Chapter 3
Mining and Concentration: What Mining to What Costs and Benefits?

Ingrid Watson, Peter van Straaten, Tobias Katz, and Louw Botha

Abstract This chapter presents the activities in the Mining Node of Global TraPs, a multi-stakeholder project on the sustainable management of the global P cycle. The scope of the Mining Node is the extraction, primary processing of ore to produce phosphate rock concentrates and transportation to a port or processing plant. Phosphate ore deposits are primarily sedimentary in origin, although igneous, and, to a much lesser extent, guano deposits are also mined. A range of mining methods is used, and a significant amount of mining is by opencast or strip mining methods. Following the extraction of the ore, it undergoes a process of concentration before being transported to a plant for further processing or a port for export. World phosphate rock concentrates are produced in 37 countries, with the top ten accounting for 90 % of world production. Global phosphate production

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I. Watson (✉)
Centre for Sustainability in Mining and Industry, University of the Witwatersrand,
Private Bag 3, WITS, Johannesburg 2050, South Africa
e-mail: ingrid.watson@wits.ac.za

P. van Straaten
School of Environmental Sciences, University of Guelph, Guelph, ON, Canada
e-mail: pvanstra@uoguelph.ca

T. Katz
GHH Fahrzeuge GmbH, Gelsenkirchen, Germany
e-mail: tobias.katz@ghh-fahrzeuge.de

L. Botha
Foskor, Moshate House, 27 Selati Road, P.O. Box 1, Phalaborwa 1390, South Africa
e-mail: louwb@foskor.co.za

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has increased to a 2011 level of 195 million metric tons and is set to increase still further to meet, primarily, the growing demand for fertilizers for food, feed, and biofuel production. The overarching objective of the Mining Node, aligned to that of the Global TraPs project, is to address the question: *How can we contribute to sustainability in the phosphorus mining sector through promoting resource efficiency and innovation to avoid and mitigate negative environmental and social impacts, and contribute to food security?* Based on this question, areas of focus for further research and case studies include (1) the optimization of mining and beneficiation recovery rates; (2) addressing environmental and social impacts; (3) small-scale phosphate mining; and (4) mining costs. Transdisciplinary projects teams, involving both science and practice, will work on these focus areas.

Keywords Phosphate mining · Phosphate beneficiation · Environmental impacts of phosphate mining · Phosphorus losses in mining and beneficiation

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1 Mining Activities on the Global Scale

The Mining Node's focus in the phosphate life cycle includes mine planning and development, extraction, primary processing of ore to produce phosphate rock (PR) concentrates and transportation to a port or processing plant (Scholz et al. 2011).

Mine planning and development is initiated following the discovery and evaluation of a resource during the exploration process and is, in turn, followed by downstream processing for fertilizer and non-fertilizer production.

1.1 Phosphate Mining and Beneficiation

Phosphate ore deposits are primarily igneous or sedimentary in nature, with the majority of phosphate ore (85 %) currently mined from sedimentary deposits, which account for about 90 % of world known phosphate reserves (IFA 2012). Sedimentary phosphate deposits are exploited in China, the United States, Morocco, Tunisia, Jordan, Syria, Saudi Arabia, Peru, India, Vietnam, Iraq, and Australia. Igneous phosphate deposits are currently being exploited in Brazil, China, Finland, Russia, South Africa, and Zimbabwe (IFA 2012). Guano-derived phosphate deposits account for only a small fraction of mined phosphates. Deposits on islands related to guano were particularly important in the mid- to late 1800s.

Phosphate ore is mined using both surface (opencast or strip mining) and underground mining methods (van Kauwenbergh 2010), with marine dredging having been investigated, for example off the coast of Mexico, the Eastern coast of the United States and currently off the Namibian coast. The mining method employed depends largely on the type, size, and depth of the deposit and economics. Phosphate mines vary in size and degree of mechanization with mining ranging from labor-intensive methods to highly mechanized operations (van Kauwenbergh 2010).

The proposed development of the Namibian Sandpiper marine phosphate project off the west coast of southern Africa provides an interesting example of planned marine dredging. The Sandpiper deposit occurs as unconsolidated sea floor sediments, located approximately 60 km off the coast of Namibia, in water depths of 180–300 m.

Phosphate sediments will be recovered using a trailing suction hopper dredge (Fig. 1), which includes a cutter head linked to a suction pipe. This is trailed along the seabed removing the target sediments and pumping it into the cargo hold (hopper). The dredger transports the sediments to an offshore discharge buoy pipeline, transferring the material to holding ponds on shore from where it is beneficiated (see Fig. 2; Midgley 2012).

Beneficiation plants are commonly associated with a mine. Once the phosphate ore is extracted, it typically undergoes a process of concentration (beneficiation), which may include primary screening, wet or dry screening, washing, flotation, magnetic separation and drying to produce what is commercially referred to as phosphate rock concentrate. Phosphate rock concentrates typically range between 28 and 40 % P_2O_5 (vs. phosphate ore which may have a grade anywhere between 5 and 39 % P_2O_5; IFA 2012).

Phosphate rock may be transported to a port for export or a domestic plant for direct use or further downstream processing. A limited amount of phosphate rock

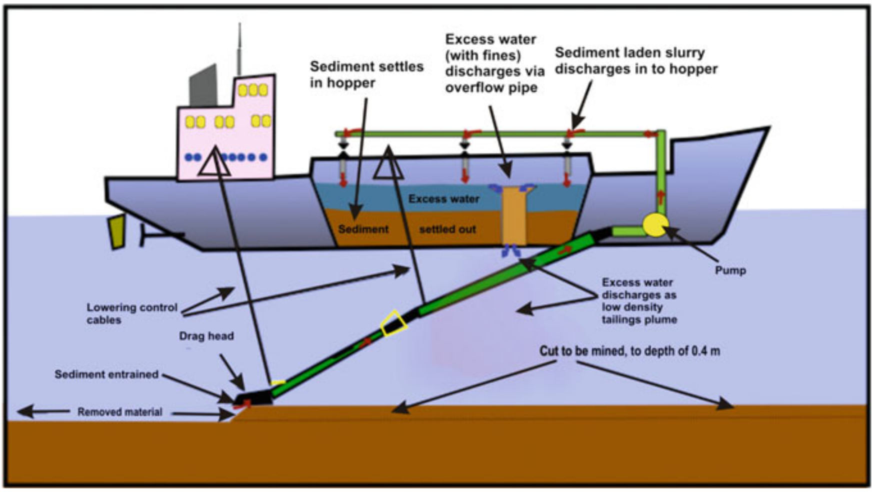
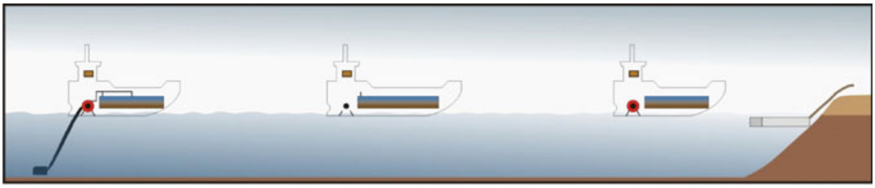


Fig. 1 A schematic of a trailing suction hopper dredge (TSHD) determined to be the optimal method by which the Sandpiper deposit can be developed (Midgley 2012)



Dredging the marine sediments 5.5 million tonnes per annum

Transporting the slurry approximately 125,500 tonnes solids per campaign week

Discharging hopper contents transferred approximately once every 3 to 4 days

Fig. 2 The proposed dredging cycle (Midgley 2012)

may be sold or used without primary processing (Prud'homme 2012). Transportation is usually accomplished by trucks, railways, conveyor belts, or pipelines (as slurry). OCP in Morocco is currently investing in 235 km of slurry pipelines to transport all phosphate ore mined (in the form of pulp) from Khouribga, down gravity, to the chemical plants and port at Jorf Lasfar. This pipeline will replace transportation by train, saving water and energy and reducing the cost per tonne of phosphate delivered to Jorf Lasfar from the current 8 dollars per tonne to less than 1 dollar (OCP 2011).

