Earth Syst. Dynam. Discuss., 4, 1005–1034, 2013
www.earth-syst-dynam-discuss.net/4/1005/2013/
doi:10.5194/esdd-4-1005-2013

Earth System Dynamics Discussions
Open Access

Recent revisions of phosphate rock reserves and resources: reassuring or misleading? An in-depth literature review of global estimates of phosphate rock reserves and resources

J. D. Edixhoven[1], J. Gupta[2], and H. H. G. Savenije[1]

[1]Department of Geography, Planology and International Development Studies, Amsterdam Institute for Social Science Research, University of Amsterdam, Plantage Muidergracht 14, 1018 TV Amsterdam, the Netherlands
[2]Faculty of Civil Engineering and Geosciences, Delft Technical Universtity, Stevinweg 1, 2628 CN Delft, the Netherlands

Received: 2 August 2013 – Accepted: 12 August 2013 – Published: 12 September 2013

Correspondence to: J. D. Edixhoven (j.d.edixhoven@tudelft.nl), J. Gupta (j.gupta@uva.nl) and H. H. G. Savenije (h.h.g.savenije@tudelft.nl)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Phosphate rock (PR) is a finite mineral indispensible for fertilizer production and a major pollutant. High grade PR is obtained from deposits which took millions of years to form and are gradually being depleted. Over the past three years, global PR reserves as reported by US Geological Survey (USGS) have seen a massive increase, from 16 000 Mt PR in 2010 to 65 000 Mt PR in 2011. The bulk of this four-fold increase is based on a 2010 report by International Fertilizer Development Center (IFDC), which increased Moroccan reserves from 5700 Mt PR as reported by USGS, to 51 000 Mt PR, reported as upgraded ("beneficiated") concentrate. IFDC used a starkly simplified classification compared to the classification used by USGS and proposed that agreement should be reached on PR resource terminology which should be as simple as possible. The report has profoundly influenced the PR scarcity debate, shifting the emphasis from depletion to the pollution angle of the phosphate problem. Various analysts adopted the findings of IFDC and USGS, and argued that that following depletion of reserves, uneconomic deposits (resources and occurrences) will remain available which will extend the lifetime of available deposits to thousands of years. Given the near total dependence of food production on PR, data on PR deposits must be transparent, comparable, reliable and credible. Based on an in-depth literature review, we analyze (i) how IFDC's simplified terminology compares to international best practice in resource classification and whether it is likely to yield data that meets the abovementioned requirements; (ii) whether the difference between ore reserves and reserves as concentrate is sufficiently noted in the literature, and (iii) whether the IFDC report and its estimate of PR reserves and resources is reliable. We conclude that, while there is a global development toward common criteria in resource reporting, IFDC's definitions contravene this development and – due to their vagueness and their lack of granularity – may cause more confusion than clarity. The difference between ore and concentrate is barely noted in the literature, causing a pervasive confusion and a high degree of error in many assessments. Finally, we conclude that the report presents an inflated

picture of global reserves, in particular those of Morocco, where largely hypothetical and inferred resources have simply been converted to “reserves”. In view of the essentiality of PR for food production, there currently is insufficient knowledge on the PR deposits available for extraction. Further research is required as to the quantity of PR deposits and their viability for future extraction.

1 Problem statement

Phosphorus is an essential plant nutrient essential to the growth of all plants and animals on which agriculture depends to maintain food production at required levels. Phosphate Rock (PR), the only source of phosphate for fertilizer production, is a finite, non-renewable resource. Due to various factors such as population growth, more phosphorus intensive diets (meat and dairy), and an increasing use of bio fuels, PR consumption is expected to increase significantly further over the next century (USGS, 2013).

While there is broad agreement that PR is a finite resource essential for human survival, the longevity of minable PR deposits is the subject of intense debate. Numerous articles have modeled depletion of PR reserves to occur by the end of the 21th century (Steen, 1998; Rosemarin, 2004; Vaccari, 2009), or peak phosphorus to occur within even a few decades from now (Déry and Andersson, 2007; Cordell et al., 2009). A number of these publications were based on mineral commodity summaries issued by USGS, which uses a resource classification system which it devised in the seventies together with the former US Bureau of Mines (USBM). This classification reports currently economic deposits as reserves; marginally or sub economic deposits as the reserve base; uneconomic deposits which have a reasonable potential of becoming economic in the future as resources; and deposits with no reasonable prospect of economic viability in the foreseeable future, as “occurrences”. In its Mineral Commodity Summaries, USGS only reported reserves and a reserve base. In 2010, USGS reported PR reserves of 16 000 Mt. The reserve base, last reported in 2009

was estimated at 47 000 Mt PR (USGS, 2009). Global PR resources had last been reported comprehensively in Notholt et al. (1989) where they had been estimated at 163 000 Mt PR in situ ore, grading 22,5 % P_2O_5 on average.

In 2010, International Fertilizer Development Center (IFDC) issued a report in which it suggested that the numbers provided by USGS were obsolete, its classification overly detailed in view of limited available information, its definitions poorly defined and that the reserves and resources reported by USGS should be reassessed (Van Kauwenbergh, 2010a). In the report, IFDC used starkly simplified definitions of reserves and resources. Global reserves were increased to 60 000 Mt PR, the vast bulk of which (51 000 Mt PR) were located in Morocco (Van Kauwenbergh, 2010a, p. 42). IFDC reported these reserves as beneficiated concentrate, which is a mining industry term for ore that has been upgraded to such extent that it can be sold as marketable product for the production of sulphuric acid or elemental phosphorus (P). Global PR resources, reported as in situ ore and including the ore from which reserves are calculated, were increased to 290 000 Mt of all grades, of which 168 000 Mt located in Morocco (report, p. 36 and 42). The report concluded that – based on is findings and a static consumption rate of around 160 Mt PR concentrate per annum – reserves for producing concentrate would remain available for 300 to 400 yr. The report states it embodies only the first phase of a more extensive investigation as to global deposits PR deposits, and that a second, more conclusive research effort is envisioned to explore future PR reserves and resources, to be performed by a network of scientists and practitioners from the mining industry.

The IFDC Report has thoroughly shaped the PR depletion debate. Shortly afterwards, USGS increased global PR reserves to 65 000 Mt PR, allegedly based on the report and information from the Moroccan producer (USGS, 2011). Resources, which had not been reported by USGS in many years, were stated at 300 000 Mt PR (USGS, 2012).

Following its report, IFDC created a network, Global TraPS (http://www.globaltraps.ch). This network focuses on the supply side of phosphorus and aims to bring together members from practice en academia in order to foster knowledge to deal with the problem of phosphorus. The project is co-led by the CEO of IFDC as a "practice" representative, while Dr. R. Scholz of the Swiss Technology Institute represents academia. Along with industry, the network attracted numerous scientists and organizations as members. Even though an in-depth review of "PR reserves and resources for the future" was and currently still is lacking, one of the main tenets formed early on, was that absolute scarcity is not a main problem for P supply because "reserves are poorly related to the total resource", which were assumed to be very large (Global TraPs, 2011a). Scholz and Wellmer argue that one "can define a sustainable P cycle if – in the long run – the economically mineable (primary and secondary) reserves of P increase higher than the losses (i.e. dissipation) to sinks which are not economically mineable" (Schollz and Wellmer, 2013, p. 14). This notion of sustainability, however, requires infinite "reserve growth" which cannot continue forever if the source from which the reserves are derived is finite. To estimate longevity of remaining PR deposits, it is critical to have a realistic understanding of the quantity of minable PR that is ultimately available for extraction under reasonable assumptions (Cathcart et al., 1984; Van Vuuren et al., 2010)[1].

