Preliminary remarks: The revision of the Comment is following the suggestions

First we want to thank for this sensitive, critical and constructive review.

We agree with the reviewer that the "voice of a school teacher" formulations which may "discredit" Edichoven et al. has to be mitigated. We are aspiring a more objective tone in the debate and the removal of some of the personal judgments."
This tone had been induced by the first paper and the harsh reviews and responses. We think that it is time to change the mode of interaction; and we hope the revision provides a contribution in this direction.

Remarks: The manuscript by Scholz and Wellmer criticizes a publication by Edixhoven et al. (2014) who were critical about the abrupt increase in the estimate of phosphorus reserves particular of Marocco – data that increased by a factor of 10 to 50 Gt phosphate in 2010 (USGS 2010) and by the IFDC (International Fertilizer Developent Center Muscle ShoalsAlabama). Scholz and Wellmer strongly defend the report by the IFDC and the increase in reserves and criticize the publication by Edixhoven et al. It would certainly have been easier if the IFDC reacted directly on the comments by Edixhoven and not through a third party. It would have also been more sensible if Scholz and Wellmer had first commented on the surprising increase by the IFDC. It is only later in the manuscript that Scholz and Wellmer reconstruct the estimates and the increase by the IFDC and the USGS.

We agree with the author that it would be better if IFDC would have answered. IFDC (personal communication the CEO Amit Roy co-leader of Scholz in Global TraPs) did not do so as they were afraid of endless, spiraling discussion (the excessive review if Mr. Edixhoven to a previous version with 96 questions and 14,000 words may be taken as an example) for which the institution does not have a budget. The text has been repeated by checked by IFDC.

If we take the definition: Reserves denote "phosphorus rock which can be economically mined at the time of the determination when using existing technologies" [1] we were facing an "surprising updating" of the Moroccon reserves. Based on the remark of the reviewer we change the formulation in the abstract:

> We reconstruct the IFDC and USGS estimates and conclude that there is no evidence for considering the somewhat surprising increase to 50 Gt phosphate concentrate as an unreasonable estimate and updating for Moroccan reserves.

From an outside view it is rather surprising what the new estimate of reserves, especially in Marocco, were motivated by. In this sense, the paper by Edixhove et al. is totally justified. But their paper also has several unclarities and some positions that cannot be defended. Yet this does not justify Scholz and Wellmer in some passages in the text to appear overly like a school teacher and to discredit the competency of Edixhoven et al in placing the reserves and resources into context. In this sense I ask for a more objective tone in the debate and the removal of some of the personal judgements. Even though these are a few minor corrections, these would help to focus the debate on a more productive and objective level. This, after all, should be in the interest of all scientists working on phosphorus.

Thanks. We got this message. We work carefully work through the whole text and look for a more objective tone (which emerged from a ping-pong of papers and reviews) and harsh formulations on both sides. We work forward that this comes to an end and an objective, scientific discussion can take place.

Comments by Edixhoven et al about the increased estimate by IDFC:

1. The report does not clearly distinguish between „phosphate ore" and „phosphate products"
2. The terms „reserves" and „resources" are not clearly defined.
3. Because of these uncertainties Edixhoven et al. argue for a more differentiated inventory of phosphorus reserves which includes „guidelines which determine the appropriate drill hole distances and a detailed granularity".

Comments by Scholz and Wellmer to Edixhoven et al.:

1. Edixhoven et al. include „incorrect and misleading statements.
2. It is erroneous to claim that the increased estimate of Marocco is based only on one publication
3. The dynamical nature of reserves is acknowledged but the correct conclusions are not being drawn including a mix--‐up of the terms „finiteness" and „staticness" and the link between the increase in estimates by the USGS and „peak P".

Yes, we share the reviewer's view

Notes:

1. Abstract 3rd row: instead IFDC (2010) – IFDC(2006 2015)

o.k. thanks

2. Scholz and Wellmer refer to the statement by Edixhoven et al. (2014) that „The IFDC reserve estimate for Marocco is solely based on Fharbi (1998)" as „biased and unreasoned" (page 3 first paragraph lines 3--‐5).

Please let me explain why we used this terminology. This is due to the 1st authors background who worked as a mathematician for 15 years in a mathematical institute (and thus acquired some knowledge about logics). Further, he is a cognitive psychologist who worked about „biases and fallacies" (in stochastic thinking) a subject whose researchers received a Nobel laureate (Daniel Kahneman [2]) recently.
But let us explain why we used the category "biased and unreasoned."
Unfortunately the rules of propositional logic that a statement is either wrong or right does not hold true for statements which are made in terms of spoken/everyday language. We may take the definition of conditional probability, i.e., p(A|B) and its difference from conjunctive probability $p(A \wedge B)$ as an example. The (spoken) language translation of p(A|B) in its ideal (according to what mathematicians suggest) to: "The probability of A given B." But there are other formulations such as. "The probability that A happens if B had happened." And then you may become continuously more incorrect ending with „The probability of that A and also B has occured" to "The probability of A and B."
Second we speak of biases (which also is a term from statistics; here we deal with biased estimators). A biased estimator systematically deviates e.g. from an expected value and this is (mostly) wrong. But in cognitive psychology we speak about a prejudice- (cognitive schema-)

based judgments which may (subjectively and) systematically under- or overestimate estimate something. This is also nicely defined in Merriam Webster's unabbridged: „prejudice (2) **:** an instance of personal and sometimes unreasoned judgment. The subject (heuristics and) "biases" has spread in many disciplines [3]. And the first author is thinking to write a paper on "heuristics and biases" on phosphorus management.

The question which emerges from the reviewers question is whether the distinction between

- wrong biased and unreasoned statement and
- of fuzzy and misleading statements on fundamental mistakes of the use of reserves data

is clear.

So far on some scientific background why we introduced the two types.

For clarifying the difference of the two types and for explaining what we understand by misleading statement to the "normal reader of ESD," we included one sentence. This sentence also relates "misleading" to the "right/correct" and "false/wrong" (which is the dichotomy to which the reviewer refers).

> As the reader may already surmise from the volume, this paper is not a normal comment. It deals with three *types of comments and thoughts* which emerged from the published version of the Edixhoven et al. (2014) paper. *Type 1* deals with some wrong, biased and unreasoned statements that are still being spread by the paper. The statement "The IFDC reserve estimate for Morocco is solely based on Gharbi (1998)." (Edixhoven et al., p.501) may serve as example. *Type 2* deals with a set of fuzzy and misleading statements on fundamental mistakes of the use of reserves data. Here, we can take the statement "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)" (ibid, 491) as example. The Edixhoven paper misses to clarify that the use of reserve data (as a proxy for the ultimate recoverable resource) for assessing global Peak P is a fundamental scientific error. Thus, the quoted sentence is misleading as it suggests the wrong interpretation that the USGS's estimates (which are criticized in the paper) are the cause of the critique of the critique of Peak P. Some *Type 3* comments provide some reflections on why there are such amazingly discrepant views on statements on reserves on phosphorus.

3. Scholz and Wellmer refer to the statement by Edixhoven et al. that the reserve estimates of the USGS are largely based on the „mineral commodity summaries" (MCS) as „fuzzy and misleading statements on fundamental mistakes" (page 3 first paragraph lins 6--‐9). Also here this judgement of an incorrect assessment by Edixhoven et al does not lead to a more objective discussion.

We think that the previous supplement and other changes help to attain the goal of becoming more objective.

We skipped "naïve" in two places

4. Scholz and Wellmer find it unfortunate that the publication by Edixhoven et al does not include a clarification that the application of reserve data for the evaluation of global peak P is a fundamental abuse and scientific error. This is completely okay.

o.k.

5. On page 4 (first paragraph, lines 13-16) Scholz and Wellmer repeat the general critique of Edixhoven et al that it „still includes assumptions, statements, and interpretations that, in our opinion, are unacceptable from a raw resources scientist's, a systems scientist's, and a geostatistial modelling perspective…". This statement is also a judgemental statement that brings miscredit to Edixhoven et al. This is unnecessary and does not contribute to an objective debate.

Thanks, we skipped the "blaming" phrase and focused the content. The text now just reads:

The paper includes, in our opinion, some statements that are unacceptable from a raw resources scientist's, a system scientist's, and a geostatistical modeling perspective.

6. In chapter 2, Scholz and Wellmer describe in detail on which data and assumptions the paper by Edixhoven et al. is based on regarding the increase in phosphorus reserves. They complain in this context that the paper by Edixhoven does not refer to a fundamental incorrect assessment that „reserves as a substitute of ultimate recoverable resource in assessments of peak P…". This critique is fully justified.

Thanks, o.k.

7. The comparison of stratabound phosphate deposits with those of iron and bauxite is not completely adequate because the dimensions of the marine areas for iron deposits as well as secondary effects of weathering (for bauxite) could be different from the processes that form phosphorus deposits. In this sense, the arguments regarding the R/C ratio (reserve/consumption) of about 100 is not necessarily a strong argument (page 7, paragraph 3.2, line 4-11).

3.1 The geological specifics of phosphate reserves have to be acknowledged

We argue that the analysis of Edixhoven et al. (2014) does not sufficiently acknowledging basic geological and economic issues that affect the dynamics of reserve data (for more arguments see Supplementary Information I for detailed reasoning).