According to the International Fertilizer Industry Association (IFA), phosphate rock concentrates are produced in 37 countries. The top ten producing countries account for 90 % of world production, with the top four contributing 72 %. Global reserves are similarly concentrated with Morocco holding around 70 % (USGS 2012). In terms of geographical distribution, close to 16 countries are producing phosphate rock in Africa and West Asia; 10 countries in Asia and Oceania; 7 countries in the Americas; and 4 countries in Europe and Central Asia.

1.2 Production Trends

Production of modern fertilizer started in the 1840s with James Murray becoming the first commercial vendor to treat phosphate-containing material with dilute sulfuric acid. The expansion of the industry stimulated the search for phosphate deposits. Extraction of high-quality apatite started in 1851 in Norway, followed by phosphate mining in the United States in the late 1860s (Smil 2000).

Current (2011) global phosphate rock production is estimated at 195 Mt (million metric tonnes), a significant increase since the 1961 level of 42.4 Mt (IFA 2011). As 80–85 % of phosphate rock is used in the fertilizer sector (IFA 2011), increases are attributable to a growing population and the need for phosphate fertilizer to grow crops for food, feed, and biofuels (Jasinski 2011).

Between 1992 and 2011, the global production of phosphate rock rose by an overall 40 %. This equates to an average annual growth rate of 2.1 %. Much of the net increase in production was driven by increased demand from the domestic market (home deliveries) (Fig. 3). Home deliveries of phosphate rock include material used in-country to make fertilizers, or other products. While the global export trade of phosphate rock remained relatively stable at around 30 Mt during the period from 1992 to 2011, home deliveries increased by 52 Mt, to reach 170 Mt in 2011. The share of home deliveries over total sales grew from 77 % in 1992 to 85 % in 2011 (IFA 2012).

Although demonstrating a general increase in output, world phosphate rock data indicate a temporary, conjectural decrease in production between 1988 and 1994, prompting some to propose a theory of “peak phosphate.” According to the IFA (2011), this decrease was in fact related to a dramatic drop in use, which is directly related to the drop in fertilizer consumption following the collapse of the former Soviet Union. Phosphate fertilizer consumption in Eastern Europe and Central Asia (EECA) decreased at a rate of 35 % per annum between 1988 and 1994, which was paralleled by the drop in phosphate rock production of a rate of 21 % per annum for this period. The EECA contributed three-quarters of the 40 Mt decline in world phosphate rock output between 1988 and 1994. Since 1994, phosphate fertilizer consumption in the EECA has gradually recovered, with phosphate rock production remaining fairly stable (IFA 2011).

The world’s top four producing countries, China, the United States, Morocco, and Russia, accounted for a stable share of 72–73 % of global production between 1992 and 2011 (IFA 2012). The following production trends are evident for these top four producers and are illustrated in Fig. 4 (IFA 2012):

- **China**, the world’s largest producer at close to 77 Mt in 2011, has seen massive growth in production driven by a national investment policy to encourage domestic phosphate fertilizer production and reduce its prevalent heavy import reliance. China’s phosphate rock exports have decreased to less than 0.8 Mt in 2011, from 5 Mt in 2001. This is due to the implementation of export restrictions on raw materials in order to increase the life span of this resource.

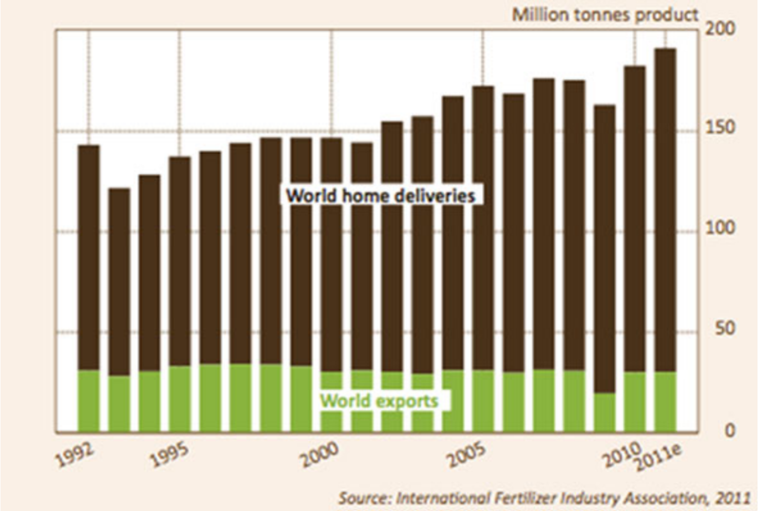


Fig. 3 Global deliveries of phosphate rock (IFA 2012)

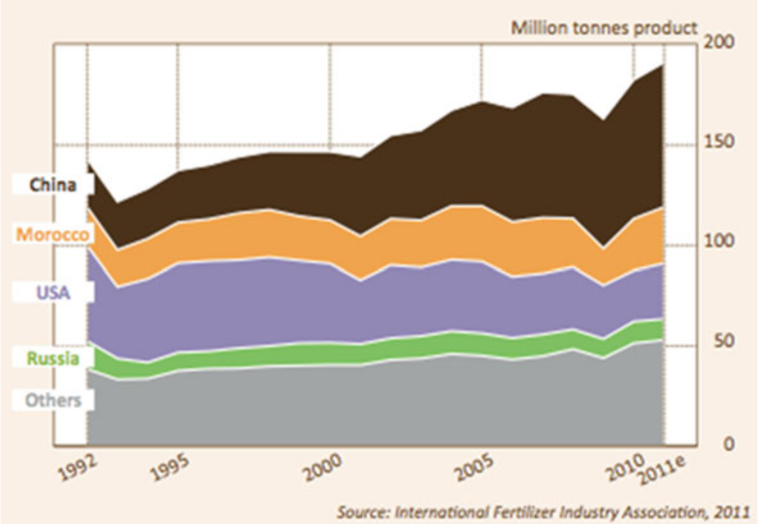


Fig. 4 Production of phosphate rock in the top four producing countries (IFA 2012)

- The **United States** has seen a gradual decline in production from 47 Mt in 1992 to 27 Mt in 2011. Factors contributing to this are a reduction in the exports of processed phosphates and phosphate rock due to exhaustion of higher-grade and quality reserves in the Central Florida Phosphate District, market factors due to rising domestic supply in large importing countries such as China, a decline in

the production of other P-based products in the USA and increased costs and unavailability of phosphate bearing lands due to environmental restrictions and legal challenges based on environmental regulations (van Kauwenbergh 2012).
- **Moroccan** phosphate production has increased to a current level of 29 Mt (for 2011), for the downstream production of phosphate fertilizers earmarked for the export markets. Morocco remains the world's largest exporter of phosphate rock with a market share ranging between 35 and 45 % of global phosphate rock trade.
- As already discussed, production in **Russia** fell between 1988 and 1994. Exports of phosphate rock have gradually declined, from close to 5 Mt in 1998 to less than 1.5 Mt. During the past decade, rock production remained stable at around 10–11 Mt, due to a gradual recovery in home deliveries of phosphate fertilizers.

