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Supplement of

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

R. W. Scholz and F.-W. Wellmer

Correspondence to:

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Section S1: Learning from the history of reserves and resources from other commodities

Geoscientists question why the continuous learning processes that can be observed in relation to other commodities around the world are not transferred to phosphate. Why should phosphate miners and explorers be less successful and less creative than their colleagues? A few examples:

- Scholz and Wellmer (2013, Fig. 3) showed that for metals the reserve/consumption (R/C) ratio is far less than that for phosphate. For phosphate, the ratio is increasing, even without considering Morocco. However, let us take the very pessimistic view that the ratio is not increasing but staying within a spread of equilibrium values that satisfy the planning scope of mining companies. This is true for all metals with a much lower R/C ratio. For copper, for example, the R/C ratio of about 40 stayed within this spread of equilibrium values despite production that more than quadrupled from about 4 Mio t in 1960 to 17 Mio t today. The question that arises is this: What R/C ratio is satisfactory for a commodity derived mainly from stratabound sedimentary deposits? This question will be answered at the end of this section.
- In the period from 1960 to the present time, the average world copper grade decreased from 2% Cu to 1% Cu (Schodde, 2010), without an increase in real prices (see Scholz & Wellmer, 2013, Fig. 15).
- With the technological breakthroughs of horizontal drilling and hydraulic fracking, the US has reversed the decline of oil and natural gas production and decreased production costs. Oil production is expected to surpass its 1970 peak in the near future (Figure 1). The 1970 peak was the peak that Hubbert modeled in 1956 with an error of only one year and the peak that started the discussions about other possible commodity peaks. Hydraulic fracking may also be taken as an example of mining a resource from a new medium (i.e., shale oil production from primary deposits vs. production from reservoir rocks into which the oil migrated); similar innovations may be considered in relation to phosphorus.
- New geologic environments become potential ore deposits due to technological developments. Nickeliferous laterites are one example; in 1950, less than 10% of world nickel production came from laterites. In 2003, that figure was 43%, and its relative share is expected to grow (Dalvi, Bacon, & Osborne, 2004); 60% of the world-based nickel resources are contained in laterite (Kuck, 2013). Now, a totally new type of nickel deposit has been discovered: awaruite, a natural iron–nickel alloy naturally occurring in peridotites,

a mafic magmatic rock. Awaruite is easier to concentrate than the sulfidic nickel mineral pentlandite (Kuck, 2013).

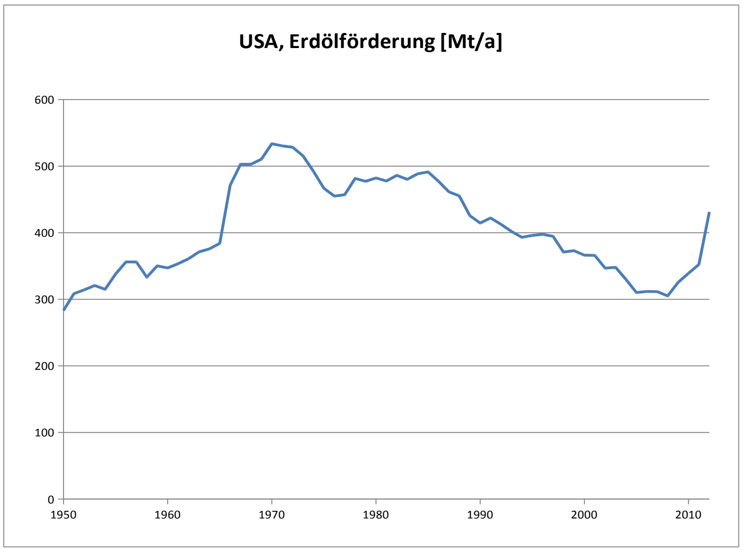

Figure S1: US oil production (Source: BGR data bank)

