies of commodities which have a political dimension for comparison might shed light on the factors which influence the sum of country and world reserves. It is therefore subject of a case study of the Global TraPs project described below in Sect. 2.4. Three levels of detail for estimating reserves can be distinguished: companies, regional planning authorities, and the highest political level. For *companies*, reserves are their future working inventory. They, therefore, normally only gather data and estimate reserves for as many years of production as the cost associated with obtaining the data and their preference for business planning justify. These reserves normally have to comply with the JORC code as mentioned above. The *regional planning authorities* (e.g., municipal or state authorities) have to look farther into the future. So what are reserves for them are resources that can be technically exploited, but their environmentally and socioeconomically acceptable conditions (the modifying factors) have not yet to be defined. *The highest political level* is normally involved when for the national budget, significant tax contributions are expected or—for social reasons or for reasons of security of raw material supply—significant subsidies are required. A good example of the interaction between these three levels is the German coal production history. Coal occurs in seams and from its geometry is comparable to phosphate.

The rapid increase in PR resources after 2007 may be due to various reasons, especially the price signals in metals and fertilizer. The increase in prices allows a lowering of the cutoff boundary between reserves and resources. A linear decrease in grade normally has the consequence of a nonlinear (in excess of being proportional) increase in reserves or resources. A reduction in grade by 10 % relatively would increase the reserves by more than 10 % as there normally is more rock with lower content of phosphorus than with more phosphorus.

2.2 Hubbert Curve Modeling

The Hubbert curve is a modeling method originally proposed to analyze US oil production. It assumes that the rate of production is proportional to the product of the amount of the resource that has been consumed times the amount remaining. The model that predicts the shape of the production versus time curve will be "bell-shaped," with two parameters: the peak year of production and the amount of ultimately recoverable resource (URR). Hubbert (1962) successfully predicted the peak of the national US oil production (Brandt 2007). However, subsequent use of Hubbert's approach was not always successful and has engendered considerable controversy (Sorrell and Speirs 2010).

Déry and Anderson (2007) tested the Hubbert model, among others, on global phosphorus production data. They just adjusted a symmetric curve to the historic production curve and predicted that the global peak occurred in 1989. More significantly, the URR predicted by the method was only 35 % even of the USGS reserve numbers of the time and only 10 % of the global reserves documented in 2010. A similar attempt has been reported by Ward (2008). So this approach clearly seems inappropriate for predicting URR of a global resource such as phosphorus. Other applications of the Hubbert model were presented by Cordell et al. (2009, 2011, April 4). They adjusted a Gaussian symmetric curve but used the USGS estimates of reserves to fix the value of the URR (and hence the area under the Hubbert curve and the so-called peak of 1989). Using the 2008 USGS reserve estimates of 16 Gt PR, the date for peak global PR production was estimated to be in 2035. But the amount of reserves is dynamic. When they incorporated the increase in reserves of 60 Gt PR (Smit et al. 2009), a new peak year was found to around 2,071, plus or minus about 20 years.

An analysis similar to that of Cordell et al. (2009) shows a peak year of production in 2087 at 442 Mt PR per year, to be followed by a decline. This peak value is about 2.5 times the 2010 value. When compared to the median UN population projection for that year, this value results in a per capita PR production about 87 % higher than the 2010 figure of 25.8 kg/capita/yr. This corresponds to an annual rate of 0.82 % per year. From 2001 to 2012 the per capita production increased at a rate of 3.4 % per year following a decline of world production after the decline of the Soviet Union (see Chap. 1 Figs. 7 and 28). Extrapolating the current trend suggests that the amount of phosphorus consumption at the peak is not implausible.

Vaccari and Strigul (2011) have shown that the peak timing of Hubbert curve-fits is very sensitive to the stage of the production data sequence. In an example using the historical record of US PR production, the method was shown to have significant difficulty identifying the peak unless the peak was already past. Furthermore, they suggest that Hubbert curve extrapolation may not be appropriate for global resource modeling. It could be appropriate for local resource fields because consumers could switch to other sources. Strictly speaking, there are alternatives to global reserves: Previously, uneconomic resources can be converted to reserves, and conservation and recovery methods may become competitive with extraction.

The Hubbert curve also predicts that production will be symmetrical in time, declining once half of the initial reserves have been consumed. Again, there may be reason to question the validity of this conclusion for global production of a resource with “no alternative.” In such a case, it may be expected that demand is “inelastic,” meaning that consumption would not be greatly sensitive to price. In such a case, high production levels would be maintained until very high costs force the adoption of much more difficult technical and societal options such as intensive recycling or by attempting to reduce per capita consumption via changes in diet. This shows the importance of exploration and recycling but also for a comprehensive monitoring of phosphorus reserves for avoiding that the reserves becomes critically small.