Emerging production in Egypt, Algeria, Australia, Syria, and Peru has offset the gradual decline in formerly large phosphate rock producing countries such as Kazakhstan, Togo, Senegal, and Nauru (IFA 2012).

1.3 Potential Medium-Term Phosphate Rock Developments

Based on the 2013 IFA survey of future phosphate rock supply, world phosphate rock capacity would increase by an overall 11 %, from 261 Mt in 2012 to 290 Mt in 2017, assuming the realization of the ongoing projects. With the exception of North America potential supply is projected to increase in all areas with Africa, China, and West Asia accounting for most of the growth. These projections clearly demonstrate that there are sufficient reserves under development in order to meet the growth of P demand in the near term. The large number of prospective projects shows the abundance of accessible reserves for several decades (Prud'homme 2013).

2 Critical Issues

Based on this overall situation review, critical issues for the Mining Node were identified by a team representing industry, industry bodies, and academic institutions. These issues focus on different aspects that, we believe, contribute to sustainable phosphate management, as follows:

- Assessing mining and beneficiation recovery and identifying possible areas for improved and efficient extraction of phosphate rock resources.
- The environmental and social impacts and costs associated with phosphate rock mining.

- Artisanal and small-scale phosphate mining with the focus on local provision of "agrominerals" to enhance crop production.
- Understanding current cost structures in mining and likely scenarios for future mining costs when recognizing and incorporating environmental and social costs.

Each of these issues is introduced in the discussion below, to provide background to the critical questions identified.

Mining is just one aspect of the phosphate life cycle, and hence, the issues identified may be crosscutting, incorporating other nodes, or the whole life cycle. In reality, the boundaries between exploration, mining, and, in some cases, processing are blurred and are often undertaken by a single organization. In addition to this, issues such as environmental and social concerns may be relevant throughout the life cycle. Mining should therefore not be seen in isolation and the linkages between the critical issues identified for mining and those for the other nodes must be identified and understood.

2.1 Mining Extraction and Beneficiation Recovery Rates

Mining recovery is best described as a ratio between the amount of valuable commodity (ore) extracted and the total amount of valuable commodity determined by ore resource evaluation. Typically, only a portion of any resource is recovered by the mining process. Total mining recovery of the reserve would involve recovering 100 % of the reserve, normally not an economical or practically viable option. Mining recovery will vary and depend largely on geological factors of the deposit (shape, thickness, weathering zone, and overburden), mining method, skill of operators and economics. These factors are described as modifying factors and can vary tremendously during the life of the mine.

According to a survey conducted by the IFA in 2010, mining extraction efficiencies would average 82 % for the 93 % of the world phosphate producers surveyed (Prud'homme 2010). Two-thirds of producers operate above this weighted average ratio (Fig. 5).

There are numerous examples of phosphate rock mining in the world where substantial amounts of resources were spoiled or passed over during the initial mining phase, due to the fact that at the time it was not economic or sustainable to mine, process, and recover these resources (van Kauwenbergh 2012). Under different economic conditions and/or with improved technology (modifying factors), mining these resources would become viable. The Namibian Sandpiper marine phosphate project is such an example, where although the deposit was delineated during the 1970s, it has only now become economic to mine (Drummond 2012).

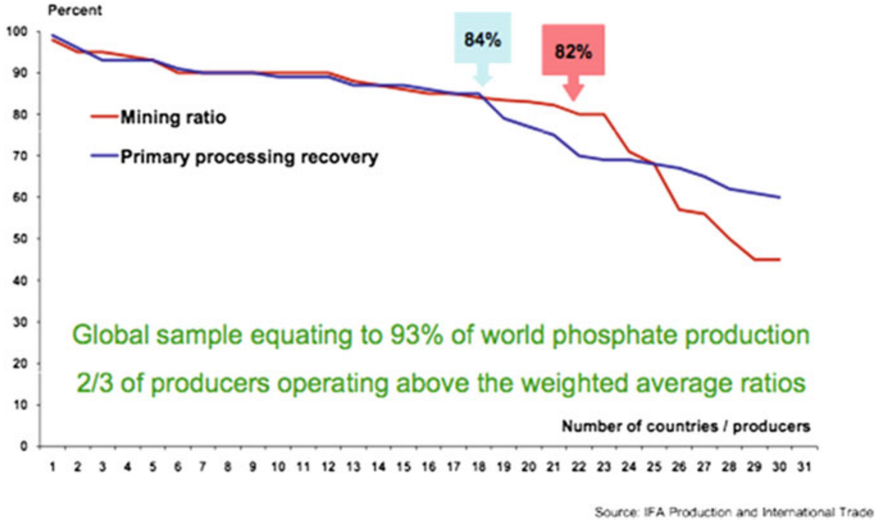
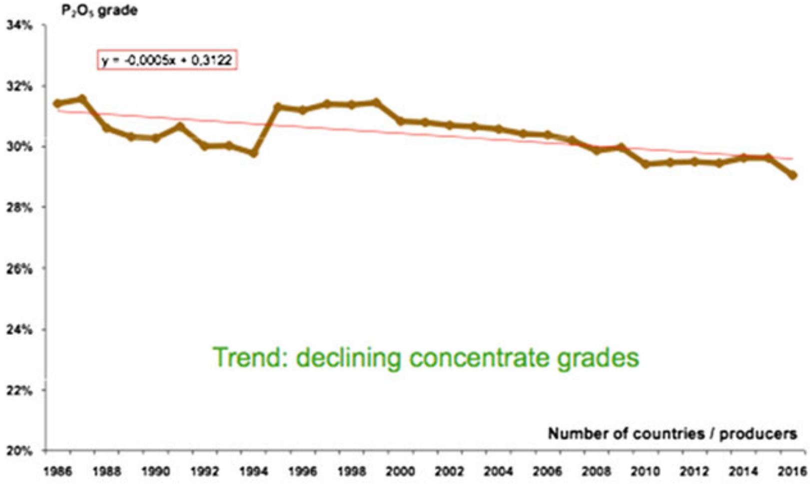


Fig. 5 Phosphate mining and primary processing recovery (Prud'homme 2010)

Beneficiation recovery refers to the quantity of P that is recovered during beneficiation. This would refer to the removal to saleable P expressed as a ratio to the ore mined portion only. Normally waste or mining discard does contain valuable commodity, but below a predetermined economically viable level. Again, the optimum extraction level of recovery would depend on the processes and technology used and economics. Depending on how the waste is disposed, and the remaining concentration of P, this may become a future source of P, given the right economic conditions and technological advances.

