



## Recent revisions of phosphate rock reserves and resources: a critique

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**Abstract.** Phosphate rock (PR) is a finite mineral indispensable for fertilizer production, while P (phosphorus) is a major pollutant if applied or discharged in excess, causing widespread eutrophication (Carpenter and Bennet, 2011). High-grade PR is obtained from deposits which took millions of years to form and which are gradually being depleted. Recently, global PR reserves as reported by the US Geological Survey (USGS) have increased from 16 000 Mt PR in 2010 to 65 000 Mt PR in 2011 and further to 67 000 Mt PR in 2014. The majority of this 4-fold increase is based on a 2010 report by the 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. The report also increased global resources from 163 000 Mt PR reported in the literature in 1989 to 290 000 Mt PR. IFDC used a simplified resource terminology which does not use the underlying thresholds for reserves and resources used in the USGS classification. IFDC 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 resource scarcity to the pollution angle of the phosphate problem. In view of the high dependence of food production on PR and the importance of data on PR reserves and resources for scientific analysis and policy making, data on PR deposits should be transparent, comparable, reliable, and credible. 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 meet these requirements, (ii) whether the difference in volume between raw PR ore and upgraded PR concentrate is sufficiently noted in the literature, and (iii) whether the IFDC report presents an accurate picture of PR reserves and resources. We conclude that, while there is a global development toward common criteria in resource reporting, IFDC’s lack of clear thresholds for reserves and resources contravenes this and that the vagueness of its definitions for reserves and resources may allow deposits to be termed reserves or resources which could not be recognized as such under leading mineral resource classifications. The difference between PR ore and PR concentrate is barely noted in the literature, causing pervasive confusion and a significant degree of error in many assessments. Finally, we find that the report most likely presents an inflated picture of global reserves, in particular those of Morocco, where the aggregate resources of three of the four Moroccan/Western Saharan major PR deposits appear to have been simply converted to “reserves”. Following the release of the IFDC report, various analysts have concluded or suggested that the available PR deposits or even the currently reported resources would likely last several thousands of years at current consumption rates. However, the data on which these statements were based do not appear to warrant such a conclusion. Further research is required as to the quantity of PR deposits and their viability for future extraction, using uniform and transparent classification terminology.

## 1 Introduction

Phosphorus (P) is a nutrient essential to the growth of all plants and animals; agriculture depends on it to maintain food production at required levels. Phosphate rock (PR), the major 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 biofuels, PR consumption is expected to increase significantly in this century (Van Vuuren et al. 2010; Rosemarin et al. 2011; Koppelaar and Weikard, 2013; USGS, 2013).

While there is broad agreement that PR is a finite resource essential for human survival, the longevity of minable PR deposits has recently been the subject of intense debate. Numerous publications have modeled the depletion of PR reserves to occur by the end of the 21st century (Steen, 1998; Rosemarin, 2004; Vaccari, 2009), or peak phosphorus to occur within a few decades to some 60 years from now (Déry and Andersson, 2007; Cordell et al., 2009, 2011). The methodology behind the peak phosphorus hypothesis or peak theory generally has been disputed in a number of scientific papers (e.g., Vaccari and Strigul, 2011; Mew, 2011; Rustad, 2012; Scholz and Wellmer, 2013a).

One point of criticism to the peak phosphorus hypothesis is that the modeling was based essentially on PR estimates sourced from the mineral commodity summaries (MCS) issued by the US Geological Survey (USGS). USGS uses a resource classification system which it devised in the 1970s together with the former US Bureau of Mines (USBM). The USGS classification reports currently demonstrated economically viable resources as reserves and a larger bracket of demonstrated resources as the reserve base. The aggregate of the reserve base and uneconomic deposits which have a reasonable potential of becoming economic in the future are reported as resources. Deposits with no reasonable prospect of economic viability in the foreseeable future are listed as “other occurrences” in the USGS classification. Importantly, the reserve base and the reserves include only those deposits which are demonstrated (measured and indicated), i.e., which have been established with sufficient geological assurance (USGS, 2014). For a schematic overview of the main elements of the USGS classification, including reserves and the reserve base, reference is made to Figs. S1 and S2 in the Supplement.

In its Mineral Commodity Summaries, USGS only reported reserves and a reserve base, and it discontinued reporting the latter in 2009. However, reserves are dynamic, in the sense that ongoing exploration, economic developments, and technical advances may promote occurrences to resources and resources to reserves. It has been long recognized in the literature that depletion of the currently identified reserves and reserve base by no means amounts to a depletion of the

PR available for extraction (for instance, USGS and USBM, 1982) and that any estimate of the longevity of PR deposits necessarily includes resources, occurrences, and unknown geocapacity (Cathcart et al. 1984, Van Vuuren et al., 2010). For the same reason, it has recently been pointed out that a reserve / consumption (R / C) ratio based on a static reserve number is inherently unsuited for estimating the longevity of usable PR deposits (Scholz and Wellmer, 2013a).

While the peak phosphorus hypothesis remains hotly debated, the finiteness of PR is generally recognized in the literature (Van Kauwenbergh, 2010a; Van Vuuren et al., 2010; UNEP, 2011; EC, 2013; EC Science Communication Unit, 2013; and many others). It is also generally noted that reliable data regarding extractable PR deposits are lacking, and thus it is currently not possible to reliably model long-term PR availability (Van Vuuren et al., 2010; EC, 2013; EC Science Communication Unit, 2013). Van Vuuren et al. (2010) conducted a scenario analysis based on the parameters of the four Millennium Ecosystem Assessment Scenarios (Carpenter and Pingali, 2005) and a range of low, medium, and high estimates of available PR reserves and resources. These authors found that, while there are no indications of short-term depletion, depletion could become increasingly important in the mid- to longer term depending on the quantity of PR that would ultimately be available for mining. Van Vuuren et al. also pointed to geopolitical risks associated with the high concentration of PR resources in a limited number of countries, a point previously made by Cordell et al. (2009). While there appears to be no immediate threat of PR depletion, geopolitical risks and considerations of intergenerational equity render it important to have reliable assessments on PR deposits available for extraction.

