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Phosphate rock production and depletion: Regional disaggregated modelling 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.

Highlights:

- Phosphate rock production is modelled using curve fitting models.
- Global production is disaggregated into major producing countries.
- Phosphorous exports will rely heavily on Morocco in the future.
- Potential bottlenecks should be further analysed for separate regions.

Keywords: phosphorus, phosphate rock, peak minerals, resource depletion, fertilizer, curve fitting modelling

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 summarised 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 analysed 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 modelled. Also two different 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 modelling. The results of the modelling are presented in Section 4. In Section 5, the modelling 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 modelled 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 modelled individually, but later combined to formulate a global outlook.

For the aggregated model, three different cases based on different assumptions on RRR are modelled. 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 increase described by Edixhoven et al. (2013). A *high URR case* is also used, where the RRR is simply assumed to be double the standard case.

In the disaggregated model, the ten largest producers are modelled individually. China, the U.S., Morocco and the former Soviet Union (FSU) countries make up the bulk of the global production, but the remaining countries with significant contributions to global production, namely Jordan, Brazil, Tunisia, Egypt, Israel and Syria, are also modelled individually, but the results are merged to form a group called *Major Producers*. These ten countries cover a vast majority of both global production and reserves. The remaining countries with any production are treated as a final unit called *Rest of the world*. Morocco and China appear to have highly uncertain reserves and since China has, by far, the largest production and Morocco the bulk of the global reserves, two different estimates are used for each of these countries creating a total of four scenarios with different total URR.

3. Theory

3.1 Modelling production of exhaustible resources

Although most would agree that mineral resources are finite resources, there is not a consensus whether this is a problem or not. A common argument not to worry about coming shortages in P supply is to look at the available *stock* in ground. The fear of “*running out*” of phosphate rock can essentially be dismissed if the stock of resources is shown to be sufficiently large. Reserve-to-production (R/P) ratios, where reserve estimates are divided with current production to provide an

estimate on how many years the resource would last, are commonly used to draw conclusions on potential coming shortages. Others assume a continued growth of demand of the resource, resulting in a more dynamic R/P model.

An alternative perspective is to try to view future supply as a *flow* problem, based on the assumption that society can only use the production *flows* that can be extracted from the available *stocks*. The stock in ground can then be seen as of secondary importance as it is flow rates that govern availability for the civilization and flow-limited production peaks may appear despite abundant stock. These arguments are common to the ones used within the peak oil debate (Jakobsson et al., 2012). For oil, it is well known that “*cheap and easy*” resources are depleted first, resulting in production costs that often increase with time (Höök et al., 2010). When investments no longer can keep pace with these rising cost, the growth in production will decrease and finally peak and decline (Bardi, 2009).

Hubbert (1956) was among the first to use bell shaped curves to describe future production of finite resources. The basic assumption is that the production will start at zero and reach zero again as time goes towards infinity. Between these points, production rate will pass through one or several maxima. The area under this curve must not be larger than the expected URR. This first bell-shaped curve was later described as the first derivate of the logistic curve (Hubbert, 1959). Later, many different, both symmetric and asymmetric curve shapes, have been found to match historical production patterns and can be considered plausible for predictive purposes (Bardi, 2005; Höök et al., 2011). The logistic curve has been found to reasonably reflect a free market situation, while a Gompertz curve can describe a more restrained development (Mohr et al., 2011). These two models behave differently and could provide complementary outlooks for possible future outcomes. This type of modelling has been most commonly used for oil, but is increasingly often used for other exhaustible resources, including minerals such as phosphorus. May et al. (2012) states that even though reserve estimates are usually less certain for mineral resources than oil, this type of modelling can be used to determine a time frame of when a peak in production could occur and frame a debate on how a transition from a depleting resource to an alternative could be done.