Historical trends have signaled a slow declining average grade (P content) for mined phosphate ore as well as derived concentrate (Fig. 6; see Prud'homme 2010; Smil 2000). Van Kauwenbergh (2010) has indicated that some of this effect is due to producers using lower-grade ores to meet growing demand and to recover more of the P. Recovery of P is inversely proportional to product grade. If a lower-grade concentrate (necessitating more P recovery) can be used to produce an intermediate such as phosphoric acid, and eventually high-grade fertilizers, lower-grade concentrate can be used, if economically profitable. The net effect is a better utilization of in situ ore resources toward beneficiable ore, thus prolonging the life of the mine. This strategy is typically implemented when phosphate rock production is integrated with localized fertilizer production. When phosphate rock is transported over long distances for fertilizer or other types of processing, the higher the grade, the less cost per tonne of P. This also leads to lower volumes that have to be processed to produce the same amount of acid or fertilizer.

Some of world supplies are more easily accessible, less costly to produce, and higher-grade reserves have been exploited. Some producers have been moving on



Source: IFA Production and International Trade

Fig. 6 Phosphate rock concentrate—trend of grade (Prud'homme 2010)

to lower-grade ore or reserves that are more expensive to exploit (van Kauwenbergh 2012). The current high market price of P makes such moves economically viable. Phosphate rock deposits under thicker overburden will be more costly to mine from the surface or by underground methods, phosphate rock deposits offshore may be more costly to mine, and lower-grade ores may be more expensive to beneficiate to make water-soluble products. Mining phosphate rock offshore or in environmentally sensitive areas may dictate higher costs for mitigation of potential environmental impacts.

Understanding mining recovery and the most efficient use of available resources in the phosphate industry is an area that requires further research. Ideally improving recovery should not come at the cost of increasing resource input (water, energy, and land) consumption, additional detrimental environmental and social impacts and limiting possible contributions to sustainability. Optimal recovery may be a preferred option.

Initiatives to address recovery should not only consider improving existing methods ("system optimization") but also focus on innovation and developing new methods (radical "system innovation") of mining and concentration (Rotmans et al. 2001). The factors driving efficiency, both endogenous (e.g., business necessity or corporate responsibility of individual companies) and exogenous (e.g., global commodity market forces, actions by political pressure groups, norms and standards of industry associations, national or international laws, requirements by purchasers down the supply chain), should be considered.

2.2 Environmental and Social Impacts

Phosphate mining, as with all mining, impacts the environment and society. The extent of impacts depends on the resource mined, the sensitivity of the receiving environment, social situation, formal and informal governance, and the practices and performance of the mining operation concerned. Impacts may be as a result of the construction, operation, and/or closure of a mine. Activities associated with the mine, such as transportation and settlements, also have a direct, indirect, or cumulative impact on the environment and broader society.

2.2.1 Environmental Impacts

Environmental impacts resulting from land-based mining operations can be generally grouped as environmental pollution, landscape and environmental change, and resource consumption. Resources consumed would include water, energy, and land. The impacts for marine dredging would be similar; however, landscape and environmental change would include disturbance of the sea floor, impact on fish habitat and marine organisms; and environmental pollution would largely be limited to water pollution (from sediments, spills, and waste). Marine dredging would however normally also have a land-based footprint (plant, waste facilities, storage, etc.).

Landscape and Environmental Change

Surface mining (open-pit or strip mining) is the most utilized method by far for mining phosphate deposits (van Kauwenbergh 2010; UNEP and IFA 2001). Surface mining generally has a larger physical footprint than underground mining. In addition to the physical mining area, the mine footprint may include processing facilities, overburden storage sites, waste impoundments, concentrate stockpiles, and other infrastructure, further increasing the surface area disturbed, and altering the topography. Within the working mine footprint, vegetation and topsoil are removed (UNEP and IFA 2001), which may impact on habitat, biodiversity, ecosystem functioning, and land productivity. Surface and underground mining may require the dewatering of large areas, leading to altered unconfined or confined aquifer characteristics.

The impacts of marine dredging are similar, although in a different receiving environment. Removing sediments from the seabed will disturb and change the habitat available, impacting on benthic flora and fauna, the water column and the broader functioning of the ecosystem (Midgley 2012). As on land, there are various mining systems that can be used in the marine environment, with differing impacts on the environment. Marine dredging will have an associated land-based footprint, including a storage facility, beneficiation plant, and waste impoundments.

Environmental Pollution

The major waste streams from phosphate mining and the adjacent mineral processing comprise waste rock, phosphatic tailings, and process water (UNEP and IFA 2001; Lottermoser 2007).

The main wastes in common phosphate mining operations include overburden, rock materials below cutoff grade, and zero-grade rock waste. Mine wastes from igneous phosphate deposits are clearly different from sedimentary phosphate deposits. Igneous phosphate deposits are in general more massive and homogeneous than layered sedimentary phosphate deposits. Mining of sedimentary phosphates requires not only the removal of overburden but also requires the physical removal of intercalated strata, such as clay-stones, carbonates, and other sedimentary rocks. Zero-grade material is "waste rock" material that has to be removed during mining operations, benching and accessing the deposit. Like in all mining operations, the overburden/soil-to-rock ratio (stripping ratios) varies considerably depending on local conditions. In PR mining operations, the stripping ratio varies from 0.5 to ≥ 3.

The assessment of what is "waste" and what is "phosphate ore" is subject to continuous revision in response to economic parameters, such as mining costs and market conditions (refer to Sect. 2.1). Some "wastes" generated from igneous phosphate mines might be re-assessed on their economic merits as they may contain valuable coproducts such as vermiculite, fluorite, Ba and Ti minerals as well as rare earth element (REE) minerals; and various clay and carbonate minerals in sedimentary phosphate deposits. Some of the coproducts of phosphate mining, e.g., vermiculite and carbonates, might become interesting targets for low-cost use in nearby agricultural communities, as well as for use in road construction.

Possible negative impacts arising from waste rock disposal include elevated radioactivity and radon levels as well as dump stability issues. Impacts are highly site specific; in most of the currently active mining operations, waste rock does not pose environmental threats (Lottermoser 2007).

Disposal of tailings, which may still contain some phosphate, has included discharge to rivers or other water bodies, and disposal to engineered storage impoundments or mined-out areas (UNEP and IFA 2001) as well as reclamation of sand particles as backfill material in mine workings (Lottermoser 2007). The disposal by discharge may pollute surface and ground water, soils and impact on ecosystem functioning. Kuo and Muñoz-Carpena (2009) cite an example from central Florida where mining activities degraded water quality in the upper Peace River basin, where the average dissolved phosphorus concentration of runoff water from waste impoundments exceeded the maximum allowable total phosphorus concentration discharging into a river established by the US Environmental Protection Agency, reinforcing the need for effective rehabilitation and ongoing management of mine wastes.

Currently, recycling and reuse efforts for waste from phosphate mining operations focuses on the utilization of waste rock for landscaping purposes

(Lottermoser 2011). In many operations, process water is recovered and reused (UNEP and IFA 2001).

2.2.2 Social Impacts

Social impacts may relate to competition for resources, health and safety concerns, in some cases resettlement, conflict resulting from unequal distribution of benefits and concerns around identity, community and way of life. At the general level, the research of social change in natural resource-based rural communities offers a broad account of the various opportunities and threats before, during the most intense activities (construction and operation), and after these (see, e.g., Krannich 2012; Freudenburg and Gramling 1992; Gramling and Freudenburg 1992). At the more specific level of P mining, the research base is rather restricted.