As with the *R*/*C* ratio, the Hubbert modeling approach suffers from the limitation that it does not account for the expansion of the URR that could be brought about by changes in economics and/or technology. The predictions of the Hubbert modeling approach might best be examined as a conceptual model to describe one scenario for how future production might play out. It could also be useful as a stage in the development of such models, as criticism may lead to the incorporation of more factors, so one may judge what the potential impact of them may be. However, one should reflect whether the assumption of a symmetric rise and fall of production is adequate (as it may be the case for single deposits such as Nauru on a supply market) or whether other types of production curves (such as logistic functions with saturated supply on a demand market) are adequate. As may be learned from shale gas, also new groundbreaking technologies of mining may change the reserves.

2.3 Price

As that of all metals and minerals, the price of PR has been showing increasing volatility and growth in the last 5 years. Some analysis of what caused the 2008 peak and what level the phosphate price will take is provided by Weber et al. (2013). They elaborate that the price of one commodity such as P should not be considered in isolation. The price of most commodities has also increased substantially over this period (see Weber et al. 2013: Figs. 2 and 4 in Chap. 7, this book). There are many factors causing the price peak and the potential transition to a new plateau including speculation and too low prices (lack of investments in mines and exploration) over a long period. A number of fertilizer plants have closed in North America, while new production facilities have been added in Morocco and other countries. Naturally we have to reflect and to investigate whether the price volatility of phosphorus including the 2008 price is an indicator scarcity of production means, accessibility of reserves or changed constraints of production (e.g. lower phosphate rock ore grades). This should become a matter of research (Chap. 7 is starting a discussion here). However, in general, the current short-term price dynamics are affected by many factors and are related to economic scarcity, i.e., short-term overshoot of demand, and therefore are not an indicator of physical scarcity. Furthermore, there is evidence that high market

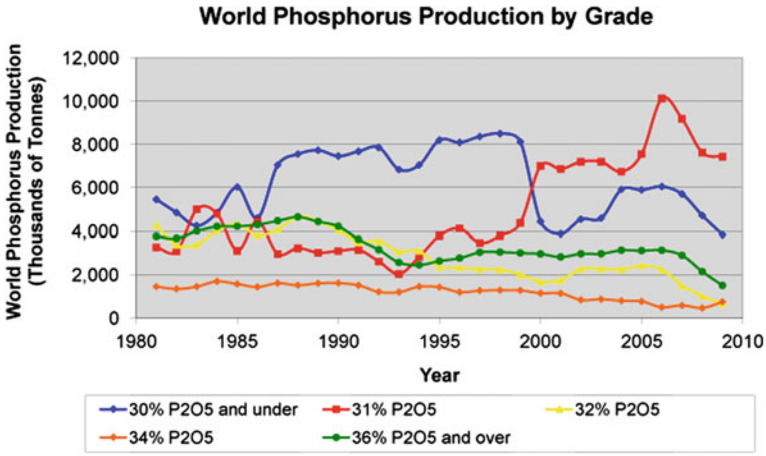

Fig. 1 Trends of grades of beneficiated P [in general, which departs P mines after beneficiation; *source* IFDC (2010)]

prices, together with concerns about physical short- and mid-term scarcity, may motivate policy makers and (financial) business agents to induce exploration efforts and the building of new mines. This could lower PR prices in the midterm.

2.4 Grade

There are no reliable data on how the average grade of mined PR was altered in the past. However, grade is only one out of many aspects which affect the economic value of PR concentrate, and there are many other aspects such as location and ore characteristics. We should also note that igneous PR is often very low in ore grade (even sometimes less than 5 %). But by beneficiation, it is upgraded. Figure 1 presents the trends of grades of beneficiated PR concentrate which shows rather a decline in low-grade (beneficiated) PR (below 30 % P_2O_5) and high-grade beneficiated P (above 34 % P_2O_5) is increasing and makes about 31 % in 2010 (though statistics on phosphorus consumption usually refer to 30 %). In general, we were facing a decline of the PR concentrate in the last 30 years (see Chap. 3, Fig. 6) which may ask for an improvement of beneficiation technologies. Of special interests are the trend in the ore grades. According to our knowledge, no data have been published on this issue so far.