Why should a similar shift not occur in phosphates? In the 1930s, more than 10% of the world's supply came from guano deposits (USBM, 1935). That share is negligible today and has been replaced by sedimentary and magmatic deposits. Even if no additional sedimentary deposits could be found (which, in our opinion, is highly unlikely), the potential remains for other geologic environments like magmatic deposits, marine phosphorite nodules, and mining of low ore grade. As shown in the case of laterites, it is not justified to conclude the ratio of tomorrow from the ratio of deposit types mined today. Neither is it justified to draw conclusions about today's knowledge of a geological environment to the knowledge of tomorrow, especially after the exploration industry moves in with active exploration activities. The state of knowledge of the geopotential field of the Total Resource Box Fig. 3 (Scholz, Wellmer, & DeYoung Jr., 2014) is dynamic, too.

If one examines the phosphate situation, equivalent learning effects can be observed. As an example, the Economic Demonstrated Resources (EDR) of phosphate in Australia shall be considered (Figure 2). One sees a ninefold increase from 2008 to 2011 in a country with very strict reporting standards. In addition, there are the inferred resources, of which not everything can be transferred into the EDR field, but certainly—judging from geologic experience—the share will be larger than zero. The inferred resources are 2.4 times larger in 2013 than the EDR.

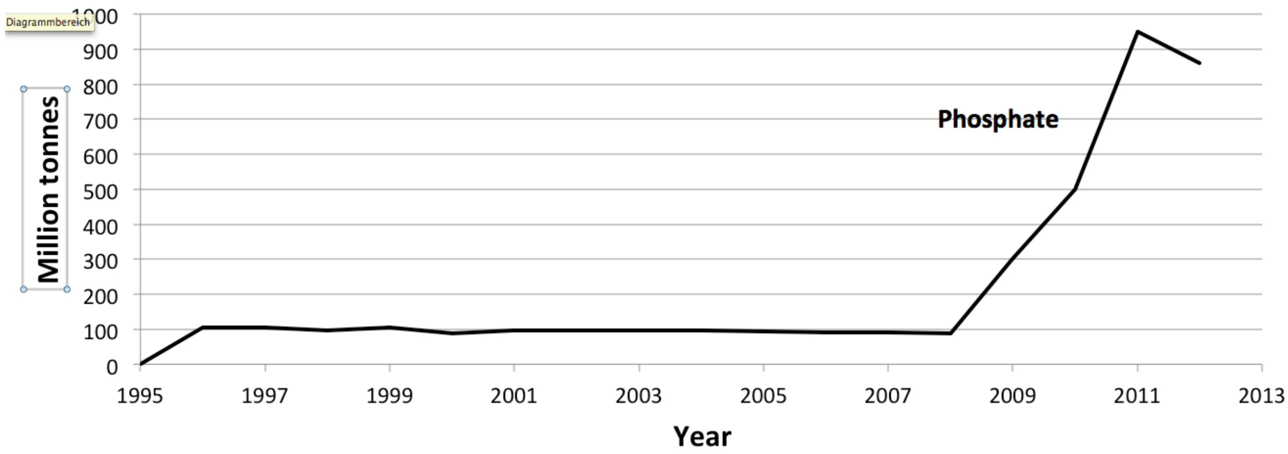

Figure S2: Australia's Economic Demonstrated Resources of phosphate (Geoscience Australia, 2014)

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 3 (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 if this is true, as outlined by Scholz and Wellmer (Anonymous Referee #2, 2014; see also Metals Economics Group, 2012). One also wonders 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).