Phosphate rock naturally contains uranium and radionuclides of uranium; similarly, associated heavy metals such as cadmium can also be present (van Kauwenbergh 1997, 2001, 2002, 2009; Cordell et al. 2009). The impact of these elements on health and the environment at individual mining and processing sites will vary.[1] According to Othman and Al-Masri (2007) based on a case study in Syria, the phosphate industry is considered to be the main source of enhancement of naturally occurring radionuclides in the Syrian environment and that these elevated levels were found to be generally located around the workplaces in the mine, fertilizer factory and export platforms, increasing the exposure of workers.

2.2.3 Mitigation and Management

The legacy of some mining projects and processing operations on human health and the environment has tainted the public perception of the industry. However, the trend among mining companies globally is toward better management of impacts and improved environmental and social performance. This is also in large part due to having environmental professionals working on site, the use of improved scientific knowledge, an improved and formalized governance framework, greater public involvement and community expectations, and voluntary initiatives adopted by industry (Lottermoser 2011). Environmental management systems are now commonly implemented at mines, with many committing to industry codes of practice and regular reporting on their performance. Mine planning, closure, and rehabilitation have improved, in many cases allowing for the sustainable use of post-mining landscapes.

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[1] Numerous environmental health and safety studies have been conducted in Florida by the Florida Institute of Phosphate Research (FIPR), now known as the Florida Industrial and Phosphate Research Institute (FIPR Institute) www.fipr.state.fl.us.

Environmental and social performances are just two aspects of what is commonly referred to as Social Responsibility (also termed corporate social responsibility (CSR) or corporate citizenship). The ISO26000: 2010 Guidance on social responsibility defines social responsibility as “the responsibility of an organization for the impacts of its decision and activities on society and the environment, through transparent and ethical behavior that; contributes to sustainable development, including health and the welfare of society; takes into account the expectations of stakeholders; is in compliance with applicable law and consistent with international norms of behavior; and is integrated throughout the organization and practiced in its relationships.” Issues addressed under this banner include human rights, labor practices, the environment, fair operating practices, consumer issues, and community involvement and development.

The social responsibility of phosphate mining companies would vary between different companies. Annual sustainability reports, where these are produced, would provide an indication of what a particular company is doing in this regard. Within the mining sector, the International Council on Mining and Metals (ICMM), through their Sustainable Development Framework, provides guidance on what would be considered good practice. The 10 principles of the United National Global Compact, although not specific to the sector, are also indicative of what is considered responsible behavior.

The concept of decoupling may be useful in the context of both mining and the broader phosphate life cycle. Decoupling means using fewer resources and less of a resource per unit of economic output and reducing the environmental impact of any resources that are used or economic activities that are undertaken (UNEP 2011a). From a mining perspective, impact decoupling (increasing phosphate extraction while reducing negative environmental impacts) is possible and relates back to the issue of recovery and reducing resource intensity, discussed earlier. As regards the phosphate life cycle, opportunities to reduce phosphate demand (resource decoupling) through more efficient use, recycling and the use of substitutes are being addressed in other nodes. Reducing demand could however have a significant impact on the phosphate mining sector.

2.3 Small-Scale Phosphate Mining and Agriculture

In addition to the large phosphate deposits that are exploited commercially, there are many small- and medium-scale deposits (van Kauwenbergh 1987; van Straaten 2002). These deposits may present an opportunity to artisanal and small-scale miners and an alternative source of phosphate supply for local farmers. This is especially relevant to developing countries and in particular sub-Saharan Africa where soil nutrients have been depleted and imported commercial fertilizers are generally not available to under-resourced farmers.

In most of sub-Saharan Africa, more than 50 % of the population relies on agriculture for their livelihood. Agriculture is the major source of income, employment, food security, and survival (van Straaten 2002). However, crop yields are a quarter of the global average, due to the depletion of soil nutrients, with more nutrients being removed each year than are added in the form of fertilizer, crop residues, and manure (UNEP 2011b). A high proportion of African farmers are resource poor in terms of capital, land, labor, and livestock (van Straaten 2002), and this together with high costs and low accessibility prevents many African farmers from acquiring fertilizers (UNEP 2011b). Poor transport, low trade volumes, and lack of local production or distribution capacity result in farm-gate imported fertilizer prices two to six times higher than the world average (UNEP 2011b).

Additional phosphate, as well as other nutrients, is needed to achieve adequate sustainable crop yields. “Agrominerals” have the potential to, at least partially, address this need. Agrominerals, such as phosphate rock, liming materials, and gypsum, are naturally occurring geological materials in both unprocessed and processed forms that can be used in crop production systems to enhance soil productivity (van Straaten 2002, 2011). Unlike conventional, chemically processed “industrial” fertilizers, which are derived from chemically processed rocks, agrominerals are commonly only physically modified, by crushing and grinding (van Straaten 2002, 2011), and can be applied directly. Where they exist, local small to medium phosphate deposits, mined by artisanal and small-scale miners, using labor-intensive methods and appropriate technologies may have the potential to contribute to agricultural production.

It is however recognized that the effectiveness of agromineral use and economics of small-scale mining pose special challenges. The phosphate rock that is locally available may not be sufficiently reactive, or the local soils may not be suitable for use of direct application phosphate rock. The use of phosphate rock for direct application is dictated by apatite mineralogy, soil, crop and agroclimatic conditions. There are innovative ways to make PR resources more reactive using local modification techniques (van Straaten 2002, 2011).

Small-scale mines are often not economically viable. Small deposits may be located far inland or far from agricultural areas; transportation can be cost prohibitive. Due to the nature of the activity, small-scale mines generally have a low recovery rate (usually below 30 % in the case of China), selecting only the high-grade P rock. This results in a significant loss of P resources and has contributed to governmental restrictions on small-scale P mining (Ma et al. 2012). Artisanal and small-scale mining is also renowned for its unsafe work practices and often results in significant pollution and land degradation. A further concern is possible health impacts associated with the use of unprocessed rock, mainly sedimentary phosphate rock, exposing users to heavy metals and radioactive nuclides.

As part of the Global TraPs project, it would be important to develop an understanding of the extent and local importance of such mining and based on this, opportunities to enhance viable small-scale phosphate mining and processing in sub-Saharan Africa, for example in Tanzania and Burkina Faso, and in Bolivia and Indonesia.

2.4 Mining Cost Structure

Information on existing mining costs is difficult to obtain in the public domain; however, the cost structure information for new projects is generally in the public domain. An analysis of these would give an indication of mining costs and how these differ based on the geology, mining method employed and mine location and how mining costs may be changing to address the increasing costs of resources (water and energy in particular) and the "cost of compliance." It is proposed that such an assessment be included as a case study in the Global TraPs project.

3 Work in Global TraPs

Not all the identified critical issues will be dealt with within the Global TraPs project, mainly for the following three reasons. Firstly, all research activities need focus to allow for the necessary depth of analysis; secondly, the duration of Global TraPs with an expected final global conference in 2015 necessitates that those questions that can be investigated in this time period will be prioritized, the remainder will be recommendations for research plans; and thirdly, the transdisciplinary setting of Global TraPs requires potential benefit of the followed research both for practice and science, which is not given with all the issues.