The reserve/consumption (R/C) ratio for most commodities is far less than that for phosphate [see 4 Fig. 3]. The ratio is not increasing or decreasing but staying within a spread of equilibrium values that satisfy the planning scope of mining companies. The paper of Edixhoven et al. misses to acknowledge that due to geostatistical reasons stratabound sedimentary minerals normally have R/C ratios in the range of 100 or even higher. The R/C ratios of (mostly) stratabound commodities iron ore and bauxite are in the same range as those of phosphorus. Yet *lens-like deposits* such as those for copper lead or zinc have R/C ratios between 20 and 40 (see Figure 1).
Although the genesis of a bauxite deposit as a weathering product is not the same as the ones of the strataform iron or phosphate deposits the geostatistical parameters are often similar making it possible to extrapolate tonnage and grade data further than in lenslike base metal deposits and thereby influencing the R/C-ratios. The range within which sample grades show a spatial interdependence frequently exceeds 100m (David 1977). Up to 700m have been reported for a phosphate deposit (Miller & Gill 1986).

Based on these arguments we think that the formulation is justified

References:
David M. (1977): Geostatistical ore reserve estimation. Developments in Geomathematics 2. Amsterdam: Elsevier
Miller E. & Gill d. (1986): Geostatistical ore-reserve estimation of South York'am phosphate deposit Zin Valley southern Israel. Trans. Inst. Min. Metall. [A] 95 A1-

8. Regarding the relatively pessimistic assessment of Edixhoven et al that the „... PR deposits are fixed, or static." is contrary to the more optimistic assessment by Scholz and Wellmer (paragraph 3.2). Scholz and Wellmer are absolutely right on this topic, but the truth is probably exactly between the two views.

Yes, this is probably right.

9. Edixhoven et al. pledge for a more differentiated inventory of the global phosphorus reserves, and include „guidelines which determine the appropriate drill hole distances and a detailed granularity". Scholz and Wellmer generally agree about this need, but consider the request for „appropriate drill hole distances and a detailed granularity" to be completely unrealistic. In the formulation of this critique, Scholz and Wellmer appear overly teacher-like. On the topic, there is no disagreement but the critique is not constructive (page 13, paragraph 4.2, line 4-14).

We mitigated some formulations in this sections (e.g., changed "bureaucratic" in to " generally valid"). We added one reference (on adaptive Bayesian drilling plans) to strengthen content related arguments and skipped one sentence which refers to "textbook state of the art" knowledge which is ignored.

10. In chapters 5.3 and 5.4, Scholz and Wellmer try to reproduce the new estimates of the USGS and the IFDC in order to substantiate their disagreement with Edixhoven et al in that the new estimates are pure restatements. This is laudable, but leaves a somewhat irritating impression: Why did USGS and IFDC not react themselves to the critique? Why did they not clearly and reproducibly lay out the literature and methods in their reports? A certain level of clarification on the authorization of the critique about the USGS and the IFDC would be appropriate

A major achievemnet of the Edichoven et. al (2014) paper is that it identified the sloppy use the mixing of PR-M and PR Ore in the USGS mineral survey data. Based on this and our knowledge about what country data are PF-M data we performed a worst case-analysis which has been slightly refined by an interactive comment. Why USGS did not differentiate, we did not know. In the quantitative assessments of IFDC (van Kauwenbergh 2006, 2010), in general (and as far as the referenced literature allows) this distinction is done.

11. Overall a very good paper, for which I recommend the minor corrections as listed above

Thanks, for this feedback and the sensitive

References

1. Van Kauwenbergh S.J. M. Stewart and R. Mikkelsen *World reserves of phosphate rock ... a dynamic and unfolding story* Better Crops with Plant Food 2013. **97**(3): p. 18-20.
2. Tversky A. and D. Kahneman *Judgment under uncertainty: Heuristics and biases.* Science 1974. **185**: p. 1124-1131.
3. Petersen M.B. *Evolutionary political psychology: On the origin and structure of heuristics and biases in politics.* Political Psychology 2015. **36**: p. 45-78.
4. Scholz R.W. and F.-W. Wellmer *Approaching a dynamic view on the availability of mineral resources: what we may learn from the case of phosphorus?* Global Environmental Change 2013. **23**: p. 11-27.

Comment on

Recent revisions of phosphate rock reserves and resources: a critique by Edixhoven et al (2014)—Clarifying comments and thoughts on key conceptions, conclusions and interpretation to allow for sustainable action

Roland W. Scholz and Friedrich-Wilhelm Wellmer

Roland W. Scholz, Prof. em. ETH Dr., Science Leader Global TraPs, Senior advisor on phosphorus cycle management at Fraunhofer Institute for Interfacial Engineering and Biotechnology (IGB), Stuttgart, Germany, and University of Zurich, Switzerland. Gartenstr. 4c, CH-8280 Kreuzlingen, Switzerland, roland.scholz@emeritus.ethz.ch

Friedrich-W. Wellmer, Prof. Dr.-Ing. Dr.h.c. mult., retired president of the Federal Institute of Geosciences and Natural Resources Hannover, Neue Sachlichkeit 32, D-30655 Hannover, Germany, fwellmer@t-online.de

Abstract

Several recent papers deal with concerns about the longevity of the supply of the mineral phosphorus. The paper by Edixhoven, Gupta, and Savanije (2014), for instance, expresses doubts about whether the upward estimate of reserves by the IFDC (2006, 2010) and the USGS (2010) provides an accurate, reliable, and comparable picture, as it is based on reports that do not clearly differentiate between phosphate ore and phosphate products (i.e., marketable phosphate rock concentrate). Further, the indistinct use of the terms reserves and resources is criticized. Edixhoven et al. (2014) call for a differentiated inventory of world phosphate reserves including "guidelines which determine the appropriate drill hole distances and a detailed granularity." The claim that "humanity is on the safe side" with respect to future phosphate supply is doubted, as the validity of the IFDC's upgrading of the Moroccan data to 50 Gt phosphate is questioned. The present comment and thoughts include remarks about incorrect and misleading statements made in the paper by Edixhoven et al. (2014). The comment elaborates first that several statements, such as that the

upgrading of the Moroccan data is “solely based” on one scientific paper, are ~~wrong~~incorrect. Secondly, the paper comments on and illuminates a set of misleading statements. These include the fact that the dynamic nature of reserves (which depend on price, technology, innovation for exploiting low-grade deposits, etc.) is acknowledged, but the right conclusions are not drawn, including the mixing of finiteness and staticness, and the way in which the critique of the USGS upgrading of the Moroccan reserves has been linked to Peak P. In particular, we clarify that reserves are primarily company data that serve mining companies for their strategic planning and may, by no means, be used as proxy data for providing global Peak P estimates. Likewise, we elaborate that drilling plans for assessing reserves have to be adjusted to site characteristics, in particular, in the case of four plateaus in Morocco and the Western Sahara comprising an area greater than 10,000 square km. We reconstruct the IFDC and USGS estimates and conclude that there is no evidence for considering the somewhat surprising increase to 50 Gt phosphate concentrate to be an unreasonable estimate for Moroccan reserves. However, the partial mixing of different units (e.g., phosphate ore and phosphate concentrate or marketable product) in the USGS data may be avoided by improving the database and using proper conversion factors. When applying these factors and assessing all reserves of marketable Gt of phosphate rock (PR-M), which is a common scale for measuring annual consumption, the magnitude of the 2014 USGS estimates of 67 Gt PR reserves does not change essentially but decreases from 64 (IFDC assessment) to 57.5 Gt PR-M (a worst-case calculation). We argue that a better harmonization of the (national) classification systems is meaningful. The discussion includes several ideas and thoughts that go beyond the paper by Edixhoven et al. (2014). We suggest that the discrepancies in the resource estimates are often caused by missing system understandings, different conceptions of sciences, and diverging worldviews. Finally, we suggest the establishment of a solidly funded, international standing committee that regularly analyzes global geopotential for assuring long-term supply security.

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1. Genesis, functions and (mis-)interpretation of reserves data

As the reader may already surmise from the volume, this paper is not a normal comment. It deals with three *types of comments and thoughts* which emerged from the published version of the Edixhoven et al. (2014) paper. *Type 1* deals with some wrong, biased and unreasoned statements that are still being spread by the paper. The statement "The IFDC reserve estimate for Morocco is solely based on Gharbi (1998)." (Edixhoven et al., p.501) may serve as example. *Type 2* deals with a set of fuzzy and misleading statements on fundamental mistakes of the use of reserves data. Here, we can take the statement "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)" (ibid, 491) as example. ~~Unfortunately,~~ Ttthe Edixhoven paper misses to clarify that the use of reserve data (as a proxy for the ultimate recoverable resource) for assessing global Peak P is a fundamental ~~(conceptual) misuse and~~ scientific error. Thus, the quoted sentence is misleading as it suggests the wrong interpretation that the USGS's estimates (which are criticized in the paper) are the cause of the critique of the critique of Peak P. Some *Type 3* comments provide some reflections on why there are such amazingly discrepant views on statements on reserves on phosphorus.