Given the near total dependence of food production on PR, data on PR deposits must be transparent, comparable, relevant and reliable (UNFC, 2010; Scholz and Wellmer, 2013). This paper provides an in-depth review of the report, its methodologies, the recent revisions of global PR reserves generally, and some of the conclusions that were drawn from these in the literature. First, we review how IFDC's simplified definitions compare to industry best practice and leading resource classifications, and whether

[1]Human use quadrupled the natural flows of P into the environment since pre-industrial times, resulting in massive eutrophication of the freshwater aquatic environment. It is argued that this increased flow is unsustainable and that the global boundary for P has been transgressed substantially (Carpenter and Bennet, 2011). This pollution aspect of P, though very important, will not be discussed in this paper. In determining sustainability of the P cycle, this aspect should, obviously, be taken into consideration.

its classification proposals offer sufficient safeguards for generating reliable assessments on PR reserves. Secondly, we review whether it is common to report reserves as concentrate, and report reserves, back-calculated to ore, as part of the resources, and if the consequences are sufficiently understood in the literature. The third and final research question addressed in this paper is whether IFDC's estimate of global reserves and resources is reliable and comparable. Here, our methodology has been to trace back and review the sources of information used in the IFDC report and compare these data to other publications that were obtained. Given that the massive increase of reserves and resources can be almost entirely attributed to Morocco, we focused on that country.

2 Background

Approximately 82 % of total mined PR is used for fertilizers and another 7 % for feed additives and the remainder for other industrial purposes. The bulk of the world's PR suitable for mining is found in large sedimentary rock deposits of marine origin. High grade deposits are located only in a limited number of places in the world, typically on (former) continental shelves. The remainder of phosphate rock production is derived from igneous rock which is low in grade (often less than 5 % P_2O_5) but may be upgraded to concentrations ranging between 35–40 % P_2O_5 (Van Kauwenbergh, 2010a). Igneous PR allows for approximately 15–20 % of current global production but forms only a few percent of the aggregate phosphate rock resources (Notholt et al., 1989).

Most PR for fertilizers is mined, upgraded, and then treated with sulphuric acid to produce phosphoric acid (the wet method). Mining losses occur depending on a number of factors. Underground mining operations result in larger losses than open pit mining as walls are needed to support the ceilings. Mining recovery may range from 95 % to 50 % of ore in the targeted ore zones (Van Kauwenbergh, 2010a, 2012), to 30 %, if deposits are mined at great depths (De Voto et al., 1979), to 0 % if the ore layer is too thin for mining (Van Kauwenbergh, 2012). Significant losses also occur in the upgrading process, as will be discussed below.

Given the economic function of resource classifications, reserves and resources are dynamic. Sub resource deposits, termed "occurrences" (USGS and USBM, 1982) or "other quantities in place" (UNCF, 2010), form no part of the resources, but may become so as prices rise or as technique evolves (USGS, 1980; Cathcart et al., 1984; Herring and Fantel, 1993). Large "occurrences", not included in the resources, are located offshore or on seamounts, or are buried deeply as a result of tectonic occurrences following their deposition, such as the bulk of the deposits located in the Western Phosphate Field in the USA, probably the largest PR formation in the world (De Voto et al., 1979, p. 37).

A recurring issue in the literature is that a very substantial *geocapacity* of undiscovered PR deposits may exist that may extend reserves and resources well beyond currently known reserves and resources (Sheldon, 1987, and, more recently, Scholz and Wellmer, 2012). However, a distinction should be made between known or hypostasized occurrences based on assumed extensions of known deposits, and truly unknown geocapacity[2]. In view of their typically high uranium content, aerial radiometric detection of PR is possible and is routinely applied in the exploration of PR deposits (Asfahani et al., 2005). Van Kauwenbergh (2006, p. 46) argues that, while there may be some potential to discover new deposits, oil exploration programs have probed most of the coastal sedimentary basins of the world during the past 20 to 30 yr, and that any large scale discoveries of phosphate rock probably would have occurred in conjunction with these activities. Smit et al. (2009) refer to a personal communication by USGS that the discovery of major new deposits is unlikely.

[2]*Hypothetical* deposis are undiscovered resources similar to known mineral bodies which may reasonably be expected to exist in the same producing district under analogous geologic conditions, while *speculative* deposits are resources that may exist under favorable geologic settings, but where no discoveries have yet been made (USGS, 1980).

The IFDC report concludes based on its findings and a static consumption rate of 160 Mt PR, that *"phosphate rock reserves to produce fertilizer will be available for 300–400 yr"* (Van Kauwenbergh, 2010a, p. 43). However, by 2011, world production had already risen to 198 Mt PR concentrate (Kelly and Matis, 2003) and global production capacity is currently being expanded to 256 Mt PR concentrate per annum, to cater for the growth in demand which is anticipated for the near future (USGS, 2013). Most analysts anticipate that PR consumption will continue to rise until the end of the 21th century, after which demand is projected to stabilize. For instance, Rosemarin et al. (2011) calculated that IFDC's 60 000 Mt PR concentrate could be depleted within 172 yr if the anticipated population growth is taken into consideration (255 Mt PR consumption by 2100), or 126 yr if Africa would develop its agriculture and experience a green revolution. Under this assumption, global PR concentrate consumption would be 314 Mt PR concentrate by 2100, double the quantity on which IFDC based its depletion analysis of current reserves. The authors also calculated that if bio fuels were to supply for 10 % of global energy requirement, the reserves reported by IFDC could be depleted in 48 yr, at which point global PR consumption would reach 475 Mt PR annually.

The depletion rate may be mitigated by increased use efficiency and adapting societies, as may be factored into a scenario analysis. Van Vuuren et al. (2009) forecasted increases in PR consumption adopting the story line of each of the four UN Millennium Assessment scenarios. Under the Adapting Mosaic (AM) Techno garden (TG) scenario's, which assume a pro-active environmental management, Van Vuuren et al. estimate aggregate P consumption to be roughly around 85 and 65 Mt P_2O_5 by the end of 2100, or 220 and 280 Mt PR concentrate at 30 % P_2O_5. For the Order from Strength (OS) and Global Orchestration (GO) scenario's, which assume reactive environmental management, the authors estimated annual consumption by the end of the century to be roughly 105 Mt P_2O_5 under the OS scenario and roughly 115 Mt P_2O_5 under a GO scenario, or roughly 350 and 380 Mt PR concentrate respectively, fairly consistent with the "business as usual" extrapolations given in Rosemarin et al. (2011). The influence of bio fuels differs in both assessments and merits further attention[3]. A mitigating factor for future demand may be the fact that a significant part of P applied to the soils is stored (immobilized) and remains available for crop uptake (Steen, 1998; Sattari et al., 2012). Sattari et al. (2012) conclude that this circumstance implies that global P application will only need to rise slightly if at all. Others argue such optimism needs to be tempered, in view of factors like erosion and persistent use inefficiencies (Porder and Townsend, 2012).