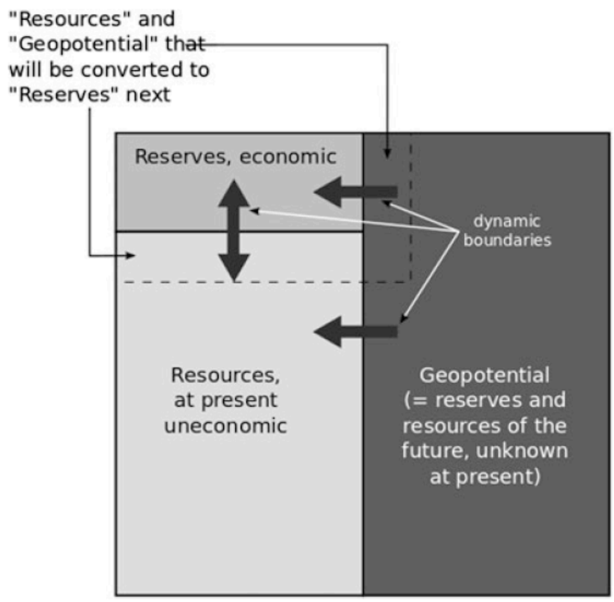

Figure S3: The total resources box (Scholz, Wellmer, et al., 2014; modified from Wellmer, 2008)

Scholz and Wellmer (Scholz & Wellmer, 2013) showed that the R/C ratios for singular, *lens-like deposits* such as those for copper, lead, or zinc have R/C ratios between 20 and 40. Commodities derived from *stratabound sedimentary* deposits with a much larger aereal extent than zinc or copper deposits, which can easily be extracted like coal, potash, and bauxite, normally have R/C ratios in the range of 100 or even higher. In order to answer the question of what satisfactory R/C ratios are for a commodity coming mainly from stratabound sedimentary deposits like phosphate, we shall do a thought experiment. We will compare phosphate with two other commodities that are considered by practically every raw-material expert in the world to be not considered critical by commodity experts, iron ore and bauxite, the raw materials for aluminum.

- Gordon, Bertram, and Graedel (2006) examine the sustainability of various elements, especially copper, and reach this conclusion: "We will see ... an increased use of abundant alternative materials, principally iron and its alloys, aluminum and magnesium. We anticipate a gradual transition to reliance on these alternative materials."
- The recent study of the Joint Research Centre of the European Commission on critical metals in the path towards the decarbonisation of the EU energy sector (Moss, Tzimas, Willis, Arendorf, & Espinoza, 2013) does not even consider iron and aluminum worth examining.
- Erdmann and Graedel (2011) compared seven important criticality studies from Europe and the US. None considered iron critical, and only one considered aluminum critical.

Now we are comparing the R/C ratios for phosphate, iron ore, and bauxite, the raw material for aluminum and iron ore, in Figure 4. Phosphate, iron ore, and bauxite are in the same range. Phosphate, even not taking the Moroccan data into account, is increasing (contrary to iron ore and bauxite, which are decreasing) mainly due to the rapid increase of Chinese consumption since 2000, which cannot be followed immediately by exploration successes to keep the R/C-ratio constant.

We may conclude the following: Taking the dynamics of reserve and resource development into account and comparing phosphate with two commodities, not considered critical by commodity expert, iron ore and bauxite, there is no reason to worry about phosphate depletion even in the mid-term future.