Prospective phosphorus management requires special attention because phosphorus is bio-essential (i.e., unsubstitutable), the phosphorus cycles are of a dissipative nature (with the consequence that the anthropogenic cycle is still causing critical eutrophication in aquatic systems), and phosphate reserves are finite today, tomorrow, and in the distant future. Thus, knowledge about the geopotential of phosphorus, as well as the prevention of non-functioning markets, is an important factor for food security.

The introduction of Edixhoven et al. refers to the debate on "the longevity of mineable PR deposits" and to "peak theory" (2015, p. 492). Then paper also questions whether the update of the Moroccan phosphate reserves by a factor of 10 to 50 Gt phosphate in 2010 (USGS, 2010) is a mirage due to geostatistical substandard estimates, or a result of insufficient research based on mixing basic measurement units, or not distinguishing *marketable phosphate rock concentrate* (phosphate concentrate) from phosphate rock? To support distinction, we suggest to use the abbreviation PR-M if we deal with *marketable* phosphate concentrate, PR-Ore if we report about phosphate ore and PR when we refer to the data of U.S. Geological Survey Mineral Commodity Summaries (USGS MCS). PR-M "varies in grade from less than 25% to over 37% P_2O_5" (van Kauwenbergh, 2010, p. 5). In general 30% P_2O_5 is taken as a base for conversion to PR-M. Is the classification by the USGS sufficient for sustainable phosphorus management, or do we need a highly disaggregated classification scheme with 10 or more categories? Are judgments that humanity has a "high planning horizon" for phosphate rock reserves (Scholz & Wellmer, 2013) unjustified, as there is "no independent and scientifically sound global inventory of PR deposits" (Edixhoven, et al., 2014, p. 500)?

~~Though the published version addresses some of the criticisms of the extensive reviews, the Edixhoven et al. (2014) version still includes assumptions, statements, and interpretations that~~The Edixhoven et al. paper includes, in our opinion, some statements that are unacceptable from a raw resources scientist's, a system scientist's, and a geostatistical modeling perspective. The paper particularly insufficiently incorporates regulating economic mechanisms of the supply–demand system and misses a transdisciplinarity perspective that acknowledges the roles and interests of the key stakeholders and the necessity of integrating knowledge from science and practice if we want to interpret, use and develop data about reserves and resources.

As may be taken from the comment of Hilton (2014) on a previous version, the paper of Edixhoven et al. can be seen as an example of a critical, skeptical contribution on the future availability of mineral commodities. We think that the question of why different scientists or stakeholders provide such different judgments about reserves and resources is of general interest. Thus, this comment includes a Section 7 which discusses whether the frequently found discrepancies are due simply to (a) different data, system models, or system boundaries, to (b) fundamental reasons that are rooted in different conceptions or schools of sciences? Or can the differences be explained by (c) different worldviews?

Section 2 of our comment comprises the research questions and main conclusions of Edixhoven et al. (2014) discussed in this comment. Then, we explain why certain fundamental issues are dealt with in an insufficient or unacceptable manner. Section 3 deals with the poor acknowledgement of the dynamic nature of reserves and the neglect of *prices as a main component of the dynamics and magnitude of reserves*. Section 4 clarifies why the *linking of reserves to Peak P* are wrong and why the suggested arguments on drilling plans are unrealistic. This is done by brief explanations on how proper Hubbert analysis and geostatistical inference would look like. Section 5 reflects on the granularity of reserves/resources classification and argues that the USGS classification is a proper reference for sustainable phosphorus management. This section also discusses the valuable contribution of Edixhoven et al. when distinguishing PR-Ore (which is the basis of a reserve) and PR-M, which is a marketable product, in reserve assessments. Section 6 reflects that the different roles of key actors have not been sufficiently acknowledged.

2. Critical statements of the Edixhoven et al. paper

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The paper by Edixhoven et al. discusses the classification and the data about phosphate rock by the USGS Mineral Commodity Summaries (MCS) (USGS 2010, 2014; see also Kelly, Matos, Buckingham, DiFrancesco, & Porter, 2008) and, in particular, focuses on the increase of phosphate rock reserves from 16 Gt PR in 2010 (USGS, 2010) to 65 Gt PR (USGS, 2010). This increase is due mainly to the increase of the Moroccan reserves from 5.7 Gt PR to 50 Gt PR, as reported in an IFDC Report (van Kauwenbergh, 2010) and “upward country restatements for countries like Syria, Algeria, and Iraq" (Edixhoven, et al., 2014, p. 500). The revision is supposed to rely only on the data of one paper (see above).

Key questions of the Edixhoven et al. (2014) paper are whether present reserves and resources data meet "industry best practice" and are "comparable and reliable" (p. 19). The paper criticizes the vague use of the categories reserves and resources, and identifies some data in which phosphate ore and phosphate concentrate are not sufficiently distinguished.

The paper offers the following conclusions: The estimates provided by the IFDC report do not present an "accurate picture" (p. 491). This is "mainly due to simple restatements of ore resources as ore reserves." (p. 504) The simplified classification of using reserves and resources is considered to be insufficient, thus the IFDC report "provides an inflated picture of global reserves." (p. 491)

In principle, the formulation of Edixhoven et al. on "criticism of the global Peak Phosphorus hypotheses." (ibid, p. 492, see the quote of the first paragraph above) fathers the wrong assessment the Morocco data by USGS (2011) and not the fundamental misuse of reserves as a substitute of ultimate retrievable resource (Type 2, see above). Thus the paper does not disclose the fundamental misuse of reserves as a substitute of ultimate recoverable resource in assessments of Peak P in some papers (Cordell, Drangert, & White, 2009). The paper finishes with a plea for "mineral resource reporting towards standardized definitions across the minerals, both to serve the needs of globalizing businesses and to allow for mineral availability studies within the context of sustainable development" (p. 503). Here, the use of UNFC (2010) classification, which has 40 theoretical cells (of which 12 respectively 14 are used) is proposed.

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3. The dynamic nature of reserves and resources is not properly acknowledged

Edixhoven et al. (2013) acknowledge that "given the economic function of resource classifications, reserves and resources are dynamic" (p. 9, line 14). When studying their paper, however, one wonders to what extent this dynamic concept has actually been incorporated. The Edixhoven et al. paper does not sufficiently take into consideration some basic mechanisms of resources theory. This holds true in particular for the phenomenon that—given certain prerequisites—both an *increase of prices and of demand induce* an increase of reserves and resources. This is key issue for all minerals and in particular for phosphate rock reserves. The subsequent section introduces in this neglected aspects of resource dynamics.

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3.1 The geological specifics of phosphate reserves have to be acknowledged

We argue that the analysis of Edixhoven et al. (2014) does not sufficiently acknowledging basic geological and economic issues that affect the dynamics of reserve data (for more arguments see Supplementary Information I for detailed reasoning).

- The reserve/consumption (R/C) ratio for most commodities is far less than that for phosphate (see 2013, Fig. 3). The ratio is not increasing but staying within a spread of equilibrium values that satisfy the planning scope of mining companies. The paper of Edixhoven et al. misses to acknowledge that due to geostatistical reasons *stratabound* sedimentary minerals normally have R/C ratios in the range of 100 or even higher. The R/C ratios of (mostly) stratabound commodities iron ore, and bauxite are in the same range as those of phosphorus. Yet, *lens-like deposits* such as those for copper, lead, or zinc have R/C ratios between 20 and 40 (see Figure 1).
- Technology will allow to economically produce lower ore grades. Since 1960, the average world copper grade decreased from 2% Cu to 1% Cu (Schodde, 2010).

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- With the technological breakthroughs phosphorus mining may be done in new media or geological environment (deep sea, river sediments, basaltic rock, etc.). Horizontal drilling and hydraulic fracking are going to surpass the 1970 peak of US oil production (see SI1, Figure 1). The history of nickel mining provides another example (see SI1). The shift from bat cave and bird guano to phosphate rock is another example.
- Price increases (together with cheaper production) are main drivers of reserve increase. The Economic Demonstrated Resources (EDR) of phosphate in Australia, a country with very strict reporting standards, increased ninefold after the tripling of the PR-M prices after the general commodity price peak in 2008 (see SI1, Figure 2).
- We assume that when Edixhoven et al. (2014) talk about "geocapacity," it is identical to our geopotential field of the Total Resource Box, see Figure 1 (Scholz & Wellmer, 2013). The authors surmise that not much can be discovered within this geopotential field. However, one wonders why companies spend significant amounts of funds for exploration and why major mining companies that concentrate on "tier one" projects (large, long-living term projects with prospectively low operating costs and high cash flows) move into the phosphate business if everything has been discovered and is already owned by others (Crowson, 2012).