In view of the above, depletion of currently identified easily accessible deposits could occur at much quicker rates than suggested in the IFDC report, depending on how society responds to potential risks of long term PR scarcity. It is therefore of great importance to have reliable knowledge regarding the quantity of PR that is available for potential extraction. This brings us to the first research question, whether, as IFDC advocates, a resource classification with little granulation is indeed desirable for the purpose of creating a reliable long term global inventory of PR.

3 Does a simplified classification offer sufficient safeguards for generating reliable assessments on PR reserves?

The IFDC report discusses the USGS classification and criticizes it for being overly detailed and its definitions such as "measured" and "identified", poorly defined. The IFDC report argues that the detailed information required to operate the USGS classification would generally not be available as mining companies have no incentive to explore deposits which will not be economic in the foreseeable future, or will be reluctant to share information regarding reserves for commercial or regulatory reasons. IFDC proposes

[3]The footprint of first and third generation biofuels may be very significant depending on the share of biofuels in the energy mix. In a recent report by the US Committee on the Sustainable Development of Algal Biofuels calculated that if third generation bio fuels were to meet 5 % of US transportation fuel demand, this would require 20 to 51 % of USA's total phosphorus use (CSDA, 2012).

a drastic simplification of terminology, defining reserves as deposits that can be economically produced with current techniques, reported as recoverable concentrate, and resources as those deposits, reported as ore in situ that may be produced "at some point in the future".

To put these proposals in perspective, we briefly discuss three main types of existing resource classifications and their rationales: inventory classifications for government purposes, classifications for financial reporting and the UN Framework classification which combines the qualities of both. We then evaluate IFDC's proposals and their consequences.

3.1 Government reporting classifications for inventory purposes

Governments have an interest in obtaining the most comprehensive inventory of mineral deposits in order to enable both short term and long term strategic planning with respect to their mineral resources (Camisani Calzolari, 2004). Government type resource classifications exist in many countries including the US and the (former) communist bloc. The American USGS classification essentially is a government type classification, aimed at enabling both commercial and long term public planning (USGS, 1980). While the classification is generic in the sense that it applies to all mineral commodities, specific rules were drafted for PR deposits (USGS, 1982). As noted by the draftsmen of these guidelines, large differences occurred in PR reporting at the time, which were not so much the result of differences in actual quantities of PR, but mainly of definitional confusion. A main goal of the PR classification was to create uniform language based on exploration practice, to permit *"real"* differences among estimates to be precisely stated (Cathcart et al., 1984).

The USGS classification is based on two key aspects of mineral resources: first, the degree of geological certainty (how well known and measured is a deposit?) and second, the degree of economic viability of a deposit. It recognizes four major categories of deposits. Resources are mineral deposits of which extraction is *"currently or potentially feasible"*, including uneconomic deposits. The reserve base is the part of an identified resource which meets specific minimum requirements for current mining practices, including grade, quality, thickness and depth and is the in-place demonstrated resource from which reserves are estimated. This category was included to deal with the fact that reserves constantly fluctuate due to economic and technical developments and to indicate the quantity of near-economic deposits available for extraction. The reserves are the part of the reserve base which could be economically extracted at the time of the determination and include only recoverable material. Finally, the classification recognizes a fourth class, termed "occurrences", to describe deposits that are too low in grade or for other reasons are not considered potentially economic for the foreseeable future (USGS, 1982).

The classification introduced a number of sub definitions and sub-sub definitions to factor the degree of the certainty of geologic certainty of existence of a deposit such as demonstrated (measured and/or indicated) and identified (demonstrated and/or inferred). These definitions will be discussed in more detail in Sect. 5.3 below, which deals with the Moroccan reserves and resources. The USGS classification also identifies a class of "undiscovered resources", which may be either hypothetical or speculative (see above).

Other government type classifications are typically based on similar principles and contain the same amount of detail, or even more. That is also the case with the UN Framework Classification (UNFC) discussed below, which has been regarded as essentially a government type, inventory classification in the past (Camisani-Calzolari, 2006). Their strength is that they not only focus on currently economic deposits, but allow analysis of deposits that may become economic, now or in the (far) future if technical and economic developments so permit.

3.2 Financial reporting classifications

In contrast with government reporting codes, classifications for *financial reporting* purposes typically aim to ensure that mining companies provide transparent, correct and reliable data to the investing public, so as to enable investors to make guided in-

vestment decisions. The JORC code, devised by the Australian Joint Ore Reporting Committee, and inspired similar reporting codes in numerous countries in the world such as SME (USA), and PERC (EU). These various JORC style codes adhere to the same standards, are 90 % similar and can effectively be regarded as one international body of rules (Camisani-Calzolari, 2006). In 2006, the Committee for Mineral Reserves International Reporting Standards (CRIRSCO) issued a template, further revised in 2013, which provides guidelines for countries which intend to adopt a JORC style code (CRIRSCO, 2013).

JORC style codes are based on the same principles and broadly use the same terminology as the USGS classification. However, as mining corporations and investors typically are only interested in deposits for which there is reasonable perspective of economic exploitation, JORC style codes are simplified to seven definitions, based on the main concepts of mineral reserves and resources, further fine-tuned by the sub-definitions measured, indicated and inferred. JORC style codes do not report a reserve base as this is deemed potentially misleading because the economic potential of a near economic deposit may not materialize within a time frame appropriate for investment purposes (JORC, 2012). While JORC style codes are detailed with respect to the reserves categories, they do not report sub-economic deposits comprehensively and, consequently, are blind to the long term perspective (Camisani-Calzolari, 2004; UNFC, 2010).

3.3 Towards integration across the commodities: the UN Framework Classification

The United Nations Framework Classification (UNFC) came about in 1997. It recognizes that effective management of resources requires an accurate assessment of the supply base of minerals on a global basis, and that accurate and consistent estimates of reserves and resources are essential for such assessments. It was extended in 2004 to include all extractable energy commodities (e.g. petroleum, coal, uranium) and became a global project when United Nations ECOSOC Resolution 2004/233 recommended its worldwide application. In 2009, the code was simplified and amended in order to align it with the CRIRCSO code as well as the leading Petroleum Resource Management System devised by the Society of Petroleum Engineers (SPE) for liquid fuels. CRIRSCO and SPE were consulted extensively in this process (UNFC, 2010). The resulting current version aims to provide “a single framework on which to build international energy and mineral studies, analyze government resource management policies, plan industrial processes and allocate capital efficiently” (UNFC, 2010). The UNFC meets both the needs for financial reporting and simultaneously contains the granulation required building a global long term inventories for public planning purposes.