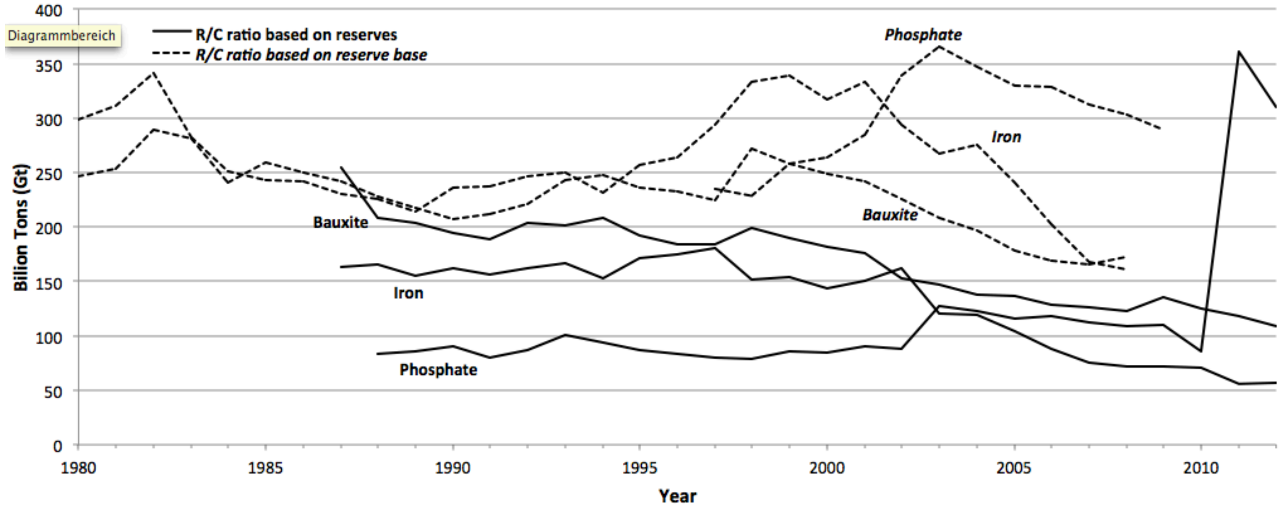

Figure S4: Comparison of the development of the R/C ratios (based on reserve base to 2008/2009 and reserves) of phosphate with iron ore and bauxite (Source: USGS MCS, BGR data bank)

Section S2: Geoengineering of deep underground mines

Scholz & Wellmer (2013) provided an estimate of the URR (ultimate recoverable resource) of the Western Phosphate Field (WPF) in the US, one of the largest phosphate provinces of the world, of an amount at least 1000 times 178.5 Mt PR-M (when taking the estimate of 2010 world production by IFA; Prud'homme, 2011) supply, to indicate that there will be no necessary physical scarcity in the near future. This, of course, is a first (rough) expert judgment rather than a sourced calculation. Edixhoven et al. (2013 and 2014) are querying this estimate. Without repeating the arguments of Scholz and Wellmer (2014; Scholz & Wellmer, 2013), certain principle aspects shall be pointed out when looking far into the future of the technology of exploitation:

- Mining in the future will be by remote control, as already utilized in the Kiruna iron ore mine in Sweden. Thus, the geothermal gradient is of less importance. Scientists in the 1970s and 1980s trying to judge if a mineralization could be classified as a resource were hardly able to foresee this advance in technology.
- The increasing losses related to going deeper in underground mining using the conventional room and pillar mine system can be avoided by using longwall mining methods with hydraulic roof support, which are already used in Germany in coal mines to a depth of 1500 m.
- The EU is considering supporting research for discovering and exploiting mineral resources down to 3000 m, which is seen as the mine of the future.
- The above estimate for future WPF reserves is an estimate which is of interest in 300 years when all today known reserves are mined.. Given the flexibility of the price and fundamental innovations in mining technology, the WPF is only of interest if more easily accessible reserves are consumed first.

Naturally, the *dynamics of the demand* must also be incorporated, and it is clear that the factual consumption of PR equivalents (please note also that nonprocessed phosphate rock is used in agriculture) is globally increasing in the next years. Currently, this is due mostly to inefficient use, primarily in Asian countries (Sattari, Bouwman, Giller, & van Ittersum, 2012; Scholz, Roy, & Hellums, 2014). There are many indicators of the inefficient (over)use of phosphate fertilizer today. An input to the agro-food chain at the magnitude of 200 Mt PR-M annually may suffice to feed an increasing population if food production becomes more nutrient efficient.

An estimate of the URR of the WPF was made in order to demonstrate how resources may become reserves. A fundamental error made by Edixhoven et al. and several others is that they mix finiteness and staticness. The world's phosphate ores are finite. But this does not imply that reserves are fixed.