In 2011, the USGS added five new countries (Algeria, India, Iraq, Mexico, and Peru) to its list of major reserve holders. Their figures indicate that Iraq (5.8 Gt PR) holds the second largest deposits of PR reserves in the world, after Morocco [50 Gt PR (Jasinski 2010, 2011)]. However, the reported grades of Iraq's reserves are below 22 % P_2O_5 (Al-Bassam et al. 2012). And most of these reserves were taken out in the 2013 accounting as the classification has been wrongly classified according to Russian instead of the US criteria of reserves. Thus, Iraq reserves are 0.46 Gt PR, and more than 5 Gt PR have become resources again and may become reserves if prices increase, new technologies develop, or market change. To judge the relevance of the grade, details of the geology of the ore have to be taken into account. If the phosphate content is easily separated (i.e., it lies in distinct mineral assemblages rather than being intimately integrated into the rest of the rock), a medium-grade concentrate can be produced from a low-grade ore at an acceptable cost.

Igneous PR of 4–5 % P_2O_5 can sometimes be upgraded to 39 % concentrate. Sedimentary PR is typically quite different from igneous phosphate rocks. The Central Florida sedimentary phosphate ore is composed of a varying proportion mixture of "pebble" at around 29 % P_2O_5 and "feed" at under 9 % P_2O_5 (whole ore average around 11 % P_2O_5). Pebble is recovered or removed by washing and screening, while sand-sized "feed" is put into the flotation circuits to raise its grade to around the same as the pebble. The pebble content of the ore was one of the major variables in production cost in Florida and the pebble content decreased as the mining district moved south, ending at around 4–5 % in the new prospects in the southern portion of the field.

PR beneficiation has been the subject of considerable research. The question in what way the decline in the ore grades may be compensated by extraction or beneficiation technologies may become a matter of research. Beneficiation usually starts with dry and/or wet sizing. Flotation may be utilized if water is available and economics justify its use. As mentioned, all igneous PR is subject to floatation because of the low ore grade, often around 5 %, and the question is what floatation technology may contribute to transfer of resources to reserves. The Crago process, the basis for many PR floatation processes, was implemented in Florida in the 1920s and 1930s. For an overview of PR beneficiation, see IFDS/UNIDO (1998). Overall recovery has improved over the years (Al Rawashdeh and Maxwell 2011), for example, report that phosphate flotation recovery in some plants has increased from 60 to 90 %, thereby compensating for lower-grade ores. In general, multiple efforts are made by PR companies to improve recovery, reduce waste, and conserve resources. With increased prices for PR concentrates, it is possible to apply more resources to beneficiation infrastructure and processing to improve recovery of already mined materials or the utilization of beds that may not have been previously utilized due to cost or technical considerations. Van Kauwenbergh (2010a) has pointed out that flotation was not used in Jordan or Morocco until the late 1990s due to cost considerations. The cost-effective implementation of this beneficiation technique has put more resources in the reserve category in these countries. The use and development of floatation is one technological means to reduce the comprehensive losses of phosphorus before processing (VFRC 2012).

2.5 Purity

In order for a PR to be suitable for a wide range of processing options, the R_2O_3/P_2O_5 ratio (i.e., ($Fe_2O_3 + Al_2O_3$)/P_2O_5 ratio) must generally be below approximately 0.10. The (R_2O_3 + MgO)/P_2O_5 ratio must generally be below 0.12 (Jasinski 2010). When phosphate rocks have impurity contents at or above these levels, problems can occur in processing. For example, products may not dry properly or the products may contain phosphates that are not water soluble. For a review of the effect of impurities on fertilizer processing, see van Kauwenbergh (2006). According to Prud'homme (2010), around 90 % of current PR production is used for phosphoric acid production mainly by the wet process, requiring a feedstock with fairly low impurities. PR used in some fertilizer processes may contain more impurities than the material used for wet-process phosphoric acid.

Common potentially hazardous elements associated with PR include arsenic, cadmium, chromium, lead, selenium, mercury, uranium, and vanadium. Cadmium and uranium show the greatest enrichment in sedimentary PR, relative to crustal rocks, by a factor of 60–70 in concentration for Cd and about 30 for U (van Kauwenbergh 1997, 2012). Igneous PR, which is about 13 % of world production, is mostly enriched in arsenic (by a factor of about 67) and selenium (by a factor of 76), but also in U (22 times) and Cd (7.5 times).