The focus of this node is summed up in the guiding question defined jointly by practice and science—*How can we contribute to sustainability in the phosphorus mining sector through promoting resource efficiency and innovation to avoid and mitigate negative environmental and social impacts, and contribute to food security?*

3.1 Knowledge Gaps and Critical Questions

Based on this overall guiding question for the Mining Node, a number of critical questions have been identified by academia, industry, and further stakeholders in Global TraPs, as follows:

- Mining extraction and beneficiation recovery
  - What is the current recovery rate in mining operations and what are the main factors impacting on this?
  - What changes or innovations may have the greatest potential impact on optimizing recovery rates?
- Environmental and social impacts
  - What are the most promising avenues for decreasing or rationalizing the environmental and social impacts and costs in future?

  - What is the typical water and energy use at different types of phosphate mining operations and what is the potential to reduce it (if warranted)?
  - How do societal factors (perceptions of mining in society) impact eventual resource availability?
- Small-scale phosphate mining
  - How can the viability of small-scale phosphate rock mining and appropriate primary processing in sub-Saharan Africa be enhanced?
- Mining cost structure
  - What is the general current cost structure in mining, and likely scenarios for future mining costs, including energy and water, and environmental mitigation costs?
  - What would the impact of internalization of environmental costs be?
  - How does mining react to price changes over time?

An essential overarching process-related question of Global TraPs, namely "how to organize transdisciplinary processes at the global level?", will be addressed in parallel to these substantive questions in the Mining Node.

3.2 *Role, Function, and Kind of Transdisciplinary Process*

Transdisciplinarity understood here as mutual learning process between science and practice (Scholz 2000) necessitates balancing between various perspectives, interests and expertise of the involved actors. To this end, the Mining Node of Global TraPs tries to achieve inclusiveness at three levels.

Within Global TraPs, the Mining Node regularly presents its plans and results to the plenary for critical review by various stakeholders involved, for example representatives from various industry organizations, international organizations like UNEP, smallholder farmers, non-governmental organizations like Greenpeace and academic institutions from around the world. This further allows to coordinate with the other nodes and the cross-cutting issue of Trade and Finance.

The Mining Node itself is again composed of actors from practice (primarily industry and industrial associations) and science with various disciplinary backgrounds (e.g., environmental and social sciences, industrial ecology, geology). Here, the current situation of P mining was reviewed, critical issues derived and the research scope of the Mining Node defined. In a joint process between science and practice, pertinent case studies were selected (see below for some first sketches) and respective results will be exchanged and critically reviewed.

Transdisciplinary case studies will be developed locally. At local case study level, it is envisaged to build transdisciplinary project teams comprising not only experts from academia and industry but also representatives from additional actor groups, such as local communities, environmental NGOs. These project teams will first try to build a common problem understanding and formulate a jointly agreed upon concrete and case-study-specific guiding question. The project team will also discuss whom to involve in each project phase based on the nature of the work (Stauffacher et al. 2008). Subsequent project steps will be implemented in close collaboration within the project team. The project team will aim at producing tangible results in the form of orientations for future action of the various actors involved, entailing different possible future pathways of the analyzed concrete case and their respective potential positive and negative outcomes. In addition, the whole process of implementing the case studies should also lead to a mutual learning process of all the participating actors and likewise help building capacity locally and trust among the different parties.

3.3 Suggested Case Studies

Based on discussions between science and practice in Global TraPs, case studies to address the critical questions have been suggested, at the various levels, as follows:

Global TraPs Level

- **Extraction Rates and Beneficiation Recovery Rates**. Assess current mining extraction rates and beneficiation recovery rates in mining operations to determine what the main factors impacting these are. It is proposed that a survey of mining companies, based on the correct questions with the right terminology, will provide this information. There is a possibility for expanding this survey to simultaneously address critical questions from the Exploration and Processing Nodes. Core stakeholders that could be involved would comprise industry associations and scientists with a background in mining and primary processing.
- **Environmental and Social Impacts**. Determine what the most promising avenue for decreasing or rationalizing environmental and social impacts and costs in the future. The objective of this case study is to raise awareness of what is currently being done by mining companies by documenting their experiences. Again there may be an opportunity to expand the scope of this case study to include environmental and social impacts during the exploration process. Again, core stakeholders will be representatives from industry and scientists from various disciplines like for instance environmental and social sciences. Further, interactions with respective NGOs should be envisaged.

Mining Node Level

- **Innovation**. Document current innovation in mining and beneficiation. There are examples of innovation on improving mining and beneficiation recovery, reducing waste and increasing resource efficiency. The objective of this case study would be to collect information on these and write them up, with the possibility of further investigation and sharing within the sector. Industry and academia should be involved in this case study.

- **Mining Costs**. Documenting and analyzing mining costs. Information on existing mining costs is difficult to obtain; however, the cost structure information for new projects is generally in the public domain. An analysis of these costs could give an indication of mining costs and how these differ between projects and locations, what the basis for these differences are, and whether mining costs are changing to incorporate the increasing costs associated with more stringent legislation, as an example. Again, mainly industry and academia are concerned by this project.
- **Mining Impacts**. Assess and compare mining impacts between different types of deposits (sedimentary and igneous, land and marine) as part of an exercise to benchmark for sustainable mining. Industry and academia are core stakeholders concerned by this project.

Case Study Level

- **Small-Scale Mining**. Determine how the viability of small-scale phosphate rock mining and appropriate processing in developing countries can be enhanced. A comparative analysis between small-scale phosphate mining in a sample of developing countries is proposed, in particular focusing on opportunities for innovation and possibilities for "up-scaling" these. A comprehensive variety of different stakeholders has to be involved in the different countries, namely small-scale miners, farmers, community leaders, regional and national administration, NGOs, and academia.
- **Mine Waste**. Building on work already done, investigate the use of mine waste for other purposes, such as use in agriculture, as building material or for the extraction of other minerals. This will require an analysis of the mine waste streams and identification of opportunities for reuse. Besides industry and academia, potential users of mine waste (farmers, building sector, and processing industry) certainly need to be involved. In addition, local and regional policy makers and administration are to be integrated.

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Appendix: Spotlight 4

Phosphorus Losses in Production Processes Before the "Crude Ore" and "Marketable Production" Entries in Reported Statistics

Roland W. Scholz, Friedrich-Wilhelm Wellmer, and John H. DeYoung, Jr.

Since the dawn of the industrial revolution in the nineteenth century, both food production and the world's population have experienced dramatic increases. Recent years have seen particularly significant benchmarks, with Africa reaching one billion people in 2009 and the world population reaching seven billion in 2011. Looking to the future, the United Nations' Food and Agricultural Organization (FAO High-Level Expert Forum 2009) and other experts have agreed that the population is likely to surpass nine billion by 2050. Increasing efficiency by avoiding losses, in particular if the latter are irreversible, is a basic concept of sustainable resources management (Pearce and Turner 1990). In the case of phosphorus, losses have traditionally only been looked at in the use phase. Two types of flows that have not been thoroughly investigated are unintended flows in the processing of other mineral commodities and pre-production losses. Unintended flows of phosphorus in metal processing take place owing to the trait that phosphates bind with metals. These flows have also been called virtual or hidden

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R. W. Scholz
Fraunhofer Project Group Materials Recycling and Resource Strategies IWKS,
Brentanostrasse 2, 63755 Alzenau, Germany
e-mail: roland.scholz@isc.fraunhofer.de

ETH Zürich, Natural and Social Science Interface (NSSI), Universitaetsstrasse 22,
CHN J74.1, 8092 Zürich, Switzerland

F.-W. Wellmer
Formerly Bundesanstalt für Geowissenschaften und Rohstoffe (BGR)—Geozentrum Hannover,
Stilleweg 2, 30655 Hannover, Germany
e-mail: fwellmer@t-online.de

John H. DeYoung, Jr.
National Minerals Information Center, USGS, 988 National Center, Reston, VA 20192, USA
e-mail: jdeyoung@usgs.gov

flows (Matsubae et al. 2011). The second flows are the losses in processes that take place before the extraction of crude ore and subsequent marketable production of phosphate rock.