UNFC recognizes four broad categories of (i) commercial projects; (ii) potentially commercial and non-commercial projects; (iii) exploration projects, and (vi) additional quantities in place. This is more or less consistent with the USGS system, even though the various classes do not overlap under UNFC. At the roots of these broad categories lies a three dimensional numerical system which uses three sets of mineral resource parameters: economic and social viability (E), field project status and feasibility (F) and geological knowledge (G). Each cube in the three dimensional system was assigned three numbers for each of the above parameters, in alphabetical order. In total, 36 classes are recognized, each uniquely defined by its three number code. As the code is open ended additional layers of detail may be added. The detailed granulation in the UNFC is particularly suited for inventory purposes, as it allows coverage of all types of mineral occurences at their specific stages of feasibility and geologic certainty of existence, regardless of their current economic potential (Camisani Calzolari, 2006).

The above review points at a significant global effort in creating common language in mineral resource classification. The major classification systems are compatible with UNFC, or – in the case of USGS – can be made compatible with them as they are based essentially on the same principles. All classifications reviewed contain a detailed granulation in the area of their focus. Classifications with an inventory purpose, partic-

ularly UNFC, allow for granulation as to deposits which are not expected to become extractable in the foreseeable future.

3.4 Evaluation of IFDC’s terminology proposals

IFDC’s simplification appears at odds with this gradual global movement toward uniform resource reporting. With respect to reserves, the various classifications contain specific requirements for each commodity to determine whether a deposit can be qualified as such. Under the USGS classification, only *measured* or *indicated* deposits may form part of the reserves. Whether these sub definitions apply is determined on the basis of sampling and the distance between the drill holes (USGS, 1976; Schollz and Wellmer, 2013). Other requirements relate to the thickness of the ore bed, the quantity of overburden, the grade and impurity level. None of these requirements are part of the IFDC definition of reserves (essentially: deposits producible at today’s costs and prices). The disadvantage of such vague definitions is that it is left up to the individual analyst to determine if a deposit constitutes a reserve, impairing comparability and reliability of reserve estimates.

IFDC proposes to discard USGS’ reserve base essentially because USGS apparently did not publish updates as to the monetary thresholds it uses for determining the reserve base. It indeed is a well established principle under all classifications that economic thresholds should be updated from time (USGS, 1982, Camisani Calzolari, 2006). The proposal fails to recognize, however, that the reserve base was created to mitigate the effect of fluctuating prices which impacts, or should impact, the reserves even more than the reserve base (USGS, 1982).

For resources, IFDC uses the definition of “phosphate rock of any grade [...] that may be produced at some time in the future”. Again, this definition is so broad that it may cover any PR deposit, depending on the author’s view of what the – distant? – future may bring. This is exemplified by IFDC’s repeated reference to a very high end resource estimate by De Voto et al. (1979) for the Western Phosphate Field in the USA (WPF), and the suggestion that numbers given in this report for the WPF could be used for the resources (Van Kauwenbergh, 2012a, p. 40). The De Voto report will be discussed later in this paper. What matters here is that only a few percent of these deposits are generally considered a resource in the literature (Sheldon, 1989, p. 59; Moyle and Piper, 2004, p. 575 and 592–593; Herring and Fantel, 1999, p. 6), and the remainder is considered an occurrence in view of the great depth at which these deposits are located (70 % at depths between 5000 and 30 000 feet, or 1500 to 9000 m, Bauer and Dunning, 1979, 162–263 and 199–200). Whether such deeply positioned deposits ever become technically and economically viable is doubtful and this is precisely what separates resources from other quantities in place. Based on our review of resource classifications, we conclude that clear thresholds are imperative to classify each deposit according to its true potential.

In sum, building a global long term inventory of available PR deposits requires a detailed classification which enables "real" differences to be accurately stated (USGS, 1982). In view of global consistency, such system should preferably be compatible with UNFC. Discarding granularity altogether appears undesirable as this impairs comparability and transparency and, ultimately, jeopardizes reliability of mineral resources assessments.

4 Is reporting of reserves as concentrate common and is the difference understood in the literature?

The IFDC report reports reserves as upgraded concentrate, and resources as ore in situ, including reserves back-calculated to ore in situ. We review whether the difference between ore and concentrate is common and sufficiently understood in the general literature on PR deposits.

4.1 The difference between ore and concentrate

For certain minerals like coal and PR, a common industry practice exists to report mine production as concentrate rather than ore, and sometimes also "reserves". "Concentrate" means ore that has been mined and upgraded so that it can be sold as marketable product, which typically requires 30 % P_2O_5 (USGS, 2013) and suitable impurity levels. Losses occur at both occasions (see *infra*). As a rule of thumb, grade is inversely proportional to recovery in upgrading, which means that the lower the quality of the ore, the lower the recovery percentage (Van Kauwenbergh, 2010a). In the IFDC report, an ore to concentrate reduction of 63 % was applied for the relatively high grade Moroccan ore, assuming only 5 % mining losses (Van Kauwenbergh, 2010a, p. 36).

Even though the practice exists in certain industries, reporting in concentrate by no means is the common standard. The USGS classification is a *generic* classification suitable for all mineral resources, which speaks against an easy assumption that reserves should be reported as concentrate under USGS criteria. The criteria for PR (USGS and USBM, 1982) do not indicate that this should be the case. JORC and CRIRSCO explicitly use of the term "ore reserves" and prescribe that *if* a reserve is denoted as concentrate, this is done in conjunction with the ore reserve number so that it is clear to the reader what is reported (JORC, 2006; CRIRSCO, 2013). The UNFC code, which is fully compatible with JORC and CRIRSCO, likewise reports economic deposits in terms of extractable ore (UNFC, 2010). While reporting in concentrate may be useful to understand the potential of a deposit, it also may be a source of confusion.

4.2 An intriguing question: does USGS report reserves as ore or concentrate?

An intriguing question is whether data provided by USGS are comparable with IFDC's numbers, as is routinely assumed in the literature but which has not been confirmed by USGS. In fact, it appears that USGS often lists reserves in terms or ore rather than concentrate. South Africa, for example, is a producer of igneous ore which is low in grade but can be upgraded to a high quality product. In 2009, the South African producer listed ore reserves of 1624 Mt (Van Kauwenbergh, 2012a, p. 38). In view of the low ore to concentrate recovery, South African reserves are listed as only 230 Mt PR in the IFDC report. However, they have been reported as 1500 Mt PR in the USGS mineral commodity summaries for years, roughly consistent with the abovementioned ore number.

Information in the IFDC report and in other sources suggests that recent individual upward country restatements for countries like Algeria and Syria in the USGS Commodity Summaries may in fact be restatements of known ore resources as ore reserves. For instance, USGS increased Algerian reserves from 125 Mt to 2200 Mt in 2010 while the Algerian producer, Ferphos, listed 2000 Mt PR ore resources in the same period (Van Kauwenbergh, 2010a; Taib, 2009, p. 2.4). For Syria, USGS increased reserves from 100 Mt to 1800 Mt of rock (USGS, 2010 and 2011), roughly consistent with the ore resource of over 2000 Mt PR reported by the Syrian producer in 2010 (Van Kauwenbergh, 2010a, p. 38). Whatever their "reserve" status, these numbers appear to represent ore, not concentrate.