Uranium for use as nuclear fuel can be extracted from phosphoric acid produced during acid-based fertilizer manufacturing. The market for uranium is expected to grow. When making diammonium phosphate (DAP) and monoammonium phosphate (MAP), most of the uranium from PR tends to be found in the fertilizer product, with a small fraction in the gypsum by-product. Among the decay products of U is radium, and radon gas is a radium daughter. Most of the radium in PR winds up in the gypsum by-product (van Kauwenbergh 2012). Making fertilizer via the dihydrate route in effect cleans the fertilizer product. Due to regulations imposed by the USEPA concerning radioactivity of the phosphogypsum product, the use and the disposal of the gypsum by-product from Florida PR are prohibited and handling and storage are very costly. Due to regulations in the USA, Florida-produced phosphogypsum is stacked in large piles requiring monitoring and maintenance in perpetuity. There has been considerable debate concerning the EPA-imposed radioactivity limits for phosphogypsum. Florida-produced phosphogypsum is below IAEA-suggested limits for naturally occurring radioactive matter (NORM; van Kauwenbergh 2010a).

Cadmium, a natural element in the Earth's crust, is among the most toxic heavy metals. It accumulates in the soil from several natural and anthropogenic sources including zinc smelting, burning coal, and weathering of coal and base metal sulfides, and potentially by extensive application of fertilizers. It may critically accumulate in humans from the food supply, breathing fumes and dust, and smoking. Interestingly, it also interferes with the use of uranium as a fuel, since it is a neutron absorber. A number of European Union countries have placed limits on Cd in fertilizer (ranging from 21.5 to 90 mg/kg P_2O_5), or on input to agricultural soil (0.15–150 g/ha/yr), or on Cd content in agricultural soils (0.5–3.0 mg/kg dry soil, van Kauwenbergh 2010a). When PR is used to manufacture single superphosphate, essentially all the Cd from the PR is found in the fertilizer. With other processes, the fraction captured in the fertilizer may be less, but can still range from 55 to 90 %. Technologies for removal of cadmium (decadmiation) are available. However, costs for removal and disposal or processing unwanted by-products or wastes have not been established.

Regulatory limitations on impurities are usually expressed relative to P_2O_5 content of the fertilizer. Soil accumulation can be controlled by regulating agricultural practices. Pending European legislation is predicated on European studies, indicating that fertilizers with 20 mg Cd/kg P_2O_5 are not expected to produce long-term accumulation in most soils (Hutton and Meeûs 2001). But those with more than 60 mg Cd/kg P_2O_5 are expected to do so (Nziguheba and Smolders 2008). Regulations in the USA are based on scientific risk-based assessments, and the allowable Cd, and other metals, levels are much higher than European standards (van Kauwenbergh 2012). The risk-based limits recommended in the USA fall below WHO-recommended limits. Van Kauwenbergh (2010a, b) has pointed out that while technologically advanced and affluent countries may be able to set high standards with respect to cadmium levels in fertilizer products, less affluent countries may be prone to take a more pragmatic approach.

2.6 Discovery and Growth of Reserves

Although major discoveries are few and infrequent, Sheldon (1987) presented an analysis showing that discovery of new PR resources in the 20th century outstripped consumption over the same period not taking reserve growth into account. And there have been new discoveries after 1987. A large share of about 74 % of this increase is from a few discoveries, primarily from Morocco. This highlights the regional inhomogeneity of phosphate reserves in the world. Concerning sedimentary deposits which occur in seams such as phosphate, salt, or coal, the major replacement of mined inventory (reserves) occurs by so-called reserve growth. As explained above, reserves are the working inventory for companies. They, therefore, normally only gather data and estimate reserves for as many years of production as the cost associated with obtaining the data and their preference for business planning justify. So by detailed exploration, resources of the same system of seams or layers in the forefront of the mining area are converted into reserves. For example, for Israel, the reserves were 180 Mt PR in 2005 and the same number as in 2010. The figures for Jordan were 900 Mt PR in 2005 and 1.500 in 2010 (Prud'homme 2011; Jasinski 2006). Even for commodities which do not occur in seams, reserve growth, once a deposit is exploited and offers the possibility of better understanding the deposit, is a common feature. Wagner (1999) showed that, for example, for lenticular Pb/Zn deposits in limestones—so-called Mississippi Valley type deposits—often a reserve growth factor of two could be achieved.

An essential aspect of future availability of P is that resources may become reserves. Today, USGS (2012) records 71 Gt PR reserves and 200 Gt PR resources. The latter do not include the western phosphate fields in the USA, which include besides 8 GT PR reserves at an average grade of 24 % P_2O_5 507 GT of "subresource-grade phosphatic material … at a depth greater than 305 m" (Moyle and Piper 2004). Though it may become more expensive to mine these phosphates, underground mining is technically and economically feasible (note that today an average world citizen consumes about 30 kg PR per person and year which costs about 6 USD, see Scholz and Wellmer 2013). It seems economically feasible, from the perspective of the cost for an average world citizen, to double the price and correspondingly the reserves. Naturally, these are heuristic like inferences that may rely on experience with coal mining. Given the essentiality of phosphorus, this issue may ask for closer investigation.