Although it is impossible to provide a precise number, evidence exists that human activities may triple the global phosphorus (P) flows (Carpenter and Bennett 2011; Paytan and McLaughlin 2007; Ruttenberg 2003). Anthropogenic phosphorus flows start with the mining of phosphate rock and continue to the final use of all phosphate products and are influenced by the changes in land use where fertilizer products are applied. The flow of agricultural phosphorus during production and use is a result of the need to nourish an increasing human population. Because the main phosphorus mineral, apatite, is found in many countries, there is a very large geopotential to provide a source of the necessary phosphorus for animal and plant nourishment from nature. Open-field agriculture may accelerate the dissipation of phosphorus to marine systems by runoff and erosion of topsoil. Phosphorus is present in many mineral or metal ores. Thus, significant phosphorus flows are linked to many industrial processes, such as steel production, which have been analyzed in detail in Japan (Matsubae et al. 2011; Matsubae-Yokoyama et al. 2009). These industrial flows have been denoted as *hidden flows*, unintentional flows of phosphorus in the flows of other commodities, such as metals or goods. Some insights into intentional and unintentional losses are provided in Chaps. 1 and 6 of this book.

Phosphorus in by-product flows (the example of phosphorus in converter slags of steel production). Formerly, a large proportion of phosphorus for agricultural use came from phosphorus-containing iron ores, which were processed with the Thomas steel process. This process resulted in a slag rich in phosphorus that could be used as fertilizer and was thus a sought-after by-product. More than 100 years ago, it was stated that this slag is (or may be) "rich in lime and contains 14–20 % of phosphoric acid" (Porter 1913). The trend today is to smelt only iron ore that is as pure and as high grade as possible; thus, Thomas steel plants have gone virtually out of existence. The only places where phosphorus-containing Thomas slag is still sold as fertilizer is in some countries such as France or Luxembourg (Jasinski 2013b) where this material comes from stockpiles from former operations. The average phosphorus content of world iron ore production today is less than 0.1 % P. The trend is to use only those iron ores that contain as little phosphorus as possible. The minimal amount of phosphorus which still must be accepted in iron ore (and in coal, coke, and, in minute amounts, flux) is removed in the converters, which produce a slag with some phosphorus. In Japan, as in most other industrial countries, slag is no longer used as fertilizer. However, research is underway to use higher-grade converter slags as fertilizer again (Ohtake 2013). In Germany in 2011, 7.7 % of slags from the iron and steel industry (LD converter slag) still contained nearly 2 % P_2O_5 and were also rich in calcium oxide (CaO). These slags could be applied as fertilizer and soil amendment, similar to the highest grade slags in Japan (Drissen 2004; Stahlinstitut VDEh, Wirtschaftsvereinigung Stahl 2013; Nippon Slag Association, undated). Most iron and steel industry slag, however, is going directly (or indirectly, via cement production) into the construction industry as construction aggregate. Such phosphorus flows are lost and cannot be recovered with current technology.

Losses of phosphorus in "hidden flows" have been addressed by students of the exhaustibility of resources; for example, in the Hotelling rule (Hotelling 1931). Instead of locking up phosphorus forever, should the material be stockpiled to wait for times when recycling phosphorus from low-grade slags becomes economic? This approach could minimize losses for the benefit of future generations. The starting point for calculating losses from the resource to a marketable product is reserves determined during exploration work by mining companies and, if reported, compiled, and published by geological surveys or other government agencies, trade associations, or research institutions; for example, the US Geological Survey (USGS) Mineral Commodity Summaries (USGS 2013). There are also potential losses of phosphorus that are not included in the determination of reserves (see the Total Resources Box figure that illustrates how the concepts of reserves, resources, and geopotential are used in this text).

As pointed out by Roy et al. (2013), mineral fertilizer increased cereal crop production of the last 60 years. Estimates on lower agricultural production indicate that about 3.5 billion people would have starved if the increase in mineral fertilizer production and use had not taken place (Smil 1999; Hager 2008); over the last 50 years, global cereal crop production has almost tripled to 2.4 Gt (FAOSTAT/IFDC data 2012) (Fig. 7).

Not using *by-product* phosphorus may or may not be viewed as a loss. Potential by-product phosphorus could be a resource for future use if known or, if still unknown, geopotential. By definition, resources are known (to various levels of certainty), but may not be economically recoverable at present. Looking toward the future, resources or geopotential could be of more interest. The geopotential is not yet known but, by geologic reasoning, it can be expected to contain deposits that will be discovered by modern exploration technologies. Reserves are essential for the supply of phosphorus from primary sources today and in the future. Reserves are defined as the category of total resources that can be economically extracted with proven technology and current economic conditions (including having available energy and using environmentally and socioeconomically acceptable practices).

Phosphorus from primary deposits. Because phosphorus from by-product sources is generally no longer used, primary phosphorus must come from phosphate rock deposits. There are mainly two types of these deposits. The dominant type is of sedimentary origin; the other type is of magmatic origin. Both types are formed by geologic processes that result in deposits

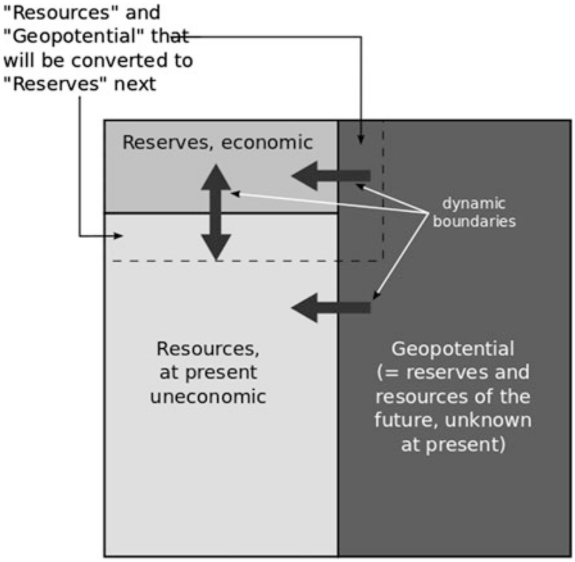

Fig. 7 The Total Resource Box illustrates the interrelationship and dynamics of reserves, resources, and geopotential; the area included by the dashed line outside the reserves box marks the resources and geopotential that will be converted to reserves next. This diagram (modified from that in Wellmer 2008) follows the convention of earlier depictions (Thom 1929, 1940, 1964; McKelvey 1972; Zwartendyk 1972) of using geologic/physical knowledge and economic viability as the horizontal and vertical dimensions of the defined "boxes"

enriched in phosphorus. The sedimentary deposits form on continental shelves or slopes with high biological activity, often stimulated by nutrient-rich upwelling currents. The magmatic deposits owe their existence to sudden and rare igneous events in which phosphate-rich magmas formed. For such mineral commodities, which are extracted from deposits where enrichment processes have taken place, Skinner (1976) postulated a bimodal distribution—the main peak being the normal distribution of an element in the earth's crust with the mean value (the background, or the clarke) and the second or minor peak being the mean of all enriched deposits, the "deposit peak." Here, the term *deposit* denotes all such parts of the total resources with unusually high concentration, regardless of whether the material may currently be economically extracted at a profit (Skinner 1976, 1979).