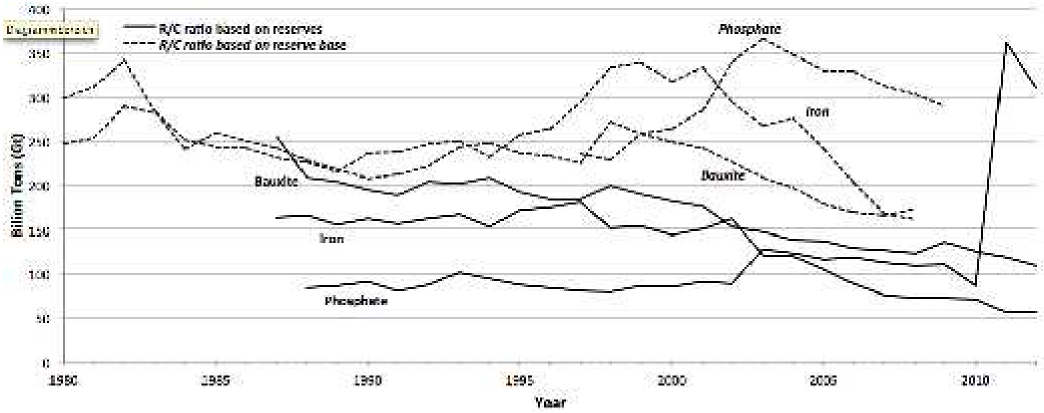

Figure 1: Comparison of the development of the R/C ratios (based on reserve base to 2008/2009 and reserves) of phosphate with iron ore and bauxite (Source: USGS MCS, BGR data bank)

3.2 The confusion between finiteness and staticness of reserves

Though Edixhoven et al. (2014, see e.g. page 495) repeatedly verbally acknowledge the dynamic nature of reserves *expressis verbis*, they do not consider that the amount of economic mineable PR (i.e. reserves) is growing if the prices increase. This holds true even if we just consider the known deposits without postulating the new phosphate ores are detected. The basic rule which can be derived from the rule of the 'feedback control system' that reserves increase with price (Wellmer & Becker-Platen, 2002) is insufficiently included in the paper. Edixhoven et al. explicitly use the term "increase" in total 43 times when dealing with reserves data or phosphorus demand. But the *relation of reserves and prices* is and only dealt once when referring to USGS/ISBM (1980) when mentioning that "sub-resource deposits" may become resources as "prices rise or techniques evolve" (Edixhoven et al., 2014, p. 494).

Edixhoven et al. mix finiteness and staticness as they insufficiently incorporate the dynamic and technological dimension of reserve dynamics. How deeply this misunderstanding is rooted can be well taken from a statement made in defense to a previous version to the present comment. Just six lines after the heading of the section "2.1.3 Our paper did not "confuse finiteness and staticness"

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(Edixhoven, 2015, p. 6) you find the statement: “From a geological viewpoint, the world’s PR deposits are fixed, or static.” Factually deposit can be defined as an “accumulation of ore or other valuable earth material of any origin“ (EduMine, 2015). There is no purely geological, natural-science definition for what amount and/or concentration or what other factors cause a substance to become a deposit. Deposits such as reserves are entities that are economically defined.

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If phosphate resources would become (economically) scarce, it is of interest whether a market can tolerate a price increase for increasing the reserves. From a global perspective, PR-M is a low-price commodity and thus may have a “flexible price” (Scholz & Wellmer, 2013). Scholz and Wellmer (2013) calculated that in 2011, each world citizen consumed on average 30 kg PR-M. Given a price of 200 USD/t PR-M in 2012 (which came down to a magnitude of 100 USD/t PR-M since 2014, Index Mundi, 2015), the average annual cost would be about USD 6 per person. Ceteris paribus, i.e., assuming that nothing else changes, we may ask whether a price of 60 USD per person for PR-M would bankrupt the world economic system. We may think about the annual costs of energy as a reference for comparison. In 2012, the world population consumed about 10 billion tons of oil equivalents (toe), i.e., 1.43 toe per person (Wellmer, 2014). For an order of magnitude calculation, roughly 60% of the consumption is oil/gas, which costs about 750 USD per ton (1 barrel costs slightly over 100 USD). Given a conversion factor of 1.5 from 1 t coal to 1 toe and a price of 75 USD for 1 t black coal (Index Mundi, 2014), the average energy cost per world citizen in 2011 amounts to a magnitude of about 700 USD, which is about 100 times the current cost of consumed PR-M per person. We may conclude that humanity would not collapse if the costs of PR-M per world citizen were to increase by a factor of 10 to 60 USD (or even higher) per year (although such a price increase might worsen social inequity of having access to phosphorus). Or in other terms: There is a big potential for phosphate price increase which would increase the reserves (without finding new ore bodies).

An important aspect of the paper is the longevity of phosphorus supply. Another issue is

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what subresources may become future reserves. Scholz and Wellmer (2013) provided an estimate of the URR of the US Western Phosphorus Fields (WPF) (see Edixhoven et al. 2014, p. 500) which refers to 300 years ahead when all current reserves are mined. Here, we assumed—acknowledging losses in mining and beneficiation--that one third of the ore body can be mined. Just this assumption would provide additional (future) reserves of a magnitude of 180 Gt PR (for more arguments, e.g., why deep underground mining of the deeper layers of the WPF layers are possible see Supplementary Information SI2).

The world's phosphate ores are finite. But this does not imply that reserves are fixed. The phosphorous content of the Earth, meaning the mass of the Earth multiplied by the background value, or the clarke, is an upper threshold. The URR related to PR-M depends on technology, geopotential, and the economic power of humankind. Physical scarcity becomes real if humanity does not have the economic (i.e., financial capital) and other means (i.e., alternative agricultural technologies or innovations for mining low-grade ore) required to produce the amount of PR-M needed to sustain the world's food supply. Reserves and the estimate of world's ultimate recoverable resources (URR) are dynamic variables. And we are far from providing a good estimate on the URR of phosphorus at the global level.

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4. Geomathematical modeling has to be properly referred to

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Any mathematical or geostatistical model is conditional on certain prerequisites. If these prerequisites do not match fully (in mathematics) or to some extent (in application), the use is meaningless. The first section refers to Peak P and reveals severe misapplications of the Hubbert Curve. The statement "peak phosphorus hypothesis is hotly debated" (Edixhoven, et al., 2013, p. 492) may be viewed as a correct description of the discussion among some scientists. However, from an applied mathematics and resources science perspectives, there is no doubt that the Hubbert analysis cannot be used for estimating the global URR as the basic prerequisites are not fulfilled

(Brandt, 2010; Rustad, 2012; Vaccari & Strigul, 2011). This has not been unambiguously stated in the Edixhoven et al. (2014) paper. This section will clarify this. The second section refers to the ~~naïve geostatistical~~ wish to "obtain guidelines which determine the appropriate drill hole distance for the various resource classes for the Moroccan deposit areas" (p. 503).

4.1 The Hubbert Curve works only for supply-driven markets under some constraints

There has already been much criticism about the grossly inaccurate application of the Hubbert analysis for estimating the ultimate recoverable PR-M. The interested reader may refer to the papers of Mew (2011), Rustad (2012), Scholz and Wellmer (2013), Vaccari and Strigul (2011), or to Supplementary Information 3.

Nevertheless, it is most amazing that the fallacious application by Cordell et al. (2009) is still highly cited and received status as a "hotly debated" issue for the case of global phosphate reserves. The Supplementary Information SI3 analyzes in some detail under what conditions Hubbert was able to provide a remarkable prediction for the ultimate US oil reserves, why the situation for global phosphate reserves differs completely, and why—due to the new technology of fracking—Hubbert's prediction was also wrong for the US (see SI3, Figure 1).

In this place we summarize the basics of the misapplication in a way that becomes understandable for those who are not used to working with mathematical models. After approximately a century of extensive exploration of and recovery from US fields, Hubbert had a realistic estimate of the future ultimate recoverable resources (URR; Harris, 1977, see Appendix). Further, Hubbert was facing a supply-driven market, meaning that all oil produced was immediately bought on the market. Based on this, he postulated that the curve of the annual consumption of oil could be described by a (symmetric) logistic curve. Hubbert earned fame by predicting the peak oil of US oil production with only a one-year deviation.

The situation for global phosphate is completely different as opposed to the US oil production. We are far from assessing the magnitude of the ultimate recoverable resources (URR) (which includes the PR-M that will be mined by humanity in the long-term future, plus what has been mined in the past). Given that phosphate concentrate is a low-cost commodity and the potential for technological progress (e.g., if prices rise), the 300 Gt PR resources (USGS, 2014) of today are with the utmost likelihood an underestimation of URR (see Supplementary Information SI3). The major inconsistency of the "peak phosphorus in the near future" statement is that Cordell, Drangert, and White (Cordell, et al., 2009) used the USGS data of 15 Gt PR of the 2008 *reserves* for an estimate of the URR. This certainly provides an underestimation of much more than factor 10. Reserves, independent of it source and validity, cannot be taken as a proxy for URR. Further, the global phosphate rock market is, by no means, a supply-driven market. In addition, the modern Hubbert analysis, which is based on a curve fitting of the production curve by a logistic function, does not provide meaningful results; it just predicts the total URR of 16 Gt PR, about half of which was mined in the past.

The Hubbert Curve may work if there is a supply-driven market with a well-confined ore body, such as the Nauru Guano deposit on Nauru island (Déry & Anderson, 2007). However, applying it to a global estimate of future PR reserves with today's knowledge does not be substantiated by scientific arguments.