For mineral resources, such as phosphate rock, high-grade mineral ores exist in finite quantities and extraction will eventually lead to an exhaustion of the resources that are economic to extract, at the same time as demand for minerals will likely continue to rise (May et al., 2012). Easy extractable deposits of phosphate rock, with a high content of P_2O_5 , are often used first, while low P_2O_5 content deposits results in more impurities and higher production costs (Van Kauwenbergh, 2010). Some studies claim that global concentrations have been, and are currently, declining steadily (Schröder et al., 2009; Cordell et al., 2009; Vaccari and Strigul, 2011). Such a trend imply that the “*easy*” deposits have already been exhausted and that future production would be forced to develop lower quality deposits with more associated costs and challenges (UNEP, 2011). This has been described as a vital mechanism behind the generation of production peaks (Bardi and Lavacchi, 2009).

3.2 Phosphorus reserves and resources

Since the ultimately recoverable resources (URR) are used as a constraint in the modelling, this assumption will have large effects on the results. The URR is assumed to be a combination of cumulative historical production and an estimate of what could be produced in the future, referred to as remaining recoverable resources (RRR). While reliable data on historical cumulative production often can be found, it is naturally impossible to know with certainty what the future beholds, but estimates of reserves and resources can help. There are a number of different classification systems for mineral deposits in the world, each with different terms to describe the size of the mineral assets, but

the most common distinction is to talk about resources and reserves. This study uses these concepts according to the commonly used definitions by the United States Geological Survey (USGS, 2013). Resources are defined as a concentration of minerals in the earth's crust in such a form and amount that economic extraction is currently or potentially feasible, while reserves are the part of the resources that that could be recoverable profitably at current market conditions, but extraction facilities does not need to be in place and running. Several different reserve or resource estimates can be used for estimating the URR in the models to account for the potential uncertainty in this factor, but still somewhat reasonable estimates for future production are necessary. Reserves and resources can be difficult to quantify, particularly with regard to the difficulties in determining the size and ore grade of a deposit in advance (Pan et al., 1992).

Phosphorus (P) is among the most abundant elements and is ranked as the 11th most common in the earth's crust (Krauss et al., 1984), and the 13th most common in seawater (Smil, 2000). However, it does not occur in its elemental form in nature due to high reactivity. About 95% of all crustal phosphorus is estimated to be bound in different forms of phosphate apatite minerals of which there are more than 200 known variants (Krauss et al., 1984). Phosphate rock deposits that are interesting for mining usually only occur under special conditions in some specific areas as a result of the phosphorus cycle (Filippelli, 2011; Krauss et al., 1984). The main phosphate rock deposits are either sedimentary or igneous, each with different mineralogical, structural, and chemical properties (Van Enk et al., 2011). Marine sedimentary deposits account for 80% of the global phosphate rock production, with large producers such as China, Morocco, U.S. and Tunisia. Sedimentary phosphate rock ores commonly have a P_2O_5 content of around 30-35% (Krauss et al., 1984). Igneous deposits are low grade in comparison, with a P_2O_5 content of often less than 5%, but can be upgraded through beneficiation to 35-40% or even higher. While igneous sources contribute with 15-20% of current production, they constitute much smaller fractions of estimated resources. In contrast to sedimentary phosphate rocks, igneous deposits are generally free from pollutants such as radionuclides and heavy metals (Smit et al., 2009). Igneous deposits can mainly be found in countries like Russia, Brazil, and South Africa.

Data availability of reserves and resources of phosphate rock is often poor, in part as mining companies and fertilizer industry have limited interest in making detailed data publicly available, thus forcing analysts to rely of second hand and third hand information (Cordell and White, 2011; Gilbert, 2009). It is also sometimes argued that the phosphate rock deposits in countries like Morocco are not fully explored, since mining companies refrain from expensive exploration of potential reserves that are not expected to be put in production in the near term (Van Kauwenbergh, 2010). It also appears like reserve data from China excludes smaller mines, implying that actual reserves might be larger than officially reported (Cordell et al., 2009). Another potential source of misconceptions is that reserve data is sometimes presented as phosphate rock ore and sometimes phosphate rock concentrate. Reserves specified in tons of phosphate rock are often assumed to be the same as the recoverable amount of phosphate rock concentrate, even if reserves often actually are phosphate rock ore that must be beneficiated in order to be sold, which normally requires a P_2O_5 content of 30% (Edixhoven et al., 2013).