Scientific modeling and policy making require reliable data (Scholz and Wellmer, 2013a). Reserve data are important, as they are still often used as a reference point in the literature on PR availability, and also by those authors who stress their dynamic nature. For instance, it is argued in the literature that the ratio between reserves and the annual consumption/production of PR concentrate (R / C ratio) can be used as an “early warning indicator” to assess future availability of a certain commodity and that a high R / C ratio justifies adopting a “long time horizon” (Scholz and Wellmer, 2013a). In addition, when reserves are increasing in a given period, this is sometimes interpreted as an indicator for the potential for further reserve growth (ibid.). However, if reserve data are to be used for such a purpose, one should have a reasonable level of certainty that the increase in reserves is based on the same standards as the reserves which had been reported prior to the increase: to the extent that resources are simply restated as reserves, such an increase in reserves has little value for scientific analysis. Moreover, resources are generally defined as the aggregate of economic, sub-economic and uneconomic deposits, i.e., including the

reserves. Reserves, by their nature, only constitute a minor part of the resources (Van Kauwenbergh, 2010a). However, if the majority of the resources are already included in the reserves, a high resource number tells little about the future potential of these resources, in addition to the reserves. Finally, it must be clear that consumption data can be validly compared with the reserves data. In the case of PR, it is often unclear whether reserves are reported as ore or upgraded concentrate (Van Kauwenbergh, 2010a), while PR production and consumption are generally reported in terms of upgraded concentrate (USGS, 2014). As will be discussed in Sect. 4, the difference may be substantial and, if ignored, may result in an unduly optimistic static R / C ratio.

To make any estimates of the 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). In addition to data on reserves, this requires reliable data of PR resources and occurrences and the potential for new discovery. Also for this reason, data on PR deposits should be transparent, comparable, relevant, and reliable.

Following the recent debate on peak phosphorus, global PR reserves as reported by USGS have increased 4-fold in 1 year. This increase was caused predominantly by a restatement of the reserves in one single country, Morocco. This paper reviews whether the current reserve data provide a solid basis for scientific analysis and policy making.

In 2010, USGS reported PR reserves of 16 000 Mt (USGS, 2010). 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, the International Fertilizer Development Center (IFDC) issued a report in which it suggested that the reserve and resource figures provided by USGS were obsolete, its classification overly detailed in view of limited available information on PR deposits, and its definitions poorly defined. The report argued that the reserves and resources reported by USGS should be reassessed (Van Kauwenbergh, 2010a). In the report, IFDC used significantly simplified definitions of reserves and resources. The IFDC report increased global reserves to 60 000 Mt PR, the vast majority of which (51 000 Mt PR) were located in Morocco and Western Sahara, which is occupied by 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 an extent that it can be sold as a marketable product for the production of phosphoric 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 were located in Morocco (Van Kauwenbergh, 2010a, p. 36 and 42). The report states that aggregate ore resources for Morocco could be even as high as 340 000 Mt PR

and world resources as high as 460 000 Mt if unexplored extensions of the Moroccan ore fields were to be taken into consideration. The report states that it embodies only the first phase of a more extensive investigation as to global PR deposits, and that a second, more conclusive research effort is envisioned to explore future PR reserves and resources.

The IFDC report has re-shaped the PR depletion debate. Shortly afterwards, USGS increased Moroccan PR reserves from 5700 Mt PR to 50 000 Mt PR, indicating that this increase was based on the IFDC report and on information from the Moroccan producer (USGS, 2011). Global PR reserves were increased from 16 000 Mt PR to 65 000 Mt PR (USGS, 2011) and are currently stated at 67 000 Mt PR (USGS, 2014). Resources, which had not been reported by USGS in many years, were stated at 300 000 Mt PR (USGS, 2012), fairly consistent with the resource number in the IFDC report.

Following its report, IFDC took co-leadership in the Global TraPS project (<http://www.globaltraps.ch>), which had been initiated shortly before by Prof. R. Scholz of ETH Zurich. This project aims to bring together participants from practice and academia in order to foster knowledge, essentially to deal with the challenge of sustainable phosphorus management. As of its inception, the project has been co-led by IFDC, represented by its CEO Dr. A. Roy as a “practice” representative, while ETH Zurich, represented by Prof. Scholz, represents academia. Along with scientists and industry participants, the project has attracted high-profile organizations such as USGS, UNEP, FAO, and Greenpeace as participants (Scholz et al., 2013). 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 (Global TraPs, 2011). Similar statements were recently made in the project’s response to the EC Consultative Communication on the Sustainable Use of Phosphorus (Scholz and Roy, 2013; see Sects. 4.2 and 5.3 of this paper).

Thus far, there appears to have been no vetting of the IFDC report and the conclusions that have been drawn from its findings in the literature. This paper reviews the IFDC report, its methodologies, the recent revisions of global PR reserves, and some of the conclusions that were drawn from these in the literature. First, we analyze how IFDC’s simplified definitions compare to industry best practice and leading resource classifications, and whether its classification terminology offers sufficient safeguards for generating reliable assessments on PR reserves. Second, we review whether it is common to report reserves as concentrate; to report reserves, back-calculated to ore, as part of the resources; and whether the consequences are sufficiently understood in the literature. The 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 in reserves and resources in the IFDC report can be almost entirely attributed to Morocco and the increase in Moroccan PR reserves accounts for some 88 % of the increase in global reserves in USGS' mineral commodity summaries (USGS, 2010, 2014), we focused on that country. A number of recent restatements for other countries are discussed in Sect. 4.2, in the context of the second research question.

## 2 Background

Approximately 82 % of total mined PR is used for fertilizers and another 5 % for livestock feed, a small percentage for feed additives and the remainder for detergents and other industrial purposes (Schröder et al., 2010). The bulk of the world's PR suitable for mining is found in large sedimentary rock deposits of marine origin. Large high-grade deposits are located only in a limited number of locations 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 and 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 sulfuric 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 35 % 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). According to a survey by the International Fertilizer Association, mining extraction efficiencies would currently average approximately 82 % on a global scale (Watson et al., 2014, with reference to Prud'homme, 2010). Significant reductions in volume and losses of  $P_2O_5$  also occur in the upgrading process (beneficiation).

Given the economic function of resource classifications, reserves and resources are dynamic. Sub-resource deposits, termed “other 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 techniques evolve (USGS and USBM, 1980; Cathcart et al., 1984; Her-ring and Fantel, 1993). Large “occurrences”, currently not included in the resources, are located offshore or on seamounts (USGS, 2014; Smil, 2000; Van Kauwenbergh, 2010a), or are buried deep as a result of tectonic occurrences following their deposition, such as the majority of the deposits located in the Western Phosphate Field in the USA, probably the largest PR

formation in the world (Bauer and Dunning, 1979, p. 133, 135).