A particularly awkward example are the Iraq reserves, which USGS restated from zero to 5800 Mt PR overnight in 2012, placing Iraq ahead of China and the USA combined (USGS, 2012). These deposits were presented as a "discovery" by USGS (Taib, 2010), ignoring that their bulk had been reported as ore resources decennia earlier (Al Bassam, 1989). In 2013, Iraq reserves were silently downgraded again by 93 % to a mere 430 Mt PR (USGS, 2013), which, again, is the ore reserve, grading 21.52 % P_2O_5, of the only operating mine in Iraq (Taib, 2013).

These examples testify that upward reserves reports not always signify a true increase of reserves established by exploration. They also call into question whether USGS reports reserves as ore or concentrate, and whether the USGS numbers are comparable with IFDC's reserves, reported as concentrate.

4.3 PR longevity estimates in recent literature; a lake of confusion

A critical scrutiny of PR literature reveals that the difference between ore and concentrate has remained largely unnoticed in the scientific arena. The result is a high degree of error in many scientific publications regarding the long term availability of PR deposits. A few examples are highlighted.

Vaccari and Strigul (2012, p. 792) argue that, on top of the reserves, the resources identified in the IFDC report will extend the lifetime of PR deposits by two millennia. Apparently, the authors added IFDC's reserves of 60 000 Mt to the resources of 290 000 Mt and divided the outcome through an annual concentrate production number of 158 tonnes of Mt PR. In fact, IFDC's reserves of 60 000 Mt PR concentrate are included in the resources and, back-calculated to ore, constitute well over half of them. This conclusion nevertheless ended up in Greenpeace's special report on phosphorus (Tirado and Alsopp, 2012), influencing public perception on PR scarcity.

In Mew (2011, p. 9), likewise, IFDC's global in situ ore resources were divided through production numbers in concentrate, yielding a longevity of the resources of more than 1000 yr where, based on the consumption assumptions used (250 Mt PR concentrate annually), about three centuries would probably have been appropriate.

Scholz and Wellmer (2012) refer to *"concentrates"* as being *"formed in different geological periods over millions of years"* (p. 4). In the same publication, the authors extrapolate a longevity of up to 3000 yr for deposits in the Western Phosphatic Field (WPF) in the US, based on a statement by Moyle and Piper that, in addition to 7600 Mt strippable resources and 17 000 underground resources up to 305 m, there are *"507 000 billion mt of subresource grade phosphatic material that underly the WPF at depth greater than 305 m"* (Scholz and Wellmer 2012, p. 6; Moyle and Piper, 2004, p. 575). The authors divide the aggregate in situ ore number through the 2010 world concentrate production number of 178.5, apparently assuming zero mining losses and zero losses in beneficiation. The authors state that, while 3000 may be too optimistic, a lifetime of 1000 years seems reasonable. However, even ignoring the static consumption level, the extrapolation clearly is way off mark. According to Bauer and Dunning (1979, p. 162, 162, 200), 24 % of the WPF deposits are located at depths up to 5000 feet (1500 m) and 70 % between 5000 feet and 30 000 feet (9000 m). These underground and deep underground deposits are not considered a resource in the literature (Sheldon, 1989, p. 59; Cathcart, 1991 and Moyle and Piper, 2004, p. 575 and 592) as they cannot be mined in the foreseeable future (Herring and Fantel, 1993, p. 6). To the extent they can, mining losses are likely to be large; De Voto et al. (1979) assume 70 % losses for the deep underground deposits which form the bulk of the field and 50 % for the intermediate deposits. Sheldon (1989, p. 59) anticipates mining losses of about 50 % even for the fraction of the WPF deposits that he does consider a reserve base, suggesting that the De Voto assumptions are rather optimistic. Conversion to concentrate would significantly further reduce quantity that can be recovered as concentrate.

These are but a few examples from a rapidly expanding body of literature regarding PR deposits. Again, clear and unambiguous reporting global reporting standards are urgently called for, to prevent this kind of basic misunderstanding and enable both the opportunities and limitations of the deposits under scrutiny to be adequately assessed.

5 Are the IFDC report and its estimate of PR reserves and resources sound and reliable?

Having set out the key issues at play in the PR debate and the general state of confusion which currently predominates it, we now turn to the final research question, whether IFDC's reserve estimate for Morocco (51 000 Mt PR concentrate on a world total of 60 000 Mt PR) is comparable, transparent and reliable.

5.1 Previous estimates of moroccan reserves and resources

Morocco controls four major phosphate deposits. Three of these fields are located in Morocco (Ouled Abdoun, Gantour and Meskala) and one in Western Sahara (Bou-

Crâa), which Morocco occupies since 1975. The Ouled Abdoun and Gantour fields have been explored in detail around the established mining centers decennia ago (Savage, 1987), but have extensions for which exact data is still lacking. The explored portion of these fields has been expanding in the last decennia of the 20th century, resulting in a gradual increase of the reported reserves and resources. Particularly the Ouled Abdoun field – which contains the richest and most extensive deposits in Morocco (Savage, 1987) – is noted to be extremely complex, as the unexplored parts have been severely disturbed geologically and are positioned much more deeply in the ground (up to 400 m) than the northernmost parts which are currently being exploited (Service Géologique du Maroc, 1986, p. 64 and 217). It has long been recognized that the Moroccan deposits are exceptionally large.

In 1987, British Sulphur Corporation, on the basis of information by Moroccan authors, reported Moroccan reserves to be 56 250 Mt PR of which 26 800 Mt PR for Ouled Abdoun (36 % of the deposit area), 8002 Mt PR for Gantour (15 % of the deposit area), 20 480 Mt PR for Meskala and 950 Mt PR for Boucraâ (Savage, 1987, p. 99). Two years later, within the context of the UNESCO Project 21, the Moroccan producer OCP reported exactly the same numbers, this time as resources, and indicated that due to expanding exploration, the total had meanwhile been set at 63 930 Mt PR (OCP, 1989a). In 1995, USGS reported that, "according to the Moroccan Ministère de l'Energie et des Mines, proven reserves of phosphate totaled 85.5 billion tons" (Michalski, 1995, at 2).

USGS, evidently aware of this magnitude, did not adopt these numbers as reserves in its mineral commodity summaries and nor did OCP. In 1994 (Dolley, 1994, p. 557) and 2007 (OCP, 2007, p. 9), OCP placed Moroccan reserves at approximately 20 000 Mt PR on a world total of 50 000 Mt PR, which coincides with the reserve base estimates in the USGS commodity summaries for these years.

5.2 The IFDC estimate based on Gharbi

The IFDC reserve estimate for Morocco is solely based on Gharbi (1998). Strikingly, Gharbi reported the same number reported in Michalski (1995), but in cubic meters, rather than megatons. Using a conversion ratio of 2.0, this yields an ore resource of 168 240 Mt PR.