Section S3: The rationale of Hubbert analysis on phosphorus reserves

Marion King Hubbert (1903–1989) wanted to overcome the simple, static snapshot view of the linear R/C ratio model for estimating future production of oil and other fuels. When facing the rapidly increasing demand and comprising the knowledge of 100 years exploration and petroleum recovery (Pratt, 1944, 1956), Hubbert, in 1956, provided (Hubbert, 1956) the remarkable prediction that oil production $P(t)$ would peak between 1965 and 1970. Factually, there was a US oil peak at that time (see Figure 1, Section SI). Later, some scientists applied the Hubbert approach to make predictions on future phosphorus on local, regional, and global scales (Déry & Anderson, 2007). However, some of these applications did not reflect on the prerequisites that must be provided for an application of the Hubbert analysis. We briefly reconstruct Hubbert's modeling to help the reader understand when and why the Hubbert analysis fails. We show that the severe critiques of some predictions of global phosphorus production are not due—as Edixhoven et al. (2014) assume—to the fact that they "sourced from the Mineral Commodity Summaries," e.g., because something is thought to be wrong with the USGS data. We elaborate that the application to the global data is due to the erroneous assumption that the current estimates of reserves may be considered as an estimate of the URR.

Hubbert was facing the following prerequisites: Since the late nineteenth century, US oil production/demand was strongly increasing. Growth was exponential between 1875 and 1930 (Hubbert, 1956). "Petroleum liquids" of "liquid hydrocarbons" have been superior to other fuels and a favorite chemical; there was a supply-driven market as everything produced was consumed. Based on 100 years of exploration and recovery in the US, there were good estimates (of magnitude) for the URR of 170 to 200 billion barrels of crude oil (BBO) and with 1250 BBO a very poor estimate of (magnitude) global URR. The world's proven reserves in 2013 are 1645 billion barrels (EIA, 2014). Currently, for the US, a little more than 100 BBO were produced and the proven reserves are around 30.5 BBO (EIA, 2014).

Hubbert (Hubbert, 1956) distinguished between "proved reserves" and what was recovered in the long run (in this section, we call this URR, although the URR is formally the sum of the cumulative production of the past plus what may be recovered in the future). The proved reserves, depending on fuel and region, covered about 10 to 20% of the supposed URR. Hubbert was aware that, with oil, (a limited) number or regional exploration cycles will increase the reserves, but in 1956 Pratt's URR estimates were his reference points. We should note that he included differentiated estimates for BBO estimates for oil from oil shales and tar sands. And, most interesting, when assessing the uranium reserves, he included an estimation of the 500 Gt "phosphoria formation" for the WPF "deposits" (Hubbert, 1956).

Later, Hubbert (Hubbert, 1959) specified the functional form of the prediction curve, and he analyzed patterns of discovery and their impact on production $P(t)$ over time, presenting the major elements of modern Hubbert analysis (Brandt, 2007). This is based on a logistic (growth) function (which in its simplest form reads $P(t)=\frac{1}{1+e^{-t}}$). This mathematical function was developed in 1844 by Pierre Verhulst to model population growth, when assuming a carrying capacity Q and a growth rate r and a population size $N=Q(t)=\int_0^t P(t)\,dt$. In the context of resource mining, the carrying capacity $Q=Q_\infty$ mutates to $URR=Q_\infty$ and the population size $N=Q(t)$ becomes the cumulative production at time t. The population growth $P(t)$ mutates to the production at a certain time t in a logistic function with a constant exploitation parameter r. The production curve $P(t)$ is symmetrical and a derivation of the sigmoidal curve of cumulative production $Q(t)$. In some applications, such as Cordell et al. (2009), without reasoning, a Gaussian curve is taken. Naturally, this curve is symmetric (it emerges theoretically from a sum of an infinite number of small errors), but also the choice of the curve is a matter of reasoning. For instance, the symmetry of the curve was already questioned by Hubbert, stating that "probably … the rate of decline of the" production is "less steep" than the rise (Hubbert, 1956, p. 26).