4.2 Drilling plans have to be adjusted to sites and interests

Edixhoven et al. criticize "the underreporting of Morrocan resources" (p. 502). The authors are looking for guidelines which "determine the appropriate drill hole distance" (p. 502) and refer to a "geological yardstick generally adopted in industry for measured reserves" (p. 502). Unfortunately, the authors leave unspecified who needs what information, for what purpose, with what level of certainty, at what costs. If we translate this issue into geostatistical decision theory, the complexity of the issue becomes evident. The question reads: Given a decision-maker's interest (related to research, business, public interest, etc.) in global/regional/local phosphate reserves and certain prior knowledge as well as financial resources, how many drill holes of what density (e.g., assessed by minimum or mean distance) according to what metric (Euclidian vs. non-Euclidian) and what statistical design or plan (square, triangle, Bayesian, etc.) of what type (diameter, depth, etc.) should be made for analyzing what parameters (volume, mass, purity, profitability, etc.) at what spatial system (system boundaries), if there is certain prior knowledge and financial resources, will best fulfill the decision-makers' interests (Chilés & Delfiner, 2012; Diggle & Ribeiro, 2007; Matheron, 1963; Nothbaum, Scholz, & May, 1994; Scholz, Nothbaum, & May, 1994; Wellmer, 1998)?

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From a company's perspective, completely different drilling plans are needed for the exploration of the magnitude of the potential excavation volume of a mining area, the elaboration of a business plan (including, for instance, information used in the application of credits), and for optimizing operations when the production is ongoing. There is no panacea, no ~~bureaucratic~~ generally valid guideline or policy order for a standard drilling plan. This also holds true for the Moroccan occurrences, with four plateaus with a total size greater than 10,000 km^2 (van Kauwenbergh, 2006, p. 284). The plateaus show a "very complex tectonic history" (p. 273), where you find both highly heterogeneous and homogeneous ore bodies. A drilling plan depends on geologic models and the site-specific exploration history that, in this case, goes back to 1908. A smart drilling plan (also for assessing the reserves) is dynamic in the sense that this information as well as the information of previous drillings , e.g., by a Bayesian rationale (Diggle & Ribeiro, 2007). ~~If we were to follow the~~A fixed (square) drilling plan as ~~ideas presented~~suggested by Edixhoven et al. (pp. 22-23)~~), we would apply a square drilling plan~~ with a (minimum) ~~1 km~~half mile (800 m) drilling~~-~~ in a huge number of drillings for an area of more than ~~distance. This would result mechanistically in~~ 10,000 km^3 for which is nobody willing to pay.~~drillings~~ ~~and would not only ignore geostatistical state of the art knowledge but also be, most probably, of limited interest to the OCP (Office Chérefien de Phosphates) and others.~~ Why should OCP do these drilling when the

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face reserves that provide 1893 years the annual production of the year 2014? (Geissler & Steiner, 2015) Drilling plans have to be related to the knowledge of experienced local geologists (a "competent person", according to the standard JORC code for reserve classification [JORC, 2012]) is can be gathered from a comparison with coal, a commodity derived from comparable strataform deposits. In the newest guidelines for the coal reserve classification in Australia, a recommended drilling grid has been deleted, and responsibility rests totally on the "competent" person to decide whether the continuity between points of observation is such that, e.g., it qualifies as an indicated resource under the JORC Code, the lowest category to be included in the USGS reserve category (Australasian Institute of Mining and Metallurgy, 2014).

5. The granularity/granulation of classifying the global reserves/resources must be functional

5.1 The constraints of granularity have to be considered

We fully agree with the demand made by Edixhoven et al. (2014) that the global estimate of phosphate reserves and resources must be reliable and comparable. We argue that the high granularity promoted in Edixhoven et al. paper is not functional for reserves on a global level.

- Reserve and, even more so, resource calculations are *estimates*. Although the JORC code (2004) and all other equivalent codes require a competent person with at least five years experience in the relevant ore-deposit type, there will always be discrepancies between the estimates of two different "competent persons." *Reserve/resource classification is not an exact science.*
- *Reserve data are normally determined by private companies*. For them, reserves comprise their working inventory. The reserves may be more dependent on business planning models and investment alternatives than on the magnitude of minerals in the ground. Companies

normally have no interest in spending funds on determining reserves far into the future.

- Consequently, if we look at JORC reserves and resources and envision a future mining sequence, there is a correlation between the data of potential future mining and the accuracy of tonnage and grade figures. This has a further consequence: the *granularity* depends on the knowledge and, thus, *is time dependent*. The JORC reserves and resources will be mined first. For them, a high degree of granularity exists. For the potential reserves and resources that do not yet fulfill JORC criteria and can only be transferred into the higher categories after further exploration, far less detailed granularity is justified. The Accessible EDR (Economic Demonstrated Resources) that the USGS takes as reserves for Australia in the Mineral Commodity Summaries (Christesen, 2014) contains only 33% JORC reserves in 2013 (Geoscience Australia, 2014).
- The JORC Code and other national and international (finance-related) codes orient themselves as *investors' needs to know*. They provide information for a quantitative risk assessment for a mining company's investment. The United Nations Framework Classification (UNFC) had to follow this granularity; otherwise, it could not achieve the aim of making different classification schemes comparable.
- *Granularity can be compared to a measuring tool*. It has to be appropriate for the quality of the data. In our opinion, the perfect granularity for assessing future availability was the *reserve base* category of the USGS MCS. The reserve base was independent of short-term variations in price or other short-term economic factors, and was changed only by losses from production and increases from discovery and technological improvements (USGS and USBM, 1982). Figure 1 of this paper shows the R/C ratios for phosphate, iron, and bauxite based on reserves and reserve base. In general (see also Scholz and Wellmer, 2013), the reserve base of these commodities is one-and-a-half to nearly three times higher than the reserves.

For estimating the reserve base of a commodity, cost models are necessary. These were supplied by the US Bureau of Mines, which no longer exists. Because the cost models could not be updated any longer, the USGS discontinued to quantify the reserve base category in 2010. Taking into account that all governmental earth science organizations in the world are under considerable financial pressure, it is not likely that the basis for a new reserve base estimate can be created in the near future.

Thus, the question arises of what granularity is appropriate for reserves and resources of phosphate. One must also take into account that an assessment of resource data of one nation can be more detailed than the average assessment of the whole world. Despite the efforts of the UNFC, the data for one country will always be more homogeneous than a worldwide data set. Australia is a good example of how much aggregation is necessary and how much detail is possible in a final report. Australia had a sophisticated reporting system in place for years. As Figure 2 shows, for the most-important EDR, 20 subcategories of the UNFC system are lumped together. Concerning the JORC classification, four categories are combined in the EDR: proven and probable reserves and measured and indicated resources (Geoscience Australia, 2014, Figure A2, p. 172).

Taking the above framework conditions into account, it seems reasonable that the USGS distinguishes only two quantitative categories in its reports in the publication MCS: reserves and resources.

As outlined above, the requirement of a competent person under the JORC code applies correspondingly to global reporting systems like that of the USGS. There can be no doubt that the USGS mineral commodity specialists responsible for their chapters in MCS and in the Minerals Yearbook as well as the IFDC experts are very experienced long-term ore deposit experts who can draw many comparisons between deposits under exploitation and those still not exploited, and can judge as best as possible which publicly available information should be taken into account for the category “reserves” and which falls into the category of resources.