IFDC adopted Gharbi's ore reserves for three of the four deposits. The Meskala deposit was termed a resource, which was later used to argue that the IFDC estimate was "very conservative" (Van Kauwenbergh, 2010b, at 1:25:00 and further). IFDC set the mining recovery rate at 95 %, a number significantly more optimistic than an estimate by Prud'homme of 82 % referenced in the IFDC report (Van Kauwenbergh, 2010a, p. 6). Subsequently, the estimated ore reserves of 138 240 Mt PR were recalculated into upgraded concentrate, reducing the volume by 63 % to 51 000 Mt of concentrate (Van Kauwenbergh, 2010a, p. 36).

The IFDC report states that this magnitude of Moroccan reserves has been recognized earlier in the literature, pointing at Savage (1987) and Emigh (1979). This time, the report itself confuses ore and concentrate. Even though the numbers may seem comparable on first glance, a superficial scrutiny unveals that they are both ore numbers[4]. Back calculated to ore, the IFDC estimate of 51 000 Mt PR concentrate is in fact almost three times higher. The Gharbi (1998) estimate begs two questions: (i) how can these increases be explained and (ii) can it reasonably be maintained that all this ore, the bulk of which IFDC recalculated into concentrate, are really ore reserves?

[4]Savage reported 56 250 Mt PR, which – according to OCP (1989) – is a resource of in situ ore and much smaller than 168 000 Mt PR ore reported in Gharbi (1998), or the 138 240 Mt PR which IFDC adopted as ore reserve (Gharbi's total, excluding Meskala). Emigh (1979), reported 30 000 m^3 of ore in situ which he recalculated to approximately 80 000 Mt PR ore or 55 500 Mt PR of concentrate (page 403, converted to metric tons). However, using IFDC's conversion ratio, 30 000 m^3 PR in situ yields 60 000 Mt PR in situ ore, a number comparable to Savage (1987) and OCP (1989).

5.3 Morocco's consistent underreporting of resources and Gharbi's incorrect use of the term "reserves"

A review of Moroccan data sources reveals that for almost two decades, the same resource numbers discussed above as reported in megatons the international, English language literature were reported in cubic meters of ore resources in the OCP annual statements and the French language scientific literature. For instance, the 1987 OCP annual statement (OCP, 1987, p. 14) listed an aggregate in situ ore resource of 63 930 million m^3 for the four fields, identical to the number reported in OCP (1989), but for the notation in cubic meters. The period which followed marked a steady rise of the reported resources, corresponding with the gradual expansion of exploration of the deposit areas. By 1995, the aggregate resources had increased to 85 500 million m^3 PR (OCP, 1995, p. 15). The annual account for 2000 (OCP, 2000, p. 17), the latest recoverable document in which a resource statement was made, reported identical numbers and clarified that this number aggregated ore of all qualities, without substantiation of grades. As each cubic meter yields two tons of ore, these documents imply that Moroccan resources have been consistently understated by 50 % for decades in the international literature.

Whatever the reason for this anomaly, while the quantity of ore reported in Gharbi (1998) is consistent with these OCP reports, Gharbi's qualification of these deposits as "reserves" is clearly not. In a more detailed study issued two years earlier, Gharbi listed the same deposits as resources, as OCP had done in the abovementioned annual statements (Gharbi and Mchichi, 1996). Moreover, Gharbi and Mchichi (1996) and these OCP annual accounts confirm that most of these deposits do not meet the requirements for reserves or reserve base in terms of the geologic certainty, at least not when USGS criteria are used.

Under the USGS classification, if drill holes are more than one mile (1.609 m) apart, deposits which otherwise meet the base requirements for resources but are located at more than 1 mile from the drillhole are regarded as an undiscovered, hypothetical resource. If the drill holes are spaced at less than a mile, the deposit may be regarded as an inferred resource (USGS and USBM, 1982). If drill holes are spaced at less than half a mile (802 m) and the ore meets the other appropriate requirements for reserves, economic and geological, the deposit may be termed an indicated reserve. The delineation of measured reserves (the reserves category with the highest degree of geologic certainty) is viewed as an industry task in the USGS classification and is regarded as often proprietary (USGS and USBM, 1982). In most places of the world, to establish "proven" reserves, boreholes are drilled on approximately 100 m centers (Van Kauwenbergh, 2010a). In addition to this, additional requirements apply in terms of grade, depth, overburden, thickness of the ore layer, and economic requirements apply to establish reserves. For want of detailed information on these other requirements, we focus on the drillhole data.

An overview in OCP (2000) shows that, out of the total 85 500 million cubic meters PR ore reported for Morocco, more than 46 810 million cubic meters PR ore have been established by drill holes spaced more than 2000 m apart; that 17 430 million cubic meters have been established by drillholes spaced at less than 500 m; and that 12 380 cubic meters have been established by drillholes spaced between 500 and 1000 m apart. Thus, using USGS criteria and based on drill hole data alone, probably over two thirds of the deposits listed by OCP would have to be classified as undiscovered hypothetical or inferred resources. How much of the aggregate Moroccan in situ ore resource ore could qualify as a recoverable ore reserve, cannot be assessed without more information. However, it is clear that the term "reserves" is inappropriate here.

Interestingly, Van Kauwenbergh (2006), p. 284, contains an in-depth discussion of Moroccan resources, including Gharbi (1998). Referencing the Gharbi estimate, Van Kauwenbergh concluded that "[t]his is a rather loose use of the term "reserve" and the word "resources" probably should have been used". Elsewhere in the same publication, the author recognized that Moroccan reserves constitute approximately one third of global reserves, "depending exactly on which reserve/resource classification is used" (van Kauwenbergh, 2006, p. 45). This statement was based on USGS data

which reported Moroccan reserves of 5700 Mt on a global aggregate of 18 312 Mt PR. Apparently, the large demonstrated, inferred and hypothetical resources which Gharbi reported for Morocco did not at the time fundamentally change the validity of USGS' assessment of Moroccan reserves and reserve base.

6 In conclusion

This paper has signaled a development in mineral resource reporting towards standardized definitions across the minerals, both to serve the needs of globalizing business and to allow for mineral availability studies within the context of sustainable development. Detailed granulation is a core element in all leading mineral resource classifications.

The IFDC report departs from this established and evolving best practice, proffering coarse definitions as a substitute for data. This simplification, in combination with a clearly incorrect interpretation of data in Gharbi (1998), allowed for an enormous inflation of Moroccan "reserves". Once this number was accepted by USGS (or seemingly so, as it is not certain whether the USGS number actually reflects concentrate), it was quickly followed by upgrades by countries as Syria, Algeria and Iraq. In the literature, these upgrades have been interpreted as "discoveries", suggesting an even greater geocapacity available for extraction (for instance, Scholz and Wellmer, 2012). This review unveils, however, that both the increase of Moroccan reserves and these subsequent increases were in all likelihood mainly due to simple restatements of ore resources as ore reserves. In case of the Moroccan reserves, this "swap" was followed by a conversion to concentrate, which to some extent veiled the enormity of the increase to the casual observer. It also rendered the IFDC reserve for Morocco inherently incomparable with USGS reports for many countries. Meanwhile, USGS fails to provide clarity on whether it reports PR as ore or concentrate, a difference that has proved a major source of error and confusion.

