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Phosphate rock production and depletion: Regional disaggregated modeling and global implications

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ABSTRACT

Numerous recent studies discuss phosphate rock extraction, and some even propose that a peak in production could be reached in coming decades. This would have great consequences as phosphate rock based fertilizers are irreplaceable in modern agriculture. Studies suggesting an impending peak commonly use curve fitting models where mathematical functions are fitted to historical world production data, while studies using other methods reach completely different results. Also, a sudden increase in global reserve estimates is commonly used to dismiss these warnings, and has somewhat altered the debate. The recent multiplication of estimated reserves is mostly based on an increase of the Moroccan reserve estimate, leading to Morocco currently making up most of the global reserves. This study models global phosphate rock production using a disaggregated curve fitting model based on the production in individual major producing countries, providing a somewhat different view than most studies, and show that the global trade of phosphate rock could be completely dependent on Morocco in the future. There are several different factors that can potentially limit global production and these factors should be considered for the individual producing countries. Society's total dependence on phosphate rock should be further investigated despite claims of large resource occurrences.

1. Introduction

Phosphorus (P) is an essential element for all life on earth and global food production is highly dependent on the use of fertilizers produced from phosphate rock (Smil, 2000). As phosphate rock is a finite resource and global production is rising fast, several studies have warned that a maximum phosphorus production could be reached within a foreseeable future (Déry and Anderson, 2007; Rosemarin et al., 2009; Cordell et al., 2009; Mórrígan, 2010; Mohr and Evans, 2013). Cordell et al. (2009) estimated that world production could reach a peak at an annual production of 203 Mt of phosphate rock concentrate around the year 2033, which led to a debate on whether a "*peak phosphorus*" was imminent or not. This was followed by a report for the International Fertilizer Development Center (IFDC) by van Kauwenbergh (2010) which suggested that Morocco's estimated reserves were in fact much larger than previously indicated. In 2011, the United States Geological Survey (USGS) increased their global reserves estimate from 16 Gt to 65 Gt, apparently based on this dramatic increase in the Moroccan reserve estimate (Edixhoven et al., 2013).

Different types of models have been used to investigate potential future shortages in phosphorus supply and the major features of a wide range of studies are summarized in Table 1. Several studies have used curve fitting models or system dynamics on global production and proposed that a peak in production could very well be reached during this current century, while other studies often relying on static or dynamic reserve to production (R/P) ratios generally express that the reserves will be sufficient for decades or centuries to come. The results from these studies vary significantly, as well as the reserve estimates used. Hence, the sudden increase in estimated global reserves critically changes the results and R/P ratios suggesting that phosphate rock supplies will not be depleted for hundreds of years have been presented.

The aim of this study is to provide new perspectives on global production and depletion of phosphate rock by providing a model somewhat different than those described in Table 1. By breaking down the aggregated world production into production trajectories of individual producing countries, the importance of the current major producing countries like Morocco, China and the USA are highlighted. Potential constraints and bottlenecks could then be analyzed in the context of these specific countries, instead of being discussed in more general terms on a global scale. To deal with the large uncertainties regarding reserve estimates, different cases using different reserve estimates are modeled. Also, two different

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Table 1
Main features of previous studies on phosphate rock depletion and production.