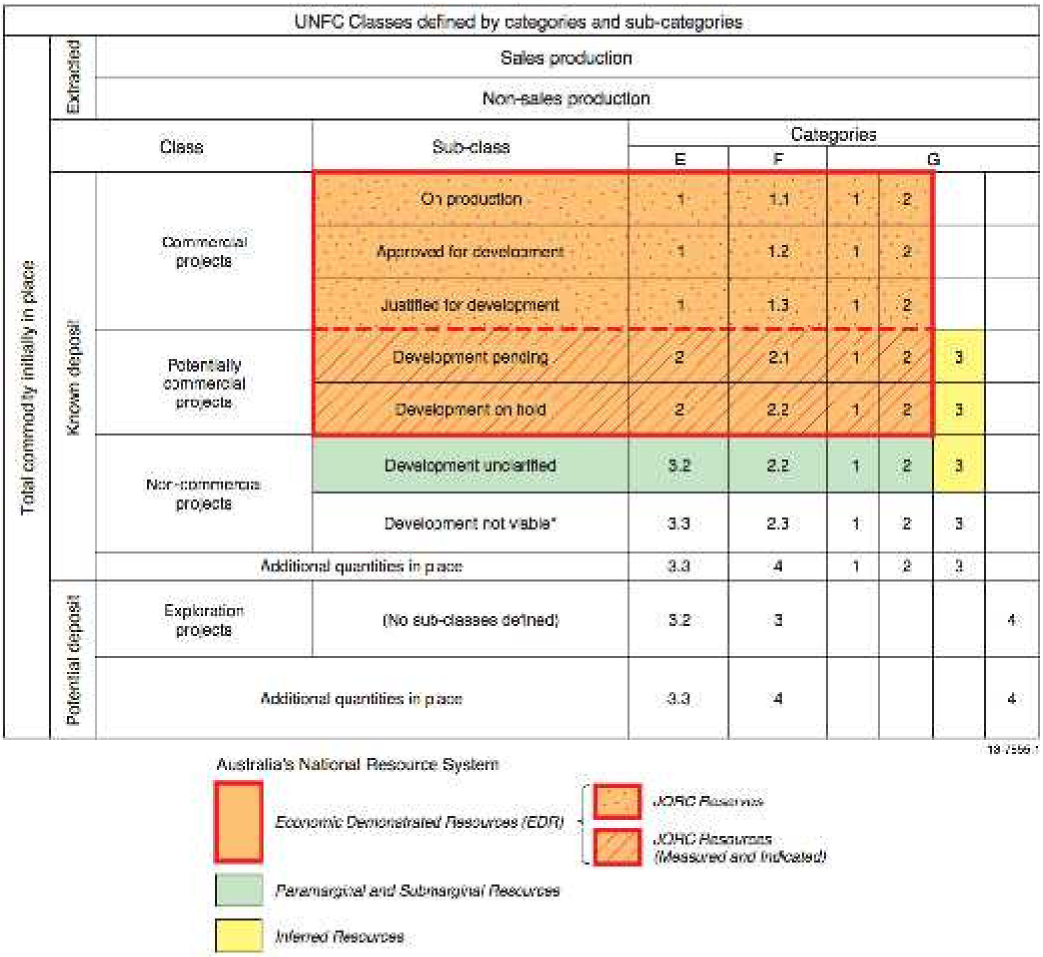

Figure 2: Correlation of Australia's national mineral resource classification system with the UNFC system (Geoscience Australia, 2014, p. 172), criteria (E) economic and social viability, (F) project status and feasibility (F), and (G) geologic knowledge.

5.2 International harmonization of the classification is meaningful

Nevertheless, conformity among the different national classifications seems reasonable. The case of the Iraq reserves may be taken as an example, where “USGS restated from zero to 5800 Mt PR overnight in 2012” and “downgraded again by 93% to a mere 430 Mt PR …” (Edixhoven, et al., 2014, p. 500). Please note that the Iraq data in the USGS MSC are factually based on PR-Ore data (see below). The uptake and correction of the Iraq data was neither a clandestine directive nor did 5370 Mt PR-Ore disappear. As has been well reported (Al-Bassam, Fernette, & Jasinski, 2012), the exploration of the 22 Iraq occurrences including 7 deposits and a resource estimate of 9.5 Gt PR-Ore has been underway since 1965 by the Iraq Geological Survey and its predecessor organization. Exploration and drilling began in 1963. For all deposits, “pilot scale beneficiation” was done “using simple beneficiation techniques” to check whether PR-M could be produced with the available technology (Al-Bassam, et al., 2012). The story of the USGS data is that the exploration in Iraq obviously reached a certain level of maturity in 2011. Unfortunately, for historical reasons the classification system labeling the Iraq reserves was the Russian system (Gert, 2007). This was well marked in the public presentation of the upgrading in the joint presentation of the Iraq and the US geological surveys (Al-Bassam, et al., 2012). In addition, the Russian system distinguishes between “reasonably assured, identified, estimated, and inferred” recoverable reserves. A second look revealed that, only some fields fulfilled the USGS criteria for reserves. The downgraded reserves did not disappear, but some reserves were downgraded to resources (Jasinski, 2013) and may appear as resources in the future after further exploration or increases in prices.

5.3 Mixing PR-Ore and PR-M (marketable phosphate rock concentrate) may be avoided

A main achievement of the Edixhoven et al. paper is the revealing of the mixing of PR-Ore and PR-M data in the USGS MSC. USGS attempts “to use reserves in terms of concentrate, but many of the foreign sources are reported in terms of ore and grade. The country specialists provide official information, if available, and some of it is reported in terms of ore and grade. . . . Data for Algeria, Syria, Iraq, South Africa are in terms or ore. US data is concentrate” (Jasinski, 2014b). The

USGS MSC 2014 (p. 119) explicitly mentions this but did not specify for which countries ore data and for which countries concentrate data are used. The question that must be answered is whether this situation essentially changes the current estimate of global phosphate reserves.

For phosphate rock reserves the entry into the USGS MCS for 2014 is 67 Gt. We know from Jasinski (2014b) that the US entry is marketable product (PR-M). According to van Kauwenbergh (van Kauwenbergh, 2006, 2010), also the Morocco and Western Sahara entry is PR-M. For Australia we know that the entry into the MCS is Accessible Economic Demonstrated Resources (EDR). Geoscience Australia (2014) reports that the Accessible EDR contains 213 Mt of P_2O_5. Taking out 31% which is classified as paramarginal and taking the average of 30% P_2O_5 for PR-M this results in 0.49 Gt PR-M instead of 0.87 Gt in the USGS MCS (Edixhoven, 2015). Thus Morocco, US, and Australia account for 51.6 Gt PR-M (instead of 52.0 in the USGS MSC entry).

As said above, the USGS conveyed (Jasinski, 2014a) the entry into the USGS MCS for Algeria, Syria, Iraq and South Africa is in terms of PR-Ore. Because we do not have information for the other remaining countries in the MCS we assume the worst case and assume that the entries also present PR-Ore. So we group all countries besides the USA, Morocco and Australia together. We will examine an investigation by van Kauwenbergh (2010) who investigated the 2010 entries of the USGS MSC to derive a number for PR-M (IFDC Reserves Product; van Kauwenbergh 2010, p. 33) and do in addition a *worst case calculation* for all countries except US, Morocco and Western Sahara and Australia for which we have data in the MSC.

If we do not take Morocco and Western Sahara, USA, and Australia into account, according to the investigation of van Kauwenbergh (2010), the conversion rate from USGS MSC 2010 entries to PR-M would be 0.8, i.e., meaning a reduction by 20%. For our *worst case calculation we a*ssume an average grade of 20% $P_2 0_5$~~. M~~. Magmatic ores are mostly lower, but most sedimentary ores are of higher grade (Steiner, Geissler, Watson, & Mew, 2015). 20% $P_2 0_5$ ore grade means that we theoretically need 1.5 t of PR-Ore to produce 1 t PR-M with 30% P_2O_5. Now we have to consider

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the mining and beneficiation efficiency. Scholz et al. (2014, pp. 48-53) intensely discuss two estimates of recent mining efficiencies, one of the IFA (International Fertilizer Industry Association; Prud'homme, 2010) and one from the IFDC (VFRC, 2012). We take the average of both which is 66%. This means instead of needing theoretically 1.5 t of PR-Ore to produce 1 to of PR-M we need in reality 1.5/0.66 = 2.3 t of PR-Ore for 1 t PR-M.

If we transfer this to the entry of the MCS, we have the entry total reserves minus the reserves for the US, Morocco and Western Sahara, and Australia, i.e., 67 Gt - 52 Gt = 15 Gt, of which we do not know if it is PR-Ore or PR-M. Taking the investigation of van Kauwenbergh of 2010 as an analogue, 15 Gt PR-ore would convert into 12 Gt PR-M. Taking the worst case scenario of above 15 Gt would convert to 6.5 Gt. In consequence the total MSC-entry for PR-M would change in the case of the van Kauwenbergh 2010 analogue to 64 Gt (and with a correction for the Australian entry to 63.8) and with the worst-case scenario to 58.5 Gt (and with a correction for the Australian entry to 58.3 Gt). Geissler and Steiner (2015) suggest a refined calculation when using the country specific ore grades for Brazil, Russia and South Africa. These three countries have lower ore grades than 20%. This would induce another reduction of 0.8 Gt PR-M and a worst case estimate of 57.5 Gt which may be seen as a “extreme worst case calculation”. This correction induces that the global share of Moroccan reserves becomes significantly higher as the non-Moroccan reserves get halved under a worst case assumptions.

It is interesting to consider the relative error. In the case of the van Kauwenbergh analogon the error relative to the MSC entry would be 5%, in the worst case scenario 13%. Although it is not directly comparable it might be helpful to compare it with errors tolerable in standard reserve calculations. If we take again a comparison with coal, being geologically similar, for example: For the accuracy of coal reserve estimation for a detailed feasibility study +/- 10 to 15% is acceptable (Standard South Africa, 2004).

5.4 The Moroccan reserves are underestimated rather than overestimated

We will now discuss why the IFDC's estimate of the Moroccan reserves does not provide an "inflated picture … of reserves" (Edixhoven et al., p. 491) and why the statement that the Morocco estimates are based on a single paper is wrong.