What part of the area under the "deposit peak" can be considered reserves (that is, can be economically extracted)? This depends on the cost structure (operating and investment costs, tax and royalty regime, etc.) to produce a saleable product. The boundary between ore (reserves) and sub-ore-grade material is called the cutoff boundary. Numerous papers address selection of the cutoff grade to optimize the economic return (e.g., Lane

1988; Bascetin and Nieto 2007). The minimum boundary is an operating cost cutoff, meaning that the grade of this cutoff just covers the operating costs of extraction and processing. This is a cutoff applied frequently in practice (Wellmer et al. 2008); it maximizes the reserves by minimizing losses.

Losses before selection of a mining site. Another type of potential *loss* may occur *before mining*. As the result of insufficient exploration, economic deposits and their reserves may not have been identified. Here, general economic arguments are important because, given the large phosphate reserves, exploration only pays if it provides added value from the company's or the nation's perspective. During times when it was perceived that there was a large amount of high-quality reserves of phosphate rock (equal to more than 300 years of current production), there was no urgent pressure to invest into exploration from a business perspective, but a company can always benefit from better understanding of deposits gained from continuously exploring the deposit and adjacent favorable areas in detail to find the optimal strategy of extraction (Wagner 1999). In recent years, there has been very active exploration for phosphate rock deposits with prices in the $150 to $200 per metric ton range. This may be because exploration has become more attractive for companies owing to increasing demand for phosphorus fertilizers and anticipated higher prices.

The starting point for calculating losses after the delineation of reserves. The actual or potential losses described above remain resources or geopotential because they have not been identified. As stated above, the starting point for defining *losses* is the identification of phosphate rock reserves and the subsequent annual production (crude ore and marketable production), such as those published in the annual USGS Minerals Yearbook and Mineral Commodity Summaries. For instance, 198 Mt of phosphate rock were mined worldwide in 2011 (Jasinski 2013a, b). Note that this "marketable production" tonnage does not refer to the phosphate rock which has been extracted or which was the subject of mining activities, but to a saleable product which was about 30 % P_2O_5. The USGS also publishes data about the P_2O_5 content of marketable production, which was 60.9 Mt in 2011, meaning a worldwide average grade of 30.8 % P_2O_5 in saleable products (Jasinski 2013b, Table 10). P_2O_5 content is a standard way of accounting for the phosphate that leaves the mine or a related production facility after primary beneficiation. The grades of reserves are generally reported as percent P_2O_5, providing a starting point for calculating losses after the delineation stage of reserves. The USGS publishes data on the mine production and P_2O_5 content of crude ore, but only for the United States. In 2011, US production of crude phosphate rock ore was 129 Mt containing 13.3 Mt P_2O_5 (Jasinski 2013b, Table 3). The reduction from crude ore to marketable production (129 to 28.1 Mt) resulted in a loss of 5.14 Mt of P_2O_5

(from 13.3 Mt of P_2O_5 in crude ore to 8.16 Mt of P_2O_5 in marketable production). This amount of P_2O_5 that is not produced amounts to 39 % of P_2O_5 in mined crude ore (or 63 % of P_2O_5 in US marketable production); if similar amounts remain in waste elsewhere in the world, that amounts to over 36 Mt of P_2O_5 each year.

Critical losses during the mining and beneficiation stages. Evidence indicates that a portion of these losses may be preventable. Some losses of phosphorus from runoff, erosion, food waste, etc., might be controlled better, but are these losses *critical* from an economic or environmental perspective during mining and beneficiation on the way from reserves to saleable product? Producers have strong economic incentives to avoid such losses as long as the increase in value of the material recovered exceeds the marginal cost of recovery.

Mining can be done either by open-pit or by underground methods. For open-pit planning, a marginal stripping ratio (i.e., the ratio between waste to be removed and ore) must be defined. The highest marginal stripping ratio comparable to the minimum cutoff boundary defined above is the stripping ratio for which the last ton of ore just covers the operating cost. As noted earlier, resources that cannot bear the higher mining costs must be left in the ground. Because sedimentary phosphate rock deposits are layered deposits, normally with a sequence of phosphate seams and interlayered waste, waste-to-ore ratios are the result of incremental decisions. After mining each seam of phosphate rock, a new decision must be made about whether the next phosphate seam below can carry the removal cost of the interlaying waste layer.

The cut of the open pit “moves” so that the waste removed is stacked in the mined-out areas. Because of this, after a decision has been made not to mine deeper, the deeper resources are, in general, practically lost. In only a few cases, lower layers may be left accessible for some years. This situation is not comparable to resources left in the ground owing to being below the cutoff grade, described above.

For reserves outlined for an open pit, the mining recovery rate is normally about 95 %; for underground mines, recoveries vary from 80 % to only around 50 % because pillars must be left in place to maintain rock stability. According to a recent survey (Prud’homme 2010), overall recovery rate was 82 %. These are final losses, which, under normal circumstances, may never be recovered.

After the ore is extracted from the orebody, *beneficiation* begins. Here, the extracted material is subjected to various types of *mineral processing*, including a process which is generally called *mineral dressing*. This process separates the *gangue*, i.e., the commercially worthless material which is mixed with the phosphate rock, from the economically processable material. In sedimentary deposits, “ore” material with low grades may be stockpiled, and the higher-ore-grade material may be subjected to *comminution* by *crushing* and *grinding*, *desliming*, or *flotation* (Zhang et al. 2006). Normally, the recovery rates in simple washing processes are lower than for flotation, but flotation is a more expensive process. Which ore-grade material is subjected to the various types of processing depends on the chemistry and mineralogy of the ore, technology, market prices, and the specific constraints imposed by the mining plan. In all cases, mineral processing produces tailings, which are the waste materials from the processes that are used to separate the gangue from the ore mineral(s). These *tailings* include some phosphorus; in the United States, this waste material is used to reclaim the mine and clay slimes in tailings ponds are a potential source of future P_2O_5 production. How much and whether this material may be subjected to reprocessing depends on many factors, including the technology of the mining facility. For other mineral commodities, especially base and precious metals, old tailings have been reprocessed owing to price increases and technological developments. Losses during processing can be either intended or unintended. Intended losses are accepted in order to achieve economic optimization. Unintended losses are the result of economic suboptimal operation. Some losses may be economically acceptable and others not; the latter may vary significantly depending upon the decision criteria and timeframe being used.

In 1988, the US Bureau of Mines examined phosphate availability and supply worldwide and concluded that the worldwide losses in the beneficiation stages varied between 21 and 60 % (Fantel et al. 1988). Using 1994 data, the German Geological Survey and the German Federal Environmental Office undertook a comprehensive material flow analysis for eight mineral commodities, including phosphate rock. For 61 % of world phosphate production, the study concluded that losses in the mining and processing stage amounted to 36 % (Kippenberger 2001). Industry sources report that, in 2010, total losses before processing are about 35 % (see Scholz et al. 2013).

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