The IFDC report notes that reserves are established based on the costs of production and the current price level, at the expense of significant costs and experienced manpower and that mining companies therefore do not spend money documenting reserves that will not be exploited for decades (Van Kauwenbergh, 2010a; see also Scholz and Wellmer, 2013a). This appears plausible as reserves, most notably JORC and USGS measured reserves, require detailed exploration based on a large number of boreholes per section as well as an economic analysis (Van Kauwenbergh, 2010a; USGS and USBM, 1982). However, companies may have incentives to perform prospective exploration to identify the best places for mining (see, for instance, Emigh, 1972; JORC, 2012). Governments, too, have an interest in assessing mineral resources for long-term planning purposes (see Sect. 3). In the US, there is a long history of government-driven exploration for PR and other commodities. For instance, the Western Phosphate Field was first explored by the Geological and Geographical Survey of the Territories between 1871 and 1877 and was mapped further by USGS in four field programs between 1909 and 2002 (Bauer and Dunning, 1979 p. 133; Scholz and Wellmer, 2013a). While detailed knowledge on PR resources and sub-resource deposits is not reported comprehensively in an easily accessible data source, it appears that a fairly extensive knowledge exists of such deposits in a large number of countries across the globe (see, for instance, Notholt et al., 1989).

A recurring issue in the literature is that a very substantial *geocapacity* of undiscovered PR deposits may exist which may extend reserves and resources well beyond currently known reserves, resources, and other occurrences (Sheldon, 1987, and, more recently, Scholz and Wellmer, 2013a). However, a distinction should be made between known or hypothetical PR resources or occurrences based on assumed extensions of known deposits, and truly speculative resources, or *geocapacity*. The USGS classification defines hypothetical resources as undiscovered resources similar to known mineral bodies which may reasonably be expected to exist in the same producing district under analogous geological conditions, while speculative resources are defined as deposits that may exist under favorable geological settings, but where no discoveries have yet been made (USGS and USBM, 1980). To allow for an analysis of the discovery rate of PR deposits, it appears preferable to classify known or hypothetical sub-resource PR occurrences as such, rather than to view them as “unknown *geocapacity*”.

Meanwhile, the potential for truly new discoveries of large-scale PR deposits appears somewhat uncertain. In view of their typically high uranium content, aerial radiometric detection of sedimentary PR is possible and can be applied in the exploration for PR deposits when circumstances allow (Asfahani et al., 2005). In addition, PR has often been found when exploring for other commodities. Van Kauwen-

bergh (2006, p. 46) argues that while there may be some potential to discover new PR deposits, oil exploration programs have probed most of the coastal sedimentary basins of the world during the past 20 to 30 years, 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 PR deposits is unlikely.

The IFDC report concludes, based on its findings and a static consumption rate of 160 Mt PR per year, that “phosphate rock reserves to produce fertilizer will be available for 300–400 years” (Van Kauwenbergh, 2010a, p. 43). However, like reserves, the consumption rate, too, is a dynamic figure which may rise as demand for agricultural commodities increases. Conversely, demand may be mitigated by increased use efficiency, recycling of phosphates in manure and excreta, changing consumption patterns due to increased awareness of PR scarcity, environmental considerations, etc. (Cordell et al., 2009; Schröder et al., 2010).

In recent years, PR production has been marked by a significant increase. By 2012, world production had risen to 217 Mt PR concentrate (Kelly and Matis, 2014) and global production capacity is expected to increase to 260 Mt PR concentrate per annum by 2017 in order to cater for further demand growth which is anticipated for the near future (USGS, 2014). It is anticipated that PR consumption will be influenced further by the rise of global population to some 9.6 billion in 2050 and some 10.9 billion people in 2100 (UN, 2013; medium scenario), as well as increasing demand for biofuels and meat and dairy products (Schröder et al., 2010; Van Vuuren et al. 2010; Koppelaar and Weikard, 2013).

Rosemarin et al. (2011) performed an analysis of depletion rates under various assumptions to determine what the R/C ratio of IFDC’s reserves could be if certain demand growth factors were to be factored into the equation. The authors calculate<sup>1</sup> that a reserve of 65 000 Mt PR concentrate could be depleted within 261 years, starting 2011, if the anticipated population growth is taken into consideration (255 Mt PR consumption by 2100), or 215 years if Africa would develop its agriculture and experience a green revo-

lution. 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 calculate that if biofuels were to be used for 10 % of global energy requirement, and unless the P in the resulting ashes and press cakes were to be fully recycled, the reserves reported by IFDC could be depleted in 137 years, starting 2011, at which point global PR consumption would reach 475 Mt PR annually. As noted in the introduction, given the dynamic nature of reserves and resources, depletion of the reserves estimated in the IFDC report would not signify that there would be no phosphate rock left to mine. The potentially higher consumption rates do, however, point to another limitation to the concept of an R/C ratio which may make it less suitable as an early warning indicator.

The PR consumption rate may be mitigated by increased use efficiency, recycling, and other areas of adaptation by society, as may be factored into a scenario analysis. Koppelaar and Weikard (2013) performed a scenario analysis assuming a demand rise to approximately 250 Mt PR by the end of the 21st century. The authors also found that, if reserves are fixed at the current IFDC/USGS estimates, production would peak around 2050, after which it would decline. The authors found that “potential” reserves, based on various geologic assessments, could shift the timeline into the 22nd century, or further if recycling and use efficiency measures were to be broadly implemented. However, the authors also cautioned that recycling measures are often not cost-efficient as PR-based supplies of P are still cheaper, and that this would remain the case even if PR prices were to triple relative to their current level. This renders the implementation of such measures dependent on public awareness and deliberate policy interventions.

Van Vuuren et al. (2010) forecasted increases in PR consumption adopting the story line of each of the four UN Millennium Ecosystem Assessment scenarios, using a low, medium, and high estimate of the PR resource base. Under the Adapting Mosaic (AM) TechnoGarden (TG) scenarios, which assume a proactive environmental management, Van Vuuren et al. estimate aggregate P consumption to be roughly around 65 and 85 Mt P<sub>2</sub>O<sub>5</sub> by the end of 2100, or 220 and 280 Mt PR concentrate at 30 % P<sub>2</sub>O<sub>5</sub>. For the Order from Strength (OS) and Global Orchestration (GO) scenarios, which assume reactive environmental management, the authors estimated annual consumption by the end of the century to be roughly 105 Mt P<sub>2</sub>O<sub>5</sub> under the OS scenario and roughly 115 Mt P<sub>2</sub>O<sub>5</sub> under the 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 biofuels differs from the

<sup>1</sup>In the original paper by Rosemarin et al. (2011), the depletion numbers for the three scenarios were set at 172, 126, and 48 years, respectively, and we adopted these numbers in the discussion version of our paper. During peer review, the reviewers noted that this calculation appeared flawed as the static consumption at the top consumption levels in the scenarios would yield longer depletion periods. We agreed and reviewed the underlying calculations with the authors. It appeared that a flaw had occurred when incorporating the underlying calculations in the paper. The depletion numbers in the paper were in fact the numbers running as of the year 2100, taking into consideration the consumption over the 21st century. The authors acknowledged that each of the three estimates needs to be increased by 89 years, being the time between the publication of the paper and the year 2100 (Rosemarin, 2014). Our paper contains the corrected numbers.

estimate in Rosemarin et al. (2011) and merits further attention, also in view of the potential for recycling<sup>2</sup>

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. conclude that this circumstance implies that global P application will only need to rise slightly, if at all, assuming that full efficiency can be achieved. Others argue that such optimism needs to be tempered in view of a range of socioeconomic and biophysical factors and that poor nutrient use efficiency remains common (Townsend and Porder, 2012).