Later, the demand of knowing a URR was given up. Modern Hubbert analysis suggests that just a curve fitting of the historic logistic production curve would predict the URR and the peak of production.

The following lessons may be learned from Hubbert's analysis on US oil. The model only works if the market is a supply-driven market. This means that the amount of a commodity that is produced at any time is bought by the market, and the market may exist also with decreasing supply after the peak (e.g., by using alternative primary energy). The regulation (feedback) rule that the reserves and also the URR depend on price is neglected. Also, a multi-phasing of the production cycle by technology development has not been detected. Figure 1 of SI1, for instance, shows that US oil production has been steadily increasing for about 10 years. This is due to the new technology of fracking, which liberates oil by hydraulic fracturing. Hubbert was well aware of oil from oil shale and tar sand deposits. But his estimates were fallacious, as he referred only to conventional extraction from shale and tar sand deposits and did not anticipate the dynamics of reserves and of the URR as a result of technological innovations.

If we look at the application of the Hubbert analysis to phosphorus, three types of applications have to be distinguished; two of them are unsubstantiated, and one provides the criteria for the Hubbert analysis.

An example of a successful application of the modern Hubbert curve analysis has been provided by Déry in relation to the guano mining on Nauru island (Déry & Anderson, 2007), once known as the smallest republic in the world. In 2007, the guano deposit had been completely stripped off after 90 years. The analysis predicted the production curve and the peak accurately when using the data from 1959 or later. The Hubbert analysis was successful, as it has been applied to a fixed deposit of guano. The economic efforts increased production until a peak after which it was more difficult to mine (the best pieces were taken), and investment efforts became less attractive. All guano, with its organic matrix, was sold immediately until the whole deposit was exploited.

A first negative example of the modern Hubbert analysis was reported by Déry and Anderson (Déry & Anderson, 2007). If you fit a logistic or Gaussian curve to the global mineral phosphorus production, you receive an estimate of a little more that 8 Gt PR-M as not yet mined URR. This is of the magnitude of factor 10 below the USGS estimate reserves (see also Vaccari & Strigul, 2011).

Cordell et al. (2009) provided an example for an incorrect Hubbert analysis with postulated known URR. As there is no estimate for a URR, she took the USGS estimate of today's reserves (i.e., of those reserves that may be mined economically with today's technology) plus the cumulative production of the past as a proxy for the URR. When using the 2010 data, she derived a peak of phosphorus production in 2033 and a decline of phosphorus production to marginal amounts of phosphate ore rock production in 50 to 100 years. When the USGS data of reserves increased from 16 Gt in 2009 to 65 Gt in 2010 (Jasinski, 2010, 2011), Cordell et al. provided the same calculation, providing somewhat larger but completely unrealistic numbers again (Cordell, White, & Lindström, 2011, April 4).

We come back to this topic at the end of this comment. Perhaps we should mention that utilizing the USGS data on reserves as an estimate of the world's URR even falls much behind the early (conservative) Club of Rome reasoning. Meadows et al. (1974, pp. pp. 58-59), for instance, multiplied the reserves by a factor of 5 to take future discoveries into account and change them when providing a prediction on when humankind runs short of some minerals. But even this turned out to be an underestimation.

If current consumption proceeds continuously, "… one day there may be a supply-driven P production peak, …" (Scholz & Wellmer, 2013, p. 11). This will hold true particularly if the unbroken increase in phosphate consumption continues. But we do not have enough scientific knowledge about the magnitude of the URR and the dynamics of demand and technology development to provide a robust estimate of a supply-driven peak. Rather, given the high environmental costs (Sharpley, 2014), we hope that we may face a demand-driven peak emerging from reducing consumption and making progress in closing the anthropogenic phosphorus cycle.

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