Naturally the paper of Gharbi (Gharbi, 1998) is an important one, the quoted paper appeared in a journal which is the official natural resources journal of the French Geological Survey BRGM and OCP officially invited to contribute to this issue. What better data can there be? Second, ~~already the reviewer~~the interactive comment of Mew (2015a), who worked for four decades (in private resources consultancy organizations) on world and Moroccan reserves for more than four decades, illuminated what exploration data have been published in OCP and others' documents. This is also reflected by a statement of IFDC which was provided to answer our question on what documents and information has been included in the assessment of the Morocco reserves:

> "In addition to Gharbi (1998), the IFDC technical bulletin/publication (van Kauwenbergh, 2010) relied on several earlier publications that recognized the vastness of the mineable reserves and the incomplete exploration of the Moroccan phosphate basins. Such publications included: Savage (1987); the OCP (OCP, 1989) contribution entitled "The Phosphate Basins of Morocco" in Notholt et al., Eds. (1989) and various other publications (Belkhadir & Chaoui, 1986; Fertilizer International, 2006; IFDC, 2006). Full references for Savage (1987), OCP (1989) and Notholt et al., (1989) are in the IFDC 2010 publication. The IFDC 2010 publication also drew from IFDC's PR knowledge base that has accumulated over 35 years of research and PR assessments including collaborative assessments with public international/national organizations and private sector companies along with the recognition that reserve figures are strongly influenced by the cost of PR/ton (IFDC, 2006, p. 43)." (IFDC, 2015)

According to van Kauwenbergh, "The phosphate rock resources of Morocco are extremely

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large and apparently still incompletely explored” (van Kauwenbergh, 2010, p. 35). In 1989, for instance, the OCP reported that 36% of the Khouribga, 18% of the Ganntour deposit, and 56.2 Gt mineable reserves were explored with a first estimate for the total resources of 140 Gt, considering the unexplored extensions of the main deposits (Savage, 1987). These data obviously refer to PR-M (van Kauwenbergh, 2013). In 1995, the aggregate resources had increased to 85.5 billion cubic meters, which equates to 171 GT PR-Oore, if we assume a density of phosphate ore rock of 2.0 for a first estimate. Also the Gharbi data from 1998 are in cubic meters; given an exploration of 45%, “the identified reserves of the Khouribga region were 37.37 billion m^3” (Gharbi, 1998, p. 128). This estimate was obviously due to the easy accessibility of the upper beds. IFDC suggested a normal conversion factor of 2 and updated the Khouribga data in 2011 based on the production data at this mine, suggesting a reserve of 28 Gt PR-M (van Kauwenbergh, 2010). Similar differentiated and reasonable estimates were given for two other areas, i.e., the Ganntour and Bu Craa deposits. This provided a reserve estimate of 51 Gt for three mining areas not including the Meskala. But IFDC assesses the four phosphate rock regions to include approximately 170 Gt PR-ore. Assuming that “regions that have not been explored contain phosphate rock that is similar in thickness and in other properties to the existing reserves are considered, the combined identified resources and hypothetical resources of the four areas are estimated at approximately 340,000 mmt.” (i.e., 340 Gt; van Kauwenbergh, 2010, p. 36)

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As Mew pointed out, “much of the confusion … stems from the fact that on average, 1 m3 of OCP ore more or less equates 1 tonne of PR.M” (Mew, 2015a, p. C8) and OCP annual reports and geological papers report PR often in cubic meters.

The IFDC report stresses that the production costs are not assessed but will increase by various factors, such as the increase of the carbonate content in some ores. Given the present exploration, the ore grades of the explored fields are exceptionally high and, on average, around 30 % and thus of the magnitude of concentration of PR-M. With respect to cost development OCP conveyed that the company had (roughly) estimated the cost for producing PR-M for reserves far above the 50 Gt PR-M which are recorded in the USGS-MSC (Terrab, 2012).

Moroccan mining activities are in a permanent development. For several years, three new mines at Khouribga and one at Ganntour have been under development (OCP, 2014). OCP considers Meskala the "largest phosphate deposit to be developed since 70'" (El Omri, 2015, p. 7). Meskala is a non-producing district and has not been included in the IFDC assessment. Given an almost 100-year history of exploration and the specifics of the geological setting, it is clear that different parts of the 10,000 km^2 are on different levels of the exploration ladder (Marjoribanks, 2010). Furthermore, in many places the distinction whether reserves or resources are "demonstrated (measured and/or indicated) and identified (demonstrated and/or inferred)" (Edixhoven, 2013, p. 11) develops over time as a combination of multiple evidences from continuing exploration and mining experience. Against this background, the conclusion that the "increase of Moroccan reserves … was … due a to simple restatements of ore resources as ore reserves" (Edixhoven et al., p. 504) seems to be a very biased statement which is far from properly acknowledging the different types of data. It is a little misleading ~~(Type 2 argument)~~ that Edixhoven et al. (2014) do not acknowledge that some "restatement[s]" of the IFDC report and in other places were based on reasonable conversions between cubic meters PR-ore and tons PR-M.

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6. *Improving the transdisciplinary dialogue between those with knowledge in science and those with experiences from practice*

Julian Hilton, in his extensive critique of the first version of the Edixhoven et al. (2013), has done an excellent job of describing many facets that characterize the rationales of key stakeholders. Let us look at just a few issues that demonstrate the complexity of phosphorus management: "Major mining companies are notorious for understating reserves, while juniors tend to overstate because they want to attract investors"; "Many emerging/developing countries depend heavily on their P resources … so resource data may be withheld for commercial and/or strategic reasons …”; “Large resource-hungry countries such as China will guard PR resources as strategic resources and hence not disclose quantities available …”; “The Era-MIN network … estimates an increase of some 50% in resource quantification” by “improved exploration and analytical techniques.” Or the issue that in developed countries is a “social license to operate.” Phosphorus mining is a matter of political decision-making that may be reversed. Based on these factors, it becomes less and less likely that the major PR producers will disclose their hands, especially where the production base is financed through the world’s stock exchanges …” (all quoted from Hilton, 2014, pp. 2-3).

The assessment and management of the geopotential of the resources and reserves of phosphorus is a complex, societally relevant issue that has to be addressed by relating knowledge from the various stakeholders and a wider range of scientific disciplines. To better understand the dynamics and pitfalls of phosphorus management, a “collaborative effort by phosphate rock producers, government agencies, international organizations and academia will be required to make a more definitive current estimate of world phosphate rock reserves and resources” (van Kauwenbergh, 2010, p. 1). Against this background, the paper by Edixhoven et al. looks like a strange academic desktop study that is missing the interaction with practitioners to understand (i) the knowledge gained in exploration and mining operations/companies and (ii) the constraints faced by different stakeholders when dealing with reserve data. Applying a “tone of moral indignation with … the intention to shame PR producers into disclosure of the reserves and resources they hold” (Hilton, 2014) is certainly not an acceptable strategy. Transdisciplinary processes, such as those induced by the Global TraPs project on “Sustainable Phosphorus Management” (Scholz, Roy, Brand, Hellums, & Ulrich, 2014), in which representatives from all key stakeholder groups participated, are a necessary means of learning both for practice (e.g., to better understand the complexity and long-term issues of sustainable resources management) as well as from scientists to acknowledge the multiple contexts and constraints to which a reliable access to reserve data is exposed.

7. General discussion and conclusions

7.1 There is sufficient knowledge for estimating phosphate reserves and resources

PR-Ore and PR-M have to be distinguished: The main contribution of Edixhoven et al. has been that data on phosphate rock ore and phosphate concentrate (both abbreviated as PR in their paper) are sometimes not properly distinguished. Given that the ore is economically mineable, the conversion factor depends, among others, on ore grade and the efficiency (or losses) of recovery and losses in the process of beneficiation. The overall USGS MCS include data for four countries which provided ore data for which no conversion from PR-Ore to PR-M has been performed. And there have been 16 countries where no specification on the national reporting was provided by USGS. A rough worst case calculation indicated that—if we take *marketable* phosphate rock concentrate with 30% P2O5 (PR-M) as the measuring unit—the current global reserve estimate amounts to an estimate of 58 Gt PR-M (which is about 13% smaller than the USGS estimate).

Initiating a process of consenting on a proper granularity of reserve estimates: Mine-specific, national, and global classification systems have different functions and ask for different levels of accuracy. From a global perspective, both with respect to providing reliable information for functioning markets as well as for assuring long-term supply security, a simple, feasible, and sufficiently reliable classification system that is acceptable to all key players is helpful. We argue that the distinction between *reserves, reserve base,* and *resources* (USGS & USBM, 1980) has been such a system. Since the reserve base category cannot be quantified anymore, there are now only the two categories, reserve and resources. We argue that the detail of the data of these categories are sufficient to analyze the dynamic natures of reserves and resources.

There is no physical scarcity of rock phosphate in the near future: Edixhoven et al. put reserves in the context of “longevity of mineable PR deposits” (Edixhoven et al, 2014, p. 492). This is misleading and wrong as reserves are mining company’s planning data and do not relate to global URR estimates for P. This is independent of who assessed the reserves. Phosphate rock is a low-cost commodity. And prices are very flexible; in addition, phosphorus reserves have the potential to increase easily due to technological advancements like economic underground mining. There will be no physical scarcity in the short and mid-term future. However, the finiteness of the P reserves asks for special efforts for monitoring the geopotential for providing timely adaptation means from a resources security perspective.