Given the above, the consumption rate of PR currently is 26 % above the level presented in the IFDC report. It could potentially evolve to be significantly higher in the near future, unless society succeeds in achieving greater efficiency in managing the P cycle and reducing dependency on mineral phosphate rock. This uncertainty adds to the importance, explained in the introduction, of having 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” as 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 become economic in the foreseeable future, or will be reluctant to share information regarding reserves for commercial or regulatory reasons. IFDC proposes 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

<sup>2</sup>Scholz and Wellmer (2013b) argue that there is a strong recycling loop in biofuels. This may be true for the P in press cakes of oil crops that will be used as animal feed which, once digested and excreted, could be returned to the land in the form of manure P. Recycling, however, is not common practice for the P residues that remain after the extraction of carbohydrates from, for example, sugarcane or the combustion of lignin-rich crops. The reason for this is that P recovery and subsequent recycling is currently not always cost-effective (Hein and Leemans, 2012; Fealy and Schröder, 2008).

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 implications.

#### 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, Russia, China, India, etc.

The American USGS classification, which USGS drew up together with USBM, is a government type classification and is aimed at enabling both commercial and long-term public planning (USGS and USBM, 1980). While the classification is generic in the sense that it applies to all mineral commodities, specific rules were drafted for the national reporting of PR deposits (USGS and USBM, 1982). As noted by the draftsmen of these guidelines, large differences occurred in PR reporting at the time, which were sometimes interpreted as differences of opinion between “resource pessimists” and “resource optimists”. According to USGS, however, these differences resulted mainly from definitional confusion as to what qualifies a resource or a reserve. For instance, Bauer and Dunning (1979) reported large resources of phosphate rock for the Western Phosphate Field in the USA which were not considered a resource in other publications in view of the depth at which these deposits were located (Sheldon, 1989, p. 59; Moyle and Piper, 2004, p. 575 and 592). Emigh (1972) reported vast quantities of PR in what he called “reserves for the future”, but hardly any of these deposits were reported even as resources in a later report by the same author on global PR resources outside the USA (Emigh, 1979). A main goal of the PR classification was to create uniform language based on exploration practice in order to permit “real” differences among estimates to be identified and analyzed (USGS and USBM, 1982; Cathcart et al., 1984).

The USGS classification, based on McKelvey’s (1972) resource box, 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 fluctuate constantly due to economic and technical developments and to provide for a more stable

bracket 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 are for other reasons not considered potentially economic for the foreseeable future (USGS and USBM, 1982). A schematic overview of the main elements of the classification is presented in Figs. S1 and S2.

To enable the thresholds between reserves and resources to be accurately stated, the classification introduced a number of sub-definitions and sub-sub-definitions to factor the degree of the geologic certainty of existence of a deposit such as demonstrated (measured and/or indicated) and identified (demonstrated and/or inferred). Under the USGS classification, the term “reserves” applies only to those deposits which are “demonstrated”. This includes deposits which are either measured or indicated, which requires that the degree of geological assurance must be high enough to assume continuity between points of observation. These requirements will be discussed in more detail in Sect. 5.3. In addition, other geologic requirements apply in terms of grade, depth, thickness of the ore seam, overburden, etc., and economic requirements apply (reference is made to Fig. 1). Other than is sometimes suggested in the literature (Van Kauwenbergh, 2010a, p. 16), deposits which are “inferred” or “marginally economic” are no part of the reserves under the USGS classification (see USGS and USBM, 1980; USGS, 2014)<sup>3</sup>. The USGS classification also identifies a class of “undiscovered resources”, which may be either hypothetical (i.e., geologic likelihood based on assumed extensions of demonstrated or indicated resources) or speculative (favorable geologic settings but no discoveries yet made; see Sect. 2).

The strength of government classifications is that they not only focus on ore which is currently economic but also allow for analysis of deposits that may become economic, now or in the (far) future, if technical and economic developments so permit (Camisani-Calzolari, 2004).

It should be noted that the USGS classification, while formally the basis for USGS estimates (USGS, 2014), is not always strictly followed when reporting reserves in USGS’ Mineral Commodity Summaries (MCS). This is because, when gathering the information on reserve estimates, USGS depends on information provided by foreign governments or, alternatively, academic articles, company reports, etc. Different standards may have been used to generate these data

<sup>3</sup>Under the USGS classification, reserves are “the part of the reserve base which could be economically extracted or produced at the time of determination”. The reserve base is defined as “the in-place demonstrated (measured plus indicated) resource from which reserves are estimated”. Deposits with a lesser degree of geological assurance, such as “inferred reserves” form no part of the reserve base and, by consequence, are no part of the reserves. See also Fig. S1.

(USGS, 2014, Appendix A). For instance, for Australian reserves, USGS uses the Australian government’s Economic Demonstrated Resources (EDR), which aggregate a number of JORC demonstrated economic categories and are methodologically comparable to USGS’ demonstrated reserves (Lambert et al., 2012; see also Figs. S3 and S4).

### 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 investment decisions. The JORC code, devised by the Australian Joint Ore Reporting Committee, 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, 2004). 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. As mining corporations and investors typically are only interested in deposits for which there is a reasonable perspective of economic exploitation, JORC-style codes are simplified to seven definitions, based on the main concepts of mineral reserves and resources and further fine-tuned by the sub-definitions measured, indicated, and inferred. For more detail, see Fig. S3. For economic purposes, the most relevant categories are JORC proved and probable reserves and JORC measured and indicated resources. 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). Also, JORC-style codes require the presence of modifying factors relating to social, political, and legal requirements, including the required mining permits before a deposit may be termed a reserve. These requirements do not equally apply under the USGS classification (Lambert et al., 2012). Therefore, the definition of reserve under a JORC-style code will be stricter than reserves under the USGS classification, and reserves reported under JORC style classifications are not necessarily comparable to reserves reported under the USGS classification. Reference is made to Fig. S4, which maps JORC proved reserves and JORC probable reserves to the USGS classification. Conversely, JORC style classifications do not report sub-economic deposits comprehensively and, consequently, are blind to the long-term perspective (Camisani-Calzolari, 2004; UNFC, 2010). JORC style classification rules are therefore less relevant for the job of creating long-

term inventories of PR deposits than classifications with an inventory purpose.