A unique feature which sets PR apart from other finite commodities is the fact that current levels of food production are not possible without it. By consequence, it is imperative that the use of PR is sustainable and equitable not only from a generational, but also from an intergenerational perspective. Also in the long to very long term it is imperative that sufficient PR remains available to meet the needs of future generations. While it is commonly recognized that aggregate PR deposits are very large, two critical questions need to be addressed to determine how much PR can be used without impairing the opportunities of future generations. The first is how much suitable concentrate could be derived from aggregate global deposits and at what costs, economically and energetically. The second question is how demand may develop when further agricultural intensification, dietary shifts and an increasing use of bio fuels are taken into consideration, also if society fails to take the appropriate steps to use this finite resource in a more diligent manner. Apart from the update on Moroccan resources, the IFDC reported added little but confusion to these questions. A truly independent and scientifically sound global inventory of PR deposits, as envisaged in the report, is yet to take place. Such review would also need to realistically assess those deposits which are not currently viewed as resources and which humanity will come to depend upon once today's reserves and resources are depleted.

References

Asfahani, J., Aissa, M., and Al-Hent, R.: Statistical factor analysis of aerial spectrometric data, Al-Awabed area, Syria: a useful guide for phosphate and uranium exploration, Appl. Radiat. Isot., 62, 649–661, 2005.

Al-Bassam, K. S.: The Akashat phosphate deposit, Iraq, in: Phosphate Deposits of the World, vol. 2 Phosphate Rock Resources, chap. 49, edited by: Notholt, A. J. G., Sheldon, R. P., and Davidson, D. F., International Geological Correlation Programme, Project 156, Cambiridge University Press, New York, USA, 1989.

Bauer, C. W. and Dunning, C. P.: Uraniferous phosphate resources of the western phosphatic field, in: Uraniferous Phopsphate Resources, United States and the Free World, edited by:

De Voto, R. H. and Stevens, D. N., United States Department of Energy, Publication GJBX-110 (79), Grand Junction, Colorado, USA, 123–249, 1979.

Camisani Calzolari, F. A.: National and international codes for reporting mineral resources and reserves: their relevance, future and comparison, Journal of the South African Institute of Mining and Metallurgy, 104, 297–305, 2004.

Carpenter, S. R. and Bennett, E. M.: Reconsideration of the planetary boundary for phosphorus, Environ. Res. Lett., 6, 014009, doi:10.1088/1748-9326/6/1/014009, 2011.

Cathcart, J. B., Sheldon, R. P., and Gulbrandsen, R. A.: Phosphate-Rock Resources of the United States, US Geological Survey, Geological Survey Circular 888, Alexandria, Virginia, USA, 1984.

Committee on the Sustainable Development of Algal Biofuels, Board on Agriculture and Natural Resources, Board on Energy and Environmental Systems: Sustainable Development of Algal Biofuels in the United States, The National Academic Press, Washington DC, 2012.

Cordell, D. Drangert, J. O., and White, S.: The story of phosphorus: global food security and food for thought, Global Environ. Change, 19, 292–305, 2009.

CRIRSCO: International Reporting Template for the public reporting of exploration results, mineral resources and mineral reserves, International Council on Mining and Metals, available at: http://www.crirsco.com/crirsco_template_may2013.pdf (last access: 30 August 2013), 2013.

De Voto, R. H. and Stevens, D. N.: Uraniferous Phosphate Resources and Technology and Economics of Uranium Recovery from Phosphate Resources United States and Free World, Vol. 1. Uraniferous Phosphate Resources, United States and Free World, United States Department of Energy, Publication GJBX-110 (79), Grand Junction, Colorado, USA, 1979.

Dery, P. and Anderson, B.: Peak phosphorus, Energ. Bull., available at: http://www.energybulletin.net/node/33164 (last access: 13 August 2007), 2007.

Dolley, T. P.: The Mineral Industry of Morocco and Western Sahara, USGS Mineral Yearbook 1994, available at: minerals.usgs.gov/minerals/pubs/country/1994/9226094.pdf (last access: 30 August 2013), 1994.

Emigh, G. D.: Uraniferous phosphate resources of the free world exclusive of the United States, in: Uraniferous Phosphate Resources and Technology And Economics of Uranium Recovery From Phosphate Resources United States and Free World, edited by: De Voto, R. H. and Stevens, D. N., United States Department of Energy, Publication GJBX-110 (79), Grand Junction, Colorado, USA, 1979.

Gharbi, A.: Les Phosphates Marocains, Chronique de la Recherche Minière, 531–532, Bureau de Récherches Géologiques et Minières, France, 1998.
Gharbi, A. and Mchichi, M.: La recherche géologique á l'Office Cherifien des Phosphates: Bilan et perspectives, Mines, Géologie & Energie, 55, 9–20, available at: http://archives.cnd.hcp.ma (last access: 30 August 2013), 1996.
Global TraPs: Newsletter 2 and 5 Global transdisciplinary proceses for sustainable phosphorus management (2010–2015), available at: http://www.globaltraps.ch (last access: 30 August 2013), 2011a.
Global TraPs: Newsletter Global transdisciplinary proceses for sustainable phosphorus management (2010–2015), available at: http://www.globaltraps.ch (last access: 30 August 2013), 2011b.
Herring, J. R. and Fantel, R. J.: USGS and USBM, Minerals Availability Field Office, Phosphate Rock Demand Into the Next Century: Impact on World Food Supply, Nonrenewable Resources, vol. 2, no. 3, Oxford University Press, 226–246, Denver, Colorado, USA, 1993.
JORC: Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves, 2012 Edn., Joint Ore Reserves Committee, available at: www.jorc.org/docs/jorccode2012.pdf (last access: 31 August 2013), 2012.
Kelly, T. D. and Matis, G. R.: Historical Statistics for Mineral and Material Commodities in the United States, US Geological Survey Data Series 140, available at :http://minerals.usgs.gov/ds/2005140/ (last access: 30 August 2013), 2013.
Mew, M.: Future phosphate rock production – peak or plateau?, available at: http://www.fertecon-frc.info/page15.htm (last access: 30 August 2013), 2011.
Michalski, B.: The mineral industry of Morocco and Western Sahara, USGS, Washington, USA, 1995.
Moyle, P. R. and Piper, D. Z.: Western phosphate field – depositional and economic deposit models, in: Life Cycle of the Phosphoria Formation: From Deposition to Post-Mining Environment, edited by: Hein, J. R., Elsevier, Amsterdam, 2004.
Notholt, A. J. G., Sheldon, R. P., and Davidson, D. F.: Phosphate Deposits of the World, vol. 2 Phosphate rock resources, Preface, xxiii-xxiv. International Geological Correlation Programme, Project 156, Cambridge University Press, New York, New York, USA, 1989.
OCP: Groupe Office Cherifien des Phosphates, annual statement for the year 1987, available at: http://archives.cnd.hcp.ma (last access: 30 August 2013), 1987.