The global resources are estimated by the USGS to be about 300 Gt of phosphate ore, out of which about 67 Gt are considered currently economically recoverable reserves (Jasinski, 2013a). According to Edixhoven et al. (2013), the USGS reserve data is routinely assumed to be listed as phosphate rock concentrate, while it appears that USGS often list reserves in terms of ore. Edixhoven et al. (2013) also claims that more than half of the phosphate rock concentrate in the resources consists of the reserves. Reserve estimates are dynamic and can change with time for a multitude of reasons.

USGS estimates have remained constant for many countries despite continuous production, while other countries have made significant changes in reserves. The USGS reserve estimates from 2001 to 2013 is depicted in Figure 1. The most notable change can be seen from 2010 to 2011 when the estimated reserves in Morocco was multiplied many times, leading to Morocco now comprising 75% of the global reserves. However, it appears questionable whether all this is truly recoverable at current prices (Edixhoven et al., 2013; GPRI, 2010).

Others argue that much more phosphorus is extractable, pointing to potentially massive quantities available in sea beds, continental shelves or even the sea water itself. Marine phosphate mining has never been done in large scale and the impact intensive dredging could have on the marine environment is unclear (Filippelli, 2011). Consequently, environmental impacts have to be carefully examined before oceanic mining can be undertaken (Scholz and Wellmer, 2013). Similar to many other elements, seawater is sometimes argued to be a more or less infinite phosphorus resource (IFA, 1998). The same argument is commonly presented for lithium, which is discussed by Vikström et al. (2013), who describes an example that extracting all the lithium in 300,000 km² of seawater, corresponding to the average discharge of the river Nile, would give roughly 20,000 tons of lithium per year. Since the sea water contains less P than Li, the same flow of seawater would contain the equivalent of about 11,000 tons per year, which is less than 0.1% of the current global phosphorus production. Considering the phosphorus would also need to be extracted from these immense amounts of water, with unavoidable losses, production from seawater at significant levels near the current or projected future demand must be considered very unlikely, even if this type of production were to come to occur at large scale.

3.3 Global phosphorus production

Phosphate rock mining originally started in South Carolina 1867 for manufacturing of phosphate fertilizers (Van Kauwenbergh, 2010). In the early 20th century, new complex fertilizers were created that contained phosphoric acid, as well as ammonium nitrate and potassium chloride, commonly called NPK fertilizers (UNEP/UNIDO, 2000). In the 1960s, new high yielding crop varieties were introduced, which contributed to large increases in crop production (Evenson and Gollin, 2003). What is sometimes neglected is that these varieties only give high yields if they can extract more nutrients from the soil and these new varieties, together with increased use of irrigation, also led to an increased use of fertilizer (IFA, 1998). Phosphate rock production grew quickly and appeared to reach a peak in production in 1988 as a result of decreasing demand and production after the fall of the Soviet Union that coincided with an increased awareness of issues with eutrophication (Cordell et al., 2009; IFA, 2011, 1998). In recent years, production has again started to rise, for reasons such as a growing global population, a sharp increase in the consumption of meat and dairy products, especially in growing economies such as China and India, as well as an increased biomass production for bioenergy purposes (Cordell et al., 2009). A more extensive description of phosphorus usage through history can be found in Ashley et al. (2011) or Cordell et al. (2009).

Production data for United States and the world as a whole from 1900 is available in USGS historic phosphate rock statistics (Buckingham and Jasinski, 2012). Production data from 1920 for total global production can be found in the British Geological Survey (BGS) mineral statistics archive (BGS, 2013). Data for most of the phosphate rock producing countries from 1913 can be obtained in the BGS archive and from 1929 in archives from U.S. Bureau of Mines and USGS (USBM, 1993). The International Fertilizer Industry Association also has publically available data for production,

export and import of phosphate rock concentrate and fertilizers, but only for the last ten years (IFA, 2014).