### 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. A key goal of the UNFC-2009 is to provide a tool to facilitate global communications, using a numerical and language-independent coding scheme (UNFC, 2010). The initial version of the USGS classification has been viewed as essentially a government type classification as its many resource categories made it ideally suited for inventory purposes (Camisani-Calzolari, 2004). The classification 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 mentioned in Sect. 3.2 as well as the leading Petroleum Resource Management System devised by the Society of Petroleum Engineers (SPE) for liquid fuels. CRIRCSO and SPE were consulted extensively in this process (UNFC, 2010). The SPE code, being a code for liquid mineral resources, is not discussed in this paper. The resulting current version of the UNFC 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, 2013). The UNFC is designed to meet both the needs for financial reporting and to simultaneously provide for sufficient resource classes and the necessary granulation required for building long-term inventories for public planning purposes.

UNFC recognizes four broad categories: (i) commercial projects; (ii) potentially commercial and non-commercial projects; (iii) exploration projects; and (vi) additional quantities in place, comparable to the “other occurrences” in the USGS classification. This is more or less consistent with the USGS system even though, unlike the USGS classification, 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, 40 classes are recognized, each uniquely defined by its three-number code, even though only 14 classes are currently in use. As the code is open-ended, additional layers of detail

may be added. A schematic overview of the UNFC classification is included in Fig. S5.

The detailed granulation in the UNFC classification is particularly suited for inventory purposes as it allows for coverage of all types of mineral occurrences at their specific stages of feasibility and geologic certainty of existence, regardless of their current economic potential (Camisani-Calzolari, 2004). Even though the UNFC is not mandatory and it is up to each country to decide which categories are applied, the code appears to be a valuable vehicle through which the major mining companies and governments may report what is available on the short, medium, and long term with greater precision (Lambert et al., 2012).

Even though PR reserves and resources are currently not reported comprehensively on a global scale, the above review does point to a significant global effort in creating common language in mineral resource classification in order to increase comparability over the various mineral resource assessments. 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 significant granulation in the area of their focus. Classifications with an inventory purpose such as UNFC are more suitable for reporting categories which provide medium- and long-term views of what is likely to be available for mining.

As noted in the introduction, USGS’ Mineral Commodity Summaries, the main data source on global PR inventories, only report reserves on a per country basis, along with an aggregate number for resources. To allow analysis of the potential of the world’s PR deposits, global PR reporting should be extended to the other resource categories as well.

### 3.4 Evaluation of IFDC’s terminology proposals

With respect to reserves, the various classifications reviewed in Sects. 3.1–3.3 contain specific requirements (thresholds) which have to be met. Under the USGS classification, only *measured* or *indicated* deposits may form part of the reserves (see Fig. S1). Whether these sub-definitions apply is determined on the basis of sampling and the distance between the drill holes (USGS and USBM, 1982; USGS, 2014, Appendix A; Scholz and Wellmer, 2013a). Other requirements relate to the thickness of the ore bed, the quantity of overburden, the ore grade, and the impurity level. The IFDC definition of reserves, in contrast, is simply phosphate rock which can be economically produced at today’s costs and prices, reported as a marketable product. Unlike the USGS classification, IFDC poses no requirements in view of geologic assurance or economic viability. This renders IFDC’s definitions inherently vague. The problem with this is that this may lead to arbitrary boundaries between reserves and resources, which in turn may increase the scope for widely diverging estimates based not on differences as to the quantity of PR available, but merely on the definitions used, a situ-



ation which the USGS classification aimed to address (see Sect. 3.1). In consequence, insufficiently delineated definitions may render data on mineral resources less comparable and less suited as a basis for scientific analysis.

For resources, IFDC uses the definition of “phosphate rock of any grade [...] that may be produced at some time in the future”. This definition, likewise, is so broad that it may cover any PR deposit, depending on the author’s view of what the – distant(?) – future may bring. Again, clear and commonly accepted terminology appears to be necessary to classify each deposit according to its true potential.

For building a global long-term inventory of available PR deposits, a detailed classification appears required which enables “real” differences to be accurately stated (USGS and USBM, 1982) and helps to prevent widely diverging resource estimates grounded in unclear terminology. To achieve global consistency, such resource terminology should preferably be compatible with UNFC. Discarding granularity altogether appears undesirable as this impairs comparability and transparency and, ultimately, jeopardizes the reliability of mineral resources assessments.

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

The IFDC report presents reserves as upgraded concentrate, and resources as ore in situ, including reserves back-calculated to ore in situ. We review whether reporting reserves as concentrate is common and whether the difference between ore and concentrate is 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” refers to ore that has been mined and upgraded so that it can be sold as a marketable product, which typically requires 30 %  $P_2O_5$  (USGS, 2013) and suitable impurity levels. Losses occur at both occasions. The mining losses have been discussed briefly in Sect. 2 of this paper. Losses of  $P_2O_5$  in the beneficiation (upgrading) process may also be significant.

The IFDC report states, based on Fantel et al. (1988), that typical losses of  $P_2O_5$  generally run from 30 to 50 % in beneficiation and that lower grade and higher impurity levels typically increase the losses of  $P_2O_5$  in beneficiation (Van Kauwenbergh, 2010a, p. 42; VRFC, 2012, p. 12). The IFDC report states that phosphate rock beneficiation technology has not changed significantly in the past 25 years and that recovery in beneficiation probably has not improved substantially (Van Kauwenbergh 2010a, p. 7). On the other hand, Prud’homme (2010) reports an average recovery in beneficiation of 84 % in a paper presented at an industry event (see Scholz et al., 2014), while Vaccari et al. (2014.) indicate that

overall recovery in beneficiation has improved over the years. The large differences in these recent assessments suggest that overall beneficiation rates and the potential for improvements are important areas for further research.

It should be noted that the  $P_2O_5$  losses in beneficiation are not equal to the reduction in volume associated with the beneficiation from extracted ore to concentrate, because the latter reduction is caused in part by a removal of non- $P_2O_5$  waste material. The substantial total reduction in volume due to the beneficiation process is apparent in the IFDC report. For instance, IFDC applied an in situ ore to concentrate reduction of 63 % for the relatively high-grade Moroccan ore, assuming only 5 % mining losses and adopting ore-to-concentrate ratios ranging from 1.7 to 3.3 (Van Kauwenbergh, 2010a, p. 36). For South Africa, which mines an igneous ore which is inherently low in  $P_2O_5$ , the IFDC report reduced the volume of in situ ore reserves by 86 %, assuming 5 % mining losses and using an ore-to-concentrate ratio of 6.7 (Van Kauwenbergh, 2010a, p. 38). Different ore-to-concentrate ratios may apply to different mining locations and individual ore seams, depending on the characteristics of the ore in question and the techniques which are employed. These examples stress the importance of knowing whether a reserve number reflects ore or concentrate.