Study	Peak year	Full depletion	Size of reserves [Gt]	Model type	Assumptions and methods
Herring and Fantel (1993)		40–169 years	12.6–37.8[b]		Linear growth or exponential production growth at a rate of 1.04–3%. Stable demand after 2025, 2050 or 2100 in the most optimistic scenarios.
Steen (1998)		60–130 years	10–22.4	Dynamic R/P	Annual production growth of 2–3%, but most likely lower.
Smil (2000)		80 years	10.5–24.5	Static R/P	Continued constant production.
Rosemarin (2004)		130 years	18	Dynamic R/P	Annual production growth rate of 3%.
Déry and Anderson (2007)	1989		2	Curve fitting	Aggregated world production data. URR is found with Hubbert linearization.
Fixen (2009)		93 years	15	Static R/P	Constant 2007–2008 production rate.
Vaccari (2009)		90 years	15	Static R/P	Continued constant production.
Udo de Haes et al. (2009)		75 years	16.8	Dynamic R/P	Annual production growth rate of 0.7%.
Cordell et al. (2009)	2033		16.5	Curve fitting	Aggregated world production data. URR is found by adding cumulative production and reserve data.
Smit et al. (2009)		69–100	18	Dynamic R/P	Annual production growth rate of 0.7–2% until 2050 and 0% increase after that.
van Kauwenbergh (2010)		300–400 years	60	Static R/P	Continued constant production.
van Vuuren et al. (2010)		50–90% of the resource base still remaining in 2100	13–72.6[b]	System dynamics	Four different scenarios for demand. Three different resource estimations; low, medium and high.
Mórrígan (2010)	1989–2033		2.5–17	Curve fitting	Using aggregated world data. URR is found with Hubbert linearization.
Sverdrup and Ragnarsdottir (2011)	~2050	30–330 years	18/25[b]	System dynamics	Demand–supply model, using price and recovery feedbacks to supply scarcity.
Cooper et al. (2011)		370 years[a]	65	Static R/P	Continued constant production.
Van Enk et al. (2011)		31–87 years/61–>200 years	15/47[b]	Dynamic R/P	Four different scenarios for the demand of food and biofuels.
Cordell et al. (2011a)	2051–2092		60	Curve fitting	Aggregated world production data. URR is found by adding cumulative production and reserve data.
Mohr and Evans (2013)	2020–2136		6.7–57	Curve fitting and System dynamics	Demand-production interaction model based on URR for regions. Three scenarios are used for different size of the URR.
Koppelaar and Weikard (2013)	~2050–>2100	100–>200 years	15.7–53.9[b]	System dynamics	Demand–supply model, using price feedbacks and global flow analysis. Recycling postpone depletion.

[a] Most countries' reserves will be depleted in less than 100 years.
[b] Reserve base is included in the highest reserve estimations

mathematical functions are used to investigate the importance of this factor on the results and create some widely different potential outlooks for future phosphate rock production.

The methods used are described in more detail in the following section while Section 3 goes deeper into the background theory and assumptions behind the modeling. The results of the modeling are presented in Section 4. In Section 5, the modeling and potential implications are discussed and finally the main conclusions are presented in Section 6.

2. Methods

In this study, potential production outlooks for global phosphate rock production are modeled using curve fitting methods, where mathematical functions are fitted to historical production data using the least squares method, constrained by the estimated ultimately recoverable resource (URR). The functions used are the logistic function

$$Q(t) = \frac{\text{URR}}{1 + e^{-k(t-t_0)}} \quad (1)$$

and the Gompertz function

$$Q(t) = \text{URR}e^{-e^{-k(t-t_0)}} \quad (2)$$

where $Q(t)$ is the cumulative production at time t, URR is the estimated ultimate recoverable resources, k is the growth factor and t_0 is the year of the maximum production (Höök et al., 2011). The slope of the logistic function will reach its maximum when half the URR has been produced and the Gompertz curve when around 37% of the URR has been produced.

The URR is approximated as the sum of cumulative historical production and estimated remaining recoverable resources (RRR). To avoid unreasonable depletion rates, a maximum depletion rate of 5% is used for every function, meaning that a maximum of 5% of the remaining resources can be extracted in any given year. These methods are described in more detail in Vikström et al. (2013). The methods are used on aggregated global production data, similar to what has been done in many previous studies using curve fitting models described in Table 1, here referred to as *aggregated global production model*. Also, an alternative method here named *disaggregated regional production model* is used, where the production in individual major producing countries are modeled individually, but later combined to formulate a global outlook.

For the aggregated model, three different cases based on different assumptions on RRR are modeled. For the *standard case*, the RRR is assumed to be equal to the USGS reserve estimate from 2012. In the *low URR case*, the RRR for Morocco is reduced significantly to correlate with the reported reserves in 2009, before the sudden