The Moroccan reserves are big: Based on almost 100 years of exploration and mining, it is clear that Morocco (including the Western Sahara area) owns the largest currently known phosphate reserves in the (terrestrial) world. Given an annual production rate of 0.028 Gt PR-M in Morocco and a current annual demand of a magnitude of 0.2 Gt PR-M, there are no incentives or needs for the national company to assess exactly what parts of the magnitude of 340 Gt PR-Ore resources (van Kauwenbergh, 2010, p. 36) identified may be mined economically with today’s costs. Edixhoven et al. (2014) did not acknowledge that the Morocco P reserves were not only upgraded after 20 years based on new exploration but also after the more than tripling of the prices of PR-M. According to our analyses and the data publically available or provided by the OCP, there is reliable evidence that at least 50 Gt PR-M may be mined with the current mining regime.

Developing a proper understanding of the accuracy of reserve estimates: The assessment of the current economically mineable phosphate ores is not a matter of exact science. Given a magnitude of 0.2 Gt PR-M phosphate concentrate of annual production and a magnitude of 60 Gt PR-M as global reserves, no one would be willing to pay for reliable information about what might be produced in 300 years for today’s costs. Also against this background, it is unfortunate that the basis to quantify the reserve base does not exist anymore (see above). When providing an assessment on the current phosphorus reserves, it is important to acknowledge that some country’s reserve estimates are provided sometimes by companies that historically worked with different classification systems such as the Russian, Australian, Chinese or others or that of the USGS. Thus, the 22-country data of the USGS MCS 2014 do not all have the same basis. It is also evident that a highly differentiated and costly assessment applying the JORC or equivalent classification systems (which are prescribed by the major stock exchanges) or fixed drilling plans are not meaningful for an estimate of global reserves. An overly ”detailed granularity” for a global assessment seem to be dysfunctional ~~and naïve~~. Nevertheless, requiring transparency and compatibility of data is a meaningful suggestion, though we have to ask how this may be achieved (see below).

7.2 Why do we have so different estimates of reserves and resources?

7.2.1 Are there differences in estimates due to misinterpreting data or systems?

In principle, both camps, the optimists and the pessimists, use the same data but interpret them differently. But some data are differently interpreted or validated. The changes of Iraq data in the USGS Mineral Commodity Summaries or the conversion of volume to tons in the case of Morocco deposits may be taken as example. The Iraq data was corrected when the incompatibility of the Russian and the USGS classification was noticed. But we find also continuous misuse of data (in modeling) such as using reserve data as substitute for URR is an example which may endanger the integrity of science.

Many papers on phosphorus scarcity, such as the Edixhoven et al. (2014) paper, lack the incorporation of *the interaction of supply and demand by feedback control systems*. Factors such as long-term supply security, intergenerative justice, and the prevention of unacceptable environmental pollution ask for understanding of the supply–demand dynamics and the identification of potential barriers to getting access to sufficient phosphates in the future. Here, “[s]tatic lifetime [i.e., the R/C ratio] … may serve as screening indicator[s] preceding early warning research” (Scholz & Wellmer, 2013, p. 11). Valid and reliable data on reserves and resources help. But when talking about these data, we have to properly acknowledge the uncertainty and the *satisficing principle* (Simon, 1955). The precision of the resources and consumption data must be good enough to draw adequate conclusions. Harmonization and transparency of the data as well as a consistent unit of recording are helpful. However, the real challenge from a sustainability-science perspective is to develop a sufficiently comprehensive system view and the capability to answer questions such as: Is the current dynamic of consumption of mineral phosphorus (in agriculture, industry, diets, etc.), the increase of efficiency in production and use (as fertilizers, food additive, increasing human population), the incorporation of recycling (farms, household level, sewage plants, etc.) or substitution (e.g., of phosphates in technical applications) sufficient, given the geopotential for phosphorus in the long-term future (i.e., what resources may be identified, what resources may become reserves, how the costs develop, etc.) and the prospective environmental and social costs related to its use?

The amount of phosphorus reserves, for instance, changes on a monthly if not daily basis as what is economic mineable depends on the (volatile) market price for PR-M. But changes in the entry change discontinuously. Two main factors here is the point if the knowledge of an exploration program has attained a certainty for providing a changed judgment. Another is the judgment whether a new price level has been attained as it has been after the 2008 price peak (Mew, 2015b; Weber et al., 2014). Both aspects played a role in the 2010 upgrading of the Morocco data. Properly interpreting this asks for system literacy on coupled human-resources systems matters (Scholz, 2011) which is often missing. Thus, (natural) resources science is a genuine interdisciplinary field and requires modeling and conceptualization about how human systems may get access to geologic resources.

But even more, often the knowledge from the science system is not sufficient for assessing the globally available resources. Much knowledge and data are in the possession of large mining companies, geological institutions, traders, financial institutions, etc. Transdisciplinarity has become one option by which we may efficiently relate knowledge from science and practice about the geosystem, market mechanisms, political regimes, environmental standards and impacts, and the multiple constraints on contexts that are related to mining in precompetitive discourses (Scholz, Roy, & Hellums, 2014). Unfortunately many scientists do not sufficiently acknowledge the important role and epistemics of practice in resources management (Scholz & Steiner, 2015).

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7.2.2 The camps of sceptics/pessimists and optimists/realists should talk to each other

In science as in society, we may find camps of optimists and pessimists/skeptics (Tilton, 1977). The pessimist mind-set that human population growth and demands increase faster than the world's resources can provide for was introduced by Thomas Malthus (1766–1843). The mixing of finiteness with staticness by neo-Malthusians may be taken as example. The opposite camp of Malthusian skeptics, sometimes labeled Cornucopians, believes that the capacity of the human mind is unlimited, and that each problem that arises, such as the problem of physical scarcity, can be overcome by technology (McKelvey, 1972).

Presumably, the truth may be found somewhere in the middle. Given the finiteness and the current level of demand, there will be a peak phosphorus level some day either as the prices become so high that consumption has to be adjusted (Scholz & Wellmer, 2013) or as humankind sophistically induces a demand driven peak by closing the anthropogenic phosphorus cycle (Scholz, Roy, & Hellums, 2014). Phosphorus atoms do not disappear. We suggest that resources science should focus on phosphorus flow analysis and management that encourages recycling and prevents the dissemination of phosphorus into the sea (Scholz & Wellmer, 2015).

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Scepticism may get political function: Sociologists argue that (environmental) "scepticism is a tactic of an elite-driven countermovement designed to combat environmentalism, and that the successful use of this tactic has contributed to the weakening of US commitment to environmental protection" (Jacques, Dunlap, & Freeman, 2008, p. 349). Likewise, skeptics may consider the critique of the high Moroccan phosphate reserve estimate as a free ticket to unrestricted increase of phosphorus use and delay of recycling attempts. A critical question in this context is whether the phosphate industry may have artificially increased the Moroccan reserve data for facilitating the purchase of increasing amounts of fertilizer or for preventing policy means to promote recycling. Contrary, one may argue that an artificial increase of reserve data rather induces the idea of oversupply and thus tends to decrease phosphate prices. Here, a high estimate of the Moroccan reserves—aligned with the argument of scarcity—may cause a politically uncomfortable situation for Morocco as it may cause territorial greediness by others. When taking a critical look at these positions, these authors do not find evidence for an interest-driven overestimation of phosphate reserves by the USGS. In our opinion, the estimates are reasonable and are updated if new information becomes available. But, as resources data are of societal and political importance, and the public at large is interested in the science knowledge about this issue, both camps should communicate to avoid unnecessary public confusion.

7.3 Rethinking the process of assessing data on reserves and resources

For any grade level, mineral phosphate reserves are finite and nonrenewable on a human time scale, and accessibility to phosphorus is essential for feeding a large world population. Thus, from the perspective of sustainability, there is a genuine interest in knowing whether and when humanity is facing supply insecurity. Wellmer and Scholz (Wellmer & Scholz, 2015) discuss the question of whether there is a right to know about the reserves, resources, and geopotential. Edixhoven et al. (p. 24) ask for a "truly independent and scientifically sound global inventory of PR deposits."

This request is facing the dilemma that—according to the rules of the global market system—the data on reserves are owned by those who generate them, and these are mostly companies who have collected the data for business purposes, given a time horizon of normally up to 50 years, only in special cases up to 100 years. Against this background, we suggest a "solidly funded international standing committee that regularly analyzes the global geopotential, focusing on the source of the future reserves and resources" (Wellmer & Scholz, 2015). Such a committee may be established under the auspices of the International Union of Geosciences (IUGS) which has a significant input from governmental earth science organization or anchored initially at EuroGeoSurveys (Association of the European Geological Surveys)" (Wellmer & Scholz, 2015). As mentioned above, the knowledge from practice should also be properly included here. The critical question, however, is whether the public is willing to pay for such an assessment of geopotential. This is a challenging and expensive issue. The principles of *precautionary action* and *the right to know* (Foerstel, 1999; Jasanoff, 1988) may be referred to here are internationally intensely discussed policy and legal means. Both concepts developed in the context of environmental pollution and later in climate change (Jacobs, 2014) but can also be applied to the field of resources if scarcity concerns call for precaution, and the present level of consumption is seen as a societally unacceptable risk for future human generations. However, such a judgment asks for comparative assessment with other environmental priorities. As the costs for this have to be covered by the public at large, this calls for a broad, international societal and political commitment. We argue that phosphorus may serve as an excellent learning case for how such a process may look and how global resource literacy may be developed.

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