Even though the practice exists in certain industries, reporting PR as concentrate by no means appears to be the common standard. The USGS classification guidelines for PR (USGS and USBM, 1982) do not indicate that reserves should be denoted as concentrate. The JORC and CRIRSCO codes use the term “ore reserves” and prescribe, in the context of coal, 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. Also, the basis of the predicted yield in beneficiation should be stated (JORC, 2012; CRIRSCO, 2013). The UNFC code, which is fully compatible with the JORC and CRIRSCO codes, likewise reports economic minerals in terms of extractable material (UNFC, 2010). While reporting in concentrate may be useful to understand the potential of a deposit, and may enable a comparison between reserves and consumption (R / C ratio), it also may be a source of confusion.

##### 4.2 Does USGS report reserves as ore or concentrate?

An intriguing question is whether data provided by USGS are comparable with IFDC’s numbers, as has been routinely assumed in the literature (e.g., Scholz and Wellmer, 2013b). According to the IFDC report, USGS has been reporting US reserves in terms of concentrate since at least the 1980s. However, a review of available data suggests that USGS Mineral Commodity Summaries list reserves in terms of ore rather than concentrate for at least a number of other countries. South Africa, as stated, 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 re-

serves of 1624 Mt PR (Van Kauwenbergh, 2010a, 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 17-fold, from 125 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 with similar magnitude, from 100 to 1800 Mt of rock (USGS, 2010, 2011). This reserve number is roughly consistent with the ore resource of about 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.

For Australia, USGS reports the government’s Economic Demonstrated Resources (EDR) as reserves, which aggregates JORC proved and probable reserves with JORC measured and indicated resources (USGS, 2014, Appendix A). As discussed, reserves are reported as extractable ore under JORC rules. While the Australian government does not specify this, the fact that the EDR consists of JORC reserves and demonstrated resources aggregated suggests that the EDR numbers for PR represent ore as well.

Another noteworthy example concerns the recent fluctuations of the Iraqi reserves, which were first entered into USGS’ Mineral Commodity Summaries in 2012, where they were stated at 5800 Mt PR, placing Iraq ahead of China and the USA combined (USGS, 2012). These deposits were presented as a “discovery” by USGS (Taib, 2012), ignoring that the majority of these deposits had been reported as ore resources decades earlier (Al Bassam, 1989). In 2013/2014 the Iraqi reserves were downgraded again by 93 % to a mere 430 Mt PR (USGS, 2013, 2014), which, again, is the ore reserve, grading 21.52 %  $P_2O_5$ , of the only operating mine in Iraq (Taib, 2013).

In the discussion version of this paper, we noted that this information calls into question whether the USGS numbers are comparable with IFDC’s reserves, reported as concentrate. In its 2014 Mineral Resource Summary, USGS clarified that “some world reserves” of PR were reported only in terms of ore and grade and not as marketable product or concentrate (USGS, 2014). USGS, however, did not specify which countries reported PR reserves as ore and which countries reported PR reserves as concentrate. This difference should be kept in mind when analyzing data reported in USGS’ MCS, particularly if these data are to be used for the calculation of an R / C ratio. For instance, Scholz and Roy (2013) recently indicated, in a response to EC Consultative Communication

on Sustainable Phosphorus of 2013 (EC, 2013), that the aggregate static R / C ratio for all other countries than Morocco, based on USGS (2013) numbers and a static consumption rate of 200 Mt PR concentrate per year, is 85 years. However, if the reserves for a number of the main non-Moroccan reserve holding countries are currently reported as ore, not concentrate, the R / C ratio could be significantly lower.

#### 4.3 Confusion of PR estimates and their static lifetime in the literature

Examination of PR literature reveals that the difference between in situ ore and concentrate has remained largely unnoticed in the scientific arena. The result is a significant degree of confusion in numerous scientific publications regarding the R / C ratios of PR reserves and resources. 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 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 ended up in Greenpeace’s special report on phosphorus (Tirado and Alsopp, 2012), influencing public perception on long-term PR availability.

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 years, where, based on the consumption assumptions used (a static consumption rate of 250 Mt PR concentrate annually), about three to four centuries would probably have been appropriate. Similarly, Van Kauwenbergh et al. (2013) argue, based on USGS’ current estimate of 300 000 Mt PR resources and a static production rate of 210 Mt PR, that “the world has over 1400 years of resources”. However, the authors ignore the difference in tonnage between in situ ore resources and mined and beneficiated concentrate, which was carefully considered in the IFDC report.

Scholz and Wellmer (2013a) extrapolate a longevity of up to 3000 years for deposits in the Western Phosphate Field (WPF) in the US, based on a statement by Moyle and Piper that, in addition to 7600 Mt strippable resources and 17 000 Mt underground resources up to 305 m, there is 507 000 Mt of sub-resource-grade phosphatic material that underlies the WPF at depth greater than 305 m (Scholz and Wellmer 2013a, p. 6; Moyle and Piper, 2004, p. 575). The authors divide the aggregate in situ ore number by 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 years may be too optimistic, a lifetime of 1000 years seems reasonable. The authors also state, based on assumptions explained elsewhere

in their publication (most notably a high price flexibility for PR), that this can be done “at most likely manageable costs”. However, even ignoring the static consumption level, the extrapolation raises serious questions. According to Bauer and Dunning (1979, p. 162, 164, 200), 24 % of the WPF deposits are located at depths up to 5000 ft (1500 m) and 70 % between 5000 ft up to even 30 000 ft (9000 m) in some of the major basins of the area. These underground and deep underground deposits are not considered a resource in the literature (Sheldon, 1989, p. 59; Cathcart, 1991; 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 65 % losses for the deep underground deposits which form the majority of the field and 50 % for the intermediate deposits. Due to tectonic disturbances of the ore seams, 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. Given that tectonic deformation occurred generally in the WPF (Bauer and Dunning, 1979 p. 135), the De Voto assumptions may be rather optimistic. Whether the deepest ore seams can ever be mined appears uncertain. The world’s deepest mine, a gold mine in South Africa, extends to some 4000 m (Mining Technology, 2013). We have not attempted to verify whether the geothermal incline or other factors would theoretically allow mining to such depths in the WPF.

These are but a few examples from a rapidly expanding body of literature regarding PR deposits. Again, it is desirable that expected or potential losses in mining and beneficiation are accounted for and explained, and that both the opportunities and limitations of the deposits under scrutiny are 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, 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 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 has occupied since 1975. The Ouled Abdoun and Gantour fields have been explored in detail around the established mining centers decades ago (Savage, 1987), but have extensions for which exact data is still lacking. The explored portion of these fields was expanding in the last decades of the 20th century, resulting in a gradual increase in 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 Earth’s crust (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 Project 156, a multiple-year research program under the aegis of the International Union of Geological Sciences and UNESCO, the Moroccan producer OCP reported exactly the same numbers. However, this time these numbers were reported as resources. Also, OCP indicated that, due to expanding exploration, the number had meanwhile increased to 64 450 Mt PR (OCP, 1989).