Nevertheless, as with most minerals and metals, there is a large regional heterogeneity of phosphate reserves in the world. There are more than 1,600 world phosphate deposits compiled (Orris and Chernoff 2004). Libya, which is also located in the North African phosphate belt, is not yet documented in the USGS Mineral Commodity Summaries. If we acknowledge that various offshore mining projects got explored (Midgley 2012), the new discovery has continued to outstrip consumption.

In some areas of the world, reserves may not be established for tax purposes. When the material in the ground is quantified and resources are changed to reserves, which have a monetary value, the land can be reclassified. Unimproved unoccupied land or agricultural lands are taxed at different rates than mine lands with valuable contained reserves. This sometimes prevents P seams to be classified as reserves.

2.7 Distribution

Scholz and Wellmer (2013) proposed using the HHI as an indicator of uneven distribution of *reserves* and of *production*. The German Raw Materials Agency (DERA 2011) divided the possible range of the HHI from 0 to the maximum of 10.000 into three ranges: 0–1.000 low, 1.000–2.000 middle, and 2.000 to the maximum of 10.000 as highly critical from a supply security perspective. They assessed the HHI for production in the year 2010 at nearly 2.000, which is in the middle range in comparison with other metals and minerals. However, the HHI for reserves was a high 5.000 in 2010. They note that if the HHI for *reserves* is much higher than for *production*, it may be due to the incomplete recording of the reserves, lack of exploration activities in certain countries, or political reserve corrections. Whether a high HHI index is indicating a critical distribution, in which sufficient supply is dependent on few countries, very much depends on the total volume of the reserves compared to the demand. Here, as phosphorus has a high static lifetime globally compared to other minerals and metals and some overcapacities in production (USGS 2004), disturbances with some major suppliers may be compensated by suppliers with smaller (production) and reserves. Thus, the relatively high HHI indices are less critical.

Since local markets for commodities even for low-value commodities are only existing in exceptional cases, and we, therefore, have to consider the world market as one commodity market, there is a regional imbalance for most of the commodities. Commodities such as phosphate or metals are mined from deposits which were formed as a result of enrichment processes which are tied to paleoecologic conditions and geologic processes. Since paleoecologic and geologic conditions varied around the world, most industrial mineral and metal deposits are unevenly distributed geographically. Even in cases where deposits of certain minerals or energy-bearing materials (like in the case of uranium, see Wedepohl 1995) formed in a wide variety of geological environments, the geologic conditions where the best deposits occur are few. Morocco has a special position. A large share of the world sedimentary PR reserves is found in this area, and Morocco area embodies a large share of resources though no complete picture about the reserves is available yet. Naturally, large mining companies concentrate their efforts on the best deposits due to the investment costs for new mines. Companies only invest if the projected operating costs of a future project are better than average, preferably in the lower third quartile (Wellmer et al. 2008). A consequence is a growing concentration of mining in countries with a very favorable geology for a specific commodity (Stephenson 2001). This may lead to high HHI indices signaling a dependency of supply on a few countries. This is a consequence of globalization. This appears to be an unwanted consequence, depending on the nations involved and their intentions.

The consequence is that international politics has to develop strategies such as to secure for certain diversity and or/security of supply to support sufficient and free flow of raw materials. Another aspect concerning high HHI is to understand the relationship between producer and customer. Certainly, a producer can try to "squeeze" the customer in a seller's market. However, historically, sellers' markets never lasted for long. This in particular holds true if the supply is shaped in a way that "blocked supply" by main providers may be compensated by other providers for a long time. This is, in principle, possible for PR. For PR, in time, the market would swing back to a buyer's market.

3 Resources in Light of Global and National Supply–Demand Dynamics

3.1 Sovereignty Over Natural Resources

Within the "New International Economic Order," the sovereignty of a nation over its natural resources is a key element. It became international law with the UN resolution 1803 of December 14, 1962, "Permanent Sovereignty over Natural

Resources" (UN 1962). The nation state has become the dominant political organization after World War II (Parsons 1951). As the case of the European Union shows, new organizational schemes such as supranational societies who take joint action with respect to supply security may emerge. And there are also critical voices which consider the nation state principle as inefficient with respect to challenging global questions such as climate change, biodiversity, resources, and environmental pollution management (Beck 2000; Scholz 2011). Nevertheless, it is self-understood that natural resources have to contribute to a nation's prosperity within the intrageneration fairness concept of sustainable development as defined in the Agenda 21 of the Rio Declaration at the UN Conference on Environment and Development in Rio de Janeiro in 1992 (1) to enable all people to achieve economic prosperity, (2) to strive toward social justice and (3) to conserve the basic needs of life. This concept is developed further in the Intergovernmental Forum on Mining, Minerals, Metals, and Sustainable Development, which was one of a number of Partnership Initiates launched at the World Summit on Sustainable Development in Johannesburg/South Africa in 2002 (UNCTAD 2012).