OCP: The phosphate deposits of Morocco, in: Phosphate Deposits of the World, vol. 2, Phosphate Rock Resources, edited by: Notholt, A. J. G., Sheldon, R. P., and Davidson, D. F., Cambridge University Press, Cambridge, United Kingdom, 301–311, 1989.
OCP: Groupe Office Cherifien des Phosphates, annual statement for the year 1995, available at: http://archives.cnd.hcp.ma (last access: 30 August 2013), 1996.
OCP: Groupe Office Cherifien des Phosphates, annual statement for the year 2000, available at: http://archives.cnd.hcp.ma (last access: 30 August 2013), 2000.
OCP: Groupe Office Cherifien des Phosphates, Rapport Annuel 2007, available at: www.ocpgroup.ma/sites/default/files/alldocs/Rapport%20annuel%202007.pdf (last access: 1 September), 2013.
Prud'homme, M.: Global Phosphate Rock Production Trends from 1961 to 2010, Reasons for the Temporary Set-Back in 1988–1994, IFA, Paris, 2011.
Rosemarin, A.: The Precarious Geopolitics of Phosphorus, Down to Earth, Science and Environment Fortnightly, 27–31, New Delhi, India, 2004.
Rosemarin, A., Schröder, J., Dagerskog, L., Cordell, D., and Smit, B.: Future supply of phosphorus in agriculture and the need to maximise efficiency of use and reuse, IFD proceedings 685, Leek, United Kingdom, 2011.
Sattari, S. Z., Bouwman, A. F., Giller, K. E., and van Ittersum, M. K.: Residual soil phosphorus as the missing piece in the global phosphorus crisis puzzle, Proc. Natl. Acad. Sci. USA, 109, 6348–6353, 2012.
Savage, C. (Ed.): World Survey of Phosphate Deposits, British Sulphur Corporation Ltd., London, England, 1987.
Scholz, R. W. and Wellmer, F.-W.: Approaching a dynamic view on the availability of mineral resources: what we may learn from the case of phosphorus? Global Environ. Change, 23, 11–27, 2012.
Schröder J. J., Cordell, D., Smit, A. L., and Rosemarin, A.: Sustainable Use of Phosphorus, EU tender EN V. B.1/ETU/2009/0025, Plant research International, Business Unit Agrosystems, Wageningen UR, 2010.
Service Géologique du Maroc: Géologie des Gîtes Mineraux Marocains, 2nd Edn., volume 3, Rabat, Ministère de l'énergie et des mines, Direction de la géologie, Rabat, Morocco, 1986.
Sheldon, R. P.: Industrial minerals, with an emphasis on phosphate rock, in: Resources and World Development, edited by: McLaren, D. J. and Skinner, B. J., John Wiley & Son limited, New York, USA, 347–361, 1987.

Sheldon, R. P.: Phosphoria formation, Western USA, in: Phosphate Deposits of the World, Vol. 2 Phosphate rock resources, International Geological Correlation Programme, Project 156, Cambridge University Press, New York, New York, USA, 1989.

Smit, A. L., Bindraban, P. S., Schröder, J. J., Conijn, J. G., and Van der Meer, H. G.: Phosphorus in agriculture: global resources, trends and developments, Report to the Steering Comittee Technology Assessment of the Ministry of Agriculture, Nature and Food Quality, the Netherlands, Plant Research International, B. V., Wageningen, 2009.

Steen, I.: Phosphorus availability in the 21st century: management of a non-renewable resource, phosphorus and potassium, Phosphorus & Potassium, British Sulphur Corporation, 217, 25–31, 1998.

Taib, M.: The mineral industry of Algeria, in: US Geological Survey Minerals Yearbook – 2009 Minerals Yearbook, US Department of the Interior, US Geological Survey, Washington DC, USA, 2009.

Taib, M.: The mineral industry of Jordan, in: US Geological Survey Minerals Yearbook – 2010 Minerals Yearbook, US Department of the Interior, US Geological Survey, Washington DC, USA, 2010.

Taib, M.: The mineral industry of Iraq, in: US Geological Survey Minerals Yearbook – 2010 (Advance release), US Department of the Interior, US Geological Survey, Washington DC, USA, 2012.

Taib, M.: The mineral industry of Iraq, in: US Geological Survey Minerals Yearbook – 2011 (Advance release), US Department of the Interior, US Geological Survey, Washington DC, USA, 2013.

Tirado, R. and Allsopp, M.: Phosphorus in Agriculture, Problems and Solutions, Greenpeace Research Laboratories Technical Report (Review) February, Amsterdam the Netherlands, 2012.

Townsend A. R. and Porder S.: Agricultural legacies, food production and its environmental consequences, Proc. Natl. Acad. Sci., 17 April 2012, 109, 5917–5918, 2012.

UNFC: United Nations Framework Classificaton for Fossil Energy and Mineral Reserves and Resources 2009, ECE energy series No. 39. United Nations, New York and Geneva, 2010.

USGS: Mineral Commodity Summaries, US Geological Survey, Washington DC, 2009.

USGS: Mineral Commodity Summaries, US Geological Survey, Washington DC, 2010.

USGS: Mineral Commodity Summaries, US Geological Survey, Washington DC, 2011.

USGS: Mineral Commodity Summaries, US Geological Survey, Washington DC, 2012.

USGS: Mineral Commodity Summaries, US Geological Survey, Washington DC, 2013.

USGS and USBM: Principles of a Resource/Reserve Classifiacation for Minerals, Geological Survey Circular 831, Alexandria, Virginia, USA, 1980.

USGS and USBM: Sedimentary Phosphate Resource Classification System of the US Bureau of Mines and the US Geological Survey, Geological Survey Circular 882, USA, 1982.

Vaccari, D. A.: Phosphorus, a looming crisis, Sci. Am., USA, 42–47, 2009.

Vaccari, D. A. and Strigul, N.: Extrapolating phosphorus production to estimate resource reserves, Chemosphere, 84, 792–797, 2011.

Van Kauwenbergh, S. J.: Fertilizer Raw Material Resources of Africa, IFDC, Muscle Shoals, Alabama, USA, 2006.

Van Kauwenbergh, S. J.: World Phosphate Rock Reserves and Resources, International Fertilizer Development Center, Muscle Shoals, Alabama, 2010a.

Van Kauwenbergh, S. J.: Presentation of the report World Phosphate Rock Reserves and Resources, delivered at the Center for Strategic and International Studies, available at: http://csis.org/multimedia/video-report-release-role-fertilizer-global-food-security-and-world-phosphate-reserves-an (last access: 31 August 2013), 2010b.

Van Kauwenbergh, S. J.: Phosphate Forecast: How Far Can We Go (How Deep Can We Dig?), Presentation delivered at the Centre for the Development of Fertlizer Technology, Universidade Federal de Uberlandia, October 2011, available at: http://www.cefert.feq.ufu.br/gerenciador/uploads/arquivos/Steven-Van-Kauwenberg-Centre-for-the-Development-of-Fertilizer-Technology.pdf (last access: 31 August 2013), 2012.

Van Vuuren, D. P., Bouwman, A. F., and Beusen, A. H. W.: Phosphorus demand for the 1970–2100 period: a scenario analysis of resource depletion, Global Environ. Change, 20, 428–439, 2010.