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, p. 2). However, USGS did not adopt these numbers as reserves in its mineral commodity summaries and neither did OCP. In its mineral commodity summary of 1996 (USGS, 1996), USGS placed Moroccan reserves at 5900 Mt PR and the reserve base at 21 000 Mt PR. In 2000, USGS reduced Moroccan reserves to 5700 Mt PR (USGS, 2000), and they remained at this level until the major revisions of 2010–2011. In 1994 (Dolley, 1994, p. 557) and 2007 (OCP, 2007, p. 9), OCP placed Moroccan reserves at approximately 20 000 Mt PR, which roughly 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 nearly the same reserve number reported in Michalski (1995), but in cubic meters, rather than megatonnes: 84 120 million m<sup>3</sup>. Given that each cubic meter yields 2 t of ore, this yields an ore resource of 168 240 Mt PR, i.e., twice the number reported 3 years earlier by Michalski. This inconsistency will be explained in Sect. 5.3.

IFDC adopted Gharbi’s ore reserves for three of the four deposits, namely Ouled Abdoun (74 740 Mt PR), Gantour (61 500 Mt PR) and Bou Crâa (2000 Mt PR), i.e., a total 138 240 Mt PR. 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 %. Subsequently, the estimated ore reserves of 138 240 Mt PR were recalculated into upgraded concentrate, reducing the

volume by approximately 61 % to 51 000 Mt of concentrate (Van Kauwenbergh, 2010a, p. 36). See Sect. 4.1 for more detail on the conversion rates.

The IFDC report states that this magnitude of Moroccan reserves had been recognized earlier in the literature, pointing to 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 examination unveils that they effectively are both ore numbers<sup>4</sup>. Back-calculated to ore, the IFDC estimate of 51 000 Mt PR concentrate is in fact almost 3 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 majority of which IFDC recalculated into concentrate, really constitutes an ore reserve?

### 5.3 The underreporting of Moroccan resources in the literature and the inconsistent use of the terms “reserves” and “resources”

A review of Moroccan data sources reveals that for almost two decades, the same resource numbers discussed above as reported in megatonnes in the international, English language literature were reported in cubic meters of ore resources in the OCP annual statements and certain French language papers. For instance, the 1987 OCP annual statement (OCP, 1987, p. 14) listed an aggregate in situ ore resource of 63 930 million m<sup>3</sup> for the four fields, roughly identical to the number reported in OCP (1989; see Sect. 5.1 above) except for the notation being 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<sup>3</sup> PR (OCP, 1995, p. 15), a number identical to the number reported by Michalski (1995), but for the notation in cubic meters. During the peer review of this paper, USGS clarified that the Michalski (1995) report contained an error and that the document on which she had based her statement (which had been provided by OCP through the Moroccan ministry of Energy and Mines) had reported 85 000 million m<sup>3</sup> and not 85 500 Mt PR (S. Jasinski, personal communication, 12 July 2014).

The annual account for 2000 (OCP, 2000, p. 17), the latest recoverable document in which a resource statement was made, reported the same numbers and clarified that

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

they represented ore of all qualities (“*toutes qualités confondues*”). As each cubic meter yields 2 t of ore, these documents imply that Moroccan resources have been consistently understated by 50 % for decades in the international literature, and that by the year 2000, Moroccan ore resources amounted to 171 000 Mt PR. This increase in Moroccan resources, of 114 750 Mt PR since OCP reported 56 250 Mt PR resources in 1989 (OCP, 1989), accounts for the majority of the increase in global PR resources between 1989 (163 000 Mt PR reported in Notholt et al., 1989) and the IFDC report (290 000 Mt PR).

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. Moreover, in a more detailed study issued 2 years earlier, Gharbi listed the same deposits as resources, as OCP had done in the abovementioned annual statements (Gharbi and Mchichi, 1996).

Here it should be noted that, as evidenced by the data in Sect. 5.1, the difference between resources and reserves is often not properly recognized in the literature describing Moroccan PR deposits, or PR deposits in general. This is a recurring problem often mentioned in the literature (see, for instance, USGS and USBM (1982), Notholt et al. (1989, p. XXIV) and McClellan and Van Kauwenbergh (2004)). McClellan and Van Kauwenbergh cautioned that many authors do not distinguish between reserves and non-economic resources when reporting the size of deposits, that substantial differences in reserve and/or resource estimates may exist between various sources, and that it is therefore “prudent to acknowledge that such discrepancies exist and that such figures should serve only as order-of-magnitude estimates”. The information in Gharbi and Mchichi (1996), OCP (2000), and the preceding OCP annual statements provides a strong indication that the deposits described in Gharbi (1998) should be termed ore resources, rather than ore reserves.

Importantly, a similar conclusion was reached in a 435-page volume by IFDC describing African PR deposits (Van Kauwenbergh, 2006, p. 284). This volume contains an in-depth discussion of Moroccan resources, including Gharbi (1998). Referencing the Gharbi estimate, the author 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 “reserves” which Gharbi reported for Morocco did not at the time fundamentally change the validity of USGS’ assessment of Moroccan reserves and reserve base. Given that the findings in the IFDC report were based solely on the same paper by Gharbi, this

raises the question why the opposite conclusion was drawn in the IFDC report, with no further explanation.

There are other indications that the term “resources” was used appropriately in Gharbi and Mchichi (1996) and the OCP annual accounts (including OCP, 2000) but not in Gharbi (1998). As a rule of thumb, only a fraction of the phosphate rock resources are technically and economically suitable for production at any point in time (Van Kauwenbergh, 2010a). In the IFDC report, however, the ore reserves for three of the country’s four deposit areas are identical to the resources. This is an anomaly which by itself should raise eyebrows. In contrast, the IFDC report places the PR reserves for the USA at 1800 Mt PR and the resources for the USA at 49 000 Mt PR. USGS’ latest estimate of US reserves amounts to a mere 1100 Mt PR (USGS, 2014).

Another indication is the degree of geological assurance and exploration of the Moroccan deposit areas. An overview in OCP (2000) shows that, out of the total 85 500 million m<sup>3</sup> PR ore reported for Morocco, more than 46 810 million m<sup>3</sup> PR ore had by then been established by drill holes spaced more than 2000 m apart, while 29 610 million m<sup>3</sup> PR ore had been established by drill holes less than 1000 m apart. For more detail, see Fig. S6.