Since resources in the ground have only a hypothetical value, it is necessary to turn them into real value for the benefit of a nation by mining, beneficiating the resource into a marketable product, and bringing the product to markets. Therefore, capital and know-how for the exploitation of the natural resources are required. The sovereign can either decide to exploit the resources himself or through national mining companies alone and develop the necessary know-how on its own or decide to open the resources to foreign mining companies which often are large multinational companies.

Exploration and mining is a high-risk business, more risky than normal industrial business (Wellmer 1986). Even when a phosphate seam is known in its general geology, the chances to develop a profitable mine are not better than 1:2 or even 1:3 judging from worldwide exploration success statistics of similar deposit types (Sames and Wellmer 1982). So there is a potential conflict of interest between the sovereign who wants to maximize the revenues of mining operations for the benefit of his nation and the mining companies. Besides the normal profit possibilities for a business, independent mining companies require a reward for their risk taking, besides the assurance for stability, i.e., that the legal and financial framework is not changed during the lifetime of the mining operation to their disadvantage.

Since the 1960s, a wide spectrum of arrangements, often specific for a commodity, have been developed worldwide to come to a fair distribution of resource revenues for the nation and the mining risk taker. Options range from the USA where in the eastern states, the surface property owners also own the subsurface mineral rights, but the miners have a special depletion allowance for this tax calculation as examples in the North African countries in which mining is done by the sovereign. In between, there exists a wide arrangement of tax and royalty agreements and carried interests, i.e., a free share in the mining operation for the state without having to carry exploration and investment costs. Vielleville and Vasani

(2008) state: “Those rights (over natural resources in their territories) … have been given shape over time. They have been limited by bilateral and multilateral investment treaties, free trade agreements and customary international law.”

3.2 Demand Dynamics and Exploration Efforts

Exploration efforts depend on the known reserves and resources and available geopotential as well as on the future demand. The world demand of phosphorus has continuously increased over the last decades after an abrupt decrease caused by the decline in the Soviet Union and reduction in fertilizer use in Japan, North America, and Europe in the early 1990s by improving the technology and efficiency of fertilization (Smil 2000). There are two main factors causing the recent trend. One is the ongoing population growth. Between 1992 and 2011, the world population grew by 27.3 %, whereas the global P production increased by 30.8 % from 146 Mt PR in 1992 (Llewellyn 1993) to 191 Mt PR in 2011 (Prud’homme 2011). This suggests a second factor driving recent trends, which is the increase in per capita consumption. This is likely due to changing standard of living, especially in China. Here, it is worth noticing that according to the US Mineral Commodity Summaries, China’s production more than tripled in the last two decades from 23 to 72 Mt PR and in 2011 was by far the world’s largest producer at 38 % of the global total.

It took until 2009 for the global total to fully recover from the drop in the late 1980s and early 1990s due to the collapse of the Soviet Union. Figure 2 shows the per capita production, based on USGS data for PR production (Jasinski 2012) and global population from the US Census (2012). We can see that the per capita production has not yet recovered, although it has been increasing steadily for the past decade.

Special attention should be paid to the rapid increase in the last 5 years. The one-year increase in per capita PR production from 2010 to 2011 was 7.1 %. For the five-year period ending in 2011, it was 4.9 % per year, and for the ten-year period ending in 2011, it was 3.0 % per year. This could indicate an accelerating trend in per capita demand, possibly associated with changes in diet or agricultural practices in some developing countries.

From an overall system theory perspective, besides population growth, consumption may be expected to respond to the changing diets (primarily in countries which turn from vegetable-based to high meat consumption), P dynamics in soil (there are large P deposits in the soils of many areas), and increasing efficiency in agrarian application and in mining and processing, recycling, etc. (van Vuuren et al. 2010; US Geological Survey 2002).