Phosphate rock is currently mined in more than 30 countries worldwide, but very few countries make up most of the total production (EcoSanRes, 2008). The U.S. has dominated production historically, but appears to have peaked in production in 1980 at a production of 54.6 Mt of phosphate rock concentrate, and has fallen to almost half of this level (Déry and Anderson, 2007). The former Soviet Union countries used to be large producers, but have now fallen to around 5% of global production. China is currently the largest producer in the world, accounting for 89 Mt or 43% of the total production of phosphate rock concentrates in 2012. China accounts for most of the sharp increase in production that has taken place since 2000 (Figure 2). After China, the largest producers are the U.S. and Morocco with roughly 14% of the global output each (Jasinski, 2013a). Other important producers are primarily found in the Middle East North Africa (MENA) region with countries like Tunisia, Jordan, Egypt, Israel, Syria, Saudi Arabia, and Algeria. The MENA region, including Morocco, currently contributes with about one quarter of the global production.

Since the phosphate price increased rapidly in 2007, several new deposits have been explored to boost production. One frontier region is Morocco, where in the national Moroccan Phosphates Company (OCP) stated in 2010 that they were to almost double production to 55 Mt/year by 2020, by opening four new mines (OCP, 2010). However, the annual report from 2011 is not as ambitious and expects an increase of 20 Mt by 2020 (OCP, 2011). Other recent mining developments are taking place worldwide. In Namibia and New Zealand, companies want to start marine mining of phosphate rock sediment. New mines are also planned to be developed in Finland (1.5 Mt/year), Kazakhstan (1.0 Mt/year) and Saudi Arabia (1.5 Mt/year) (De Ridder et al., 2012).

In 2011, only about 17% of the produced phosphate rock concentrate was exported directly, with the largest share being upgraded to phosphoric acid or phosphate fertilizers (IFA, 2014). The total global trade of all forms of phosphate was only 22.5 Mt P₂O₅ in 2011 (OCP, 2011), which means that around 63% of the phosphorus was consumed locally in the producing countries. Of the global phosphorus trade, 9.8 Mt P₂O₅ (43%) was in the form of phosphate rock (IFA, 2014). Especially China and the United States consume most of their production domestically, why Morocco accounts for the bulk of the world's exports to the countries dependent on imports and provides 36.7% of the global export market (OCP, 2011). Following their expansion plans, Moroccan export share are expected to increase substantially.

4. Results

4.1 Aggregated global production model

The main features of the global aggregated model are summarised in Table 2 and the results are depicted in Figure 3. The low-URR case, using a URR estimate similar to studies performed before the 2011 increase of reserve estimates, with a maximum production reached in 2030-2040, while the high-URR case peaks far into the next century at levels several times over current levels. The standard case, using the current USGS reserves for the URR estimate reaches a peak in the mid-2080s, both when using a Gompertz and logistic function. Table 2 also presents the R/P-ratio connected to the different reserves used for the URR estimates for comparison. The standard case reserves are equal to the static R/P ratio of 320 (years), which is significantly longer into the future than the roughly 70 years the standard case curve fitting model peaks. The aggregated global model indicates that the total global

production could reach a maximum sometime during the coming century if current global trends continue, but this model says nothing about the quantities that individual countries are expected to produce or potential bottlenecks in these countries.

4.2 Disaggregated regional production model

As an alternative to the aggregated global model, a disaggregated regional production model is also used, where the major producers are modelled individually. Four different cases with different URR estimates for China and Morocco (Table 2) and the same mathematical functions as in the aggregated model are used. The main results of the disaggregated model of individual regions can be seen in Table 3 and the results are depicted as total global production in Figure 4 and 5. The resulting production curves have many similarities to the results in the aggregated model, but also provide some new insight on individual regional production.

The first two cases of the logistic model (Figure 4a and 4b) with the low Morocco reserve estimate reaches results similar to what was proposed by Cordell et al. (2009) with a peak in production around 2030, although at higher maximum production levels, since the reserve estimates used are higher. Under these assumption the total production will rely largely on China in coming decades before the production peaks and starts to fall drastically as soon as a couple of decades from now.

The Gompertz models using the low Morocco URR estimate are also quite similar to the Cordell et al. (2009) model, although the low China URR case (Figure 5a) suggest a global peak in production as soon as just after 2020. These production trajectories also reach a peak within two decades and start to fall fast.

The