While we have not been able to obtain guidelines which determine the appropriate drill hole distances for the various resource classes for the Moroccan PR deposit areas, USGS and USBM (1982) contains data for the US deposits in the southeastern and northwestern phosphate provinces, where phosphate deposits are of the same sedimentary type as the Moroccan deposits. Given the geological differences which may exist between regions and countries, it is not certain if USGS bore hole requirements are an appropriate yardstick for Moroccan deposits (Scholz and Wellmer, 2013b). However, the USGS drill hole requirements may provide a rough indication.

According to USGS and USBM (1982), the geologic yardstick generally adopted in industry for measured reserves is a sampling density of more than 64 boreholes per square mile (USGS and USBM, 1982, p. 2), which amounts to 25 boreholes per square kilometer, or some 200 m between the holes (equivalent to 100 m centers used in most places in the world; Van Kauwenbergh, 2010a). If the distance between the boreholes is no more than half a mile (800 m), a deposit may qualify as a demonstrated, indicated resource which may be entered into the USGS reserve base or the USGS reserves, assuming that the economic requirements for the reserves or the reserve base are met in terms of grade, impurity level, thickness of the seam, etc. (USGS and USBM, 1982, p. 3). If the distance between boreholes is greater than half a mile but less than one mile, it may be regarded as an inferred resource which does not qualify as a reserve using USGS criteria (USGS and USBM, 1982, p. 3 and Sect. 3.1).

Notwithstanding the uncertainty surrounding the appropriate drill hole requirements for the Moroccan resources, the wide distances between drill holes in much of the Moroccan

deposit areas as reported in Gharbi and Mchichi (1996) and OCP (2000; more than 2000 m between the boreholes for the majority of the area) provide a further indication that the term resources is used appropriately in these documents, and inappropriately in Gharbi, 1998. This appears to follow also from the fact that OCP (2000) describes these resources as “*toutes qualités confondues*” or “all qualities aggregated”. Moreover, as already discussed, OCP issued reserve estimates of approximately 20 000 Mt PR in 1994 and 2007 (Dolley, 1994 and OCP, 2007), roughly in line with USGS’ reserve base estimates for these years (USGS, 1996, 2007). One may assume that OCP was aware of the abovementioned resource figures in its annual statements when it issued these estimates.

In Sect. 1, we pointed to a recent response of the Global TraPs project to the EC Consultative Communication on the Sustainable Use of Phosphorus (Scholz and Roy, 2013). In it, the authors argued that the estimate of Morocco PR reserves in the IFDC report is a conservative one as the various sites have not been completely explored. The authors conclude that currently economically minable PR reserves are likely above 100 Gt PR, i.e., twice as high as the Moroccan reserves estimated in the IFDC report. The authors base this statement on information in the IFDC report regarding the assumed unexplored extensions of the three major Moroccan ore fields. In Sect. 5.1 we noted that these assumed extensions extend to depths up to 400 m are very complex as the unexploited parts have been severely disturbed geologically and that, for that reason, it is hard to draw conclusions from them (Service Géologique du Maroc, 1986, p. 64 and 217). These extensions were not included in the resources in OCP (1989), Gharbi and Mchichi (1996), OCP (2000) or any other document which we reviewed. Moreover, this use of the term “reserves” is obviously incompatible with the resource classifications discussed in this paper. Under JORC, USGS, or UNFC, reserves are only those deposits which are demonstrated as economically viable and have been established with a high degree of geologic assurance (measured or indicated, using USGS terminology; see Fig. S1). A lack of exploration can therefore never signify that “reserves” are understated. At best, unexplored extensions of known ore bodies could qualify as hypothetical, undiscovered resources, using USGS definitions (see Fig. S1). This recent contribution to the discussion on global PR reserves once more underlines the need for clear use of mineral resource terminology.

## 6 Conclusions

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. The USGS and UNFC codes have a broad focus which allows for reporting of both eco-

conomic and non-economic deposits. JORC-style codes, designed to guide investor decisions, have a narrow focus on currently economic deposits and are therefore less relevant to the long-term perspective. Detailed granulation is a core element of both the USGS and the UNFC classifications as well as JORC style classifications. Such granulation entails that deposits are classified according to clear thresholds which convey their relevancy and socioeconomic potential.

The IFDC report, in contrast, simplifies existing nomenclature to two coarse definitions, without underlying thresholds. This simplification, in combination with a questionable interpretation of data in Gharbi (1998), allowed for an enormous increase in Moroccan “reserves”. This increase in Moroccan reserves in the IFDC report, accepted by USGS, was followed by upward restatements by a number of countries including Syria, Algeria, and Iraq. In the literature, these and other increases have been interpreted as indicators of the potential for reserve growth and the rate by which this may occur (Scholz and Wellmer, 2013a). This review unveils, however, that the increase in Moroccan reserves in the IFDC report was in all likelihood mainly due to a simple restatement of ore resources as ore reserves, and this may have been the case for certain other recent restatements as well. In the case of the Moroccan reserves, this “swap” was followed by a conversion to concentrate, which to some extent veiled the scale of the increase to the casual observer. It also rendered IFDC’s reserve estimate for Morocco inherently incomparable with USGS PR data for at least a number of countries, which apparently report their reserves in terms of ore, rather than as upgraded concentrate.

In the literature, the high increase in the static R/C ratio has been used to argue that it is appropriate to assume a “high planning horizon” for PR (Scholz and Wellmer, 2013a) and that “humanity is on the safe side”, also in view of large resources and geocapacity that will be available in addition to reserves (Scholz and Wellmer, 2013b). However, to compute an R/C ratio and draw such conclusions from it, there should be clarity as to what constitutes a reserve and it should be clear that the reserve can be compared with the upgraded concentrate in which global annual consumption is reported. To draw proper conclusions from an increase in reserves, one should consider the extent to which the growth is “real”, in the sense that the increase in reserves is based on the same standards as the reserves which were reported prior to the increase. In addition to that, it should be kept in mind that annual consumption, like reserves, is a dynamic figure that will change over the years.

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. In the interest of long-term food security, it is imperative that the use of PR be sustainable and equitable from not only an intragenerational but also an intergenerational perspective. 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 economic, energetic, and environmental costs. The second question is how demand may develop when population growth, further agricultural intensification, dietary shifts, and an increasing use of biofuels are taken into consideration, and also if society fails to take the appropriate steps to use this finite resource in a more efficient manner. An in-depth and scientifically sound global inventory of PR deposits, as envisaged in the IFDC report, has yet to take place. In addition to reserves and resources, such a review would also need to realistically assess those deposits which are not currently viewed as resources and which humanity will come to depend upon after today’s reserves and resources become depleted. Preferably, such a review should also consider the potential for further, truly new discoveries.

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