The future demand of P is difficult to predict as there are many competing factors. Mid- and large-scale recycling is starting, and agriculture may become more efficient, whereas high demands may emerge in some parts of the world with highly weathered soils. Increasing reserves and increasing efficiency may, at least

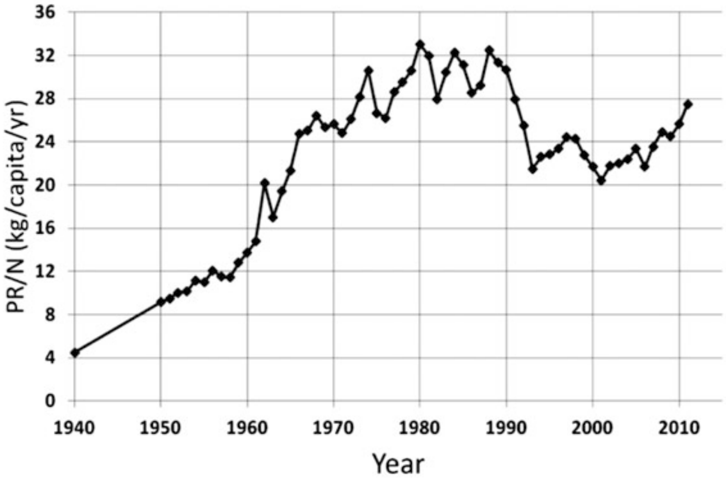

Fig. 2 Per capita global phosphate rock production (PR rock/capita)

in principle, balance the further demand. Global learning curves on efficient P use may reduce the P use per capita.

A challenging question for prospecting and exploration is in what way the feedback control cycle of mineral supply and demand functions. This could include mechanisms such as that increasing prices increase resources, recycling, innovation, and exploration efforts. (Wellmer and Becker-Platen 2002) and the fact that prices that are too high for society may develop for phosphorus, putting downward pressure on demand. Though phosphorus is a low-price commodity (see above), current and prospective price increases may be critical for certain parts of society.

A refinement of the use of the *R*/*C* ratio would be to make forecasts assuming current per capita rates, coupled with UN population forecasts. Figure 3 shows these forecasts under three UN population scenarios: high, medium, and low growth. Under the peak modeling assumption, when half of the reserves have been consumed, then production will decline and shortages will become critical. However, at least at the present time, production of PR is governed more by demand than by availability of reserves. In such a case, production would not decline unless population and/or per capita demand do.

The prediction of the constant per capita demand model can be compared to Hubbert curve predictions by showing the points at which half of the current reserves would have been used and the point at which current reserves will have been completely used. The latter point is shown in Fig. 3 as a solid diamond. For the medium scenario, this will occur in the year 2350, sooner than predicted using the *R*/*C* ratio. The point of 50 % depletion would occur for the medium population scenario in 2,145. But under this assumption, production does not begin to decrease significantly. Of course, various factors could shift this scenario either way. If we would face an increase in per capita consumption (see Fig. 2), we can expect on the

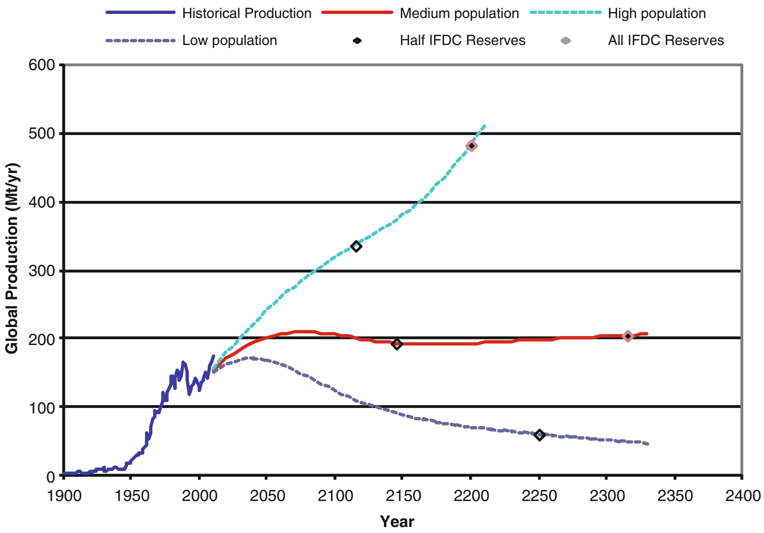

Fig. 3 Projected PR production based on fixed per capita rate coupled with UN projections of population growth

one hand that this point could be reached much sooner than that. On the other hand, reserve growth, i.e., reserves grow in parallel with production and consumption as discussed above under “Discovery,” will continue for the foreseeable future and would push this point further into the future. As with the *R*/*C* ratio, this analysis is not intended to predict actual depletion, but rather as a warning indicator.

Figure 4 shows a scenario according to Scholz and Wellmer (2013) that the production curve will go through a series of plateaus before 1 day a peak is reached. The reduction in consumption equivalent to a plateau between 1990 and 2009 was due to learning effects in the industrialized countries (using less fertilizer per area without reducing the crop output) and reduction in consumption in the Eastern Bloc. The next plateau will probably be reached when the Chinese learn to use fertilizers as efficiently as the developed nations. China’s croplands show the same P imbalance as those in North America or Europe (MacDonald et al. 2011).

4 Work in Global TraPs

4.1 *Knowledge and Critical Questions*

The most critical question for the Exploration Node is a better *understanding of the reserve and resources figures*. A case study was decided in the Global TraPs project. The USGS and the German Geological Survey, which are both in leadership positions in the Global TraPs project (Steering Board, Practice Leader of the Exploration Node), will support these studies.

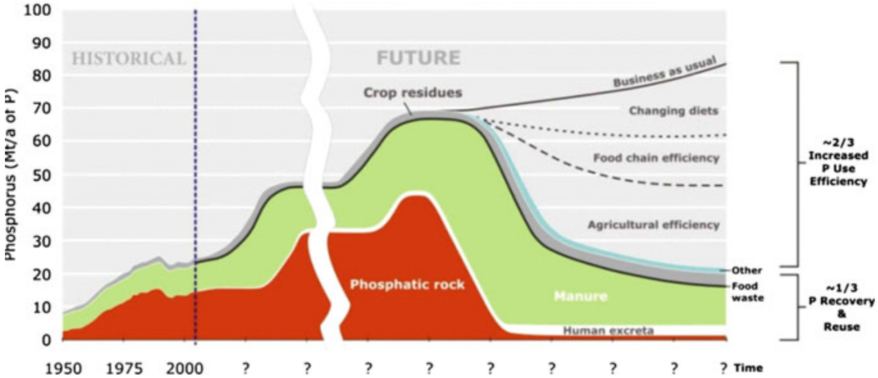

Fig. 4 Scenario for PR production and consumption (Scholz and Wellmer 2013, historical data, and exit strategy after Cordell et al. 2009)

The study will examine (1) what standard methods may be used for assessing availability and the recording of reserves in the USGS Mineral Commodity Summaries, a question which has already been dealt with before (Orris and Chernoff 2004). Further, the questions (2) of how would reserve estimates respond to changes in the price of PR (which may depend on many aspects which are difficult to predict such as innovation of exploration, mining, and beneficiation technologies) and (3) how does the elasticity of demand look like, i.e., how sensitive is consumption to price, are subject of investigation. With the latter question, particularly, whether prices stress the system is of overarching interest. Finally, (4) the risk due to the uneven global distribution and midterm vulnerabilities of phosphorus supply and how it may be compensated is an issue, which is also of interest for exploration efforts (e.g., from the perspective of increasing the potential diversity of reserves and supply).

4.2 Role, Function, and Kind of Transdisciplinary Case Process

The questions dealt with in the Exploration Node are of genuine interest for *private and state-run mining companies* and *geological surveys* whose task is—among others—to provide timely and relevant information on the natural resources we rely on. From the science perspective, these questions are of interest for geological economics and sustainability and all sciences which deal with supply security. Thus, also institutions such as UNEP International Resources Panel and similar institutes are interested in these questions.

Td process is precompetitive and may include competing companies for the purpose of developing a joint view on scarcity and mining options. In principle, this is delicate as owning and not revealing information is a business advantage, whereas valid public information about mining options, demands, and market constraints may avoid wrong investments and motivate proper ones.

4.3 Suggested Case Studies

Many of the above critical questions should be answered in the case study *Phosphorus Resource and Reserves Figures*. The study should be launched via master or PhD thesis in close cooperation with the US Geological Survey.

The reserve data published by the USGS annually in the Mineral Commodity Summaries (MCS) are considered by many to be the most reliable available figures in the world. Many users of reserve data use the MCS without acknowledging the dynamic character of these figures and their limitations. The USGS does not actively determine the reserves and resources of the world as a world authority but collects information from a variety of more or less publicly available sources which are examined and screened. The sources of information for reserve figures are company data or data from local or regional government bodies up to national governments, but also international or multinational institutions such as the IFDC can be a source of valuable information. The different interests of these organizations in data may be a source of biasing data. Data may be working and planning inventory for *companies* and serve as basis for receiving credits from banks, and they are the foundation of policy means (e.g., taxes, resources conservation, recycling, subsidies) for governmental bodies. As also nations are in economic competition, special attention should be paid that the Global TraPs project provides a forum that allows all participants to equally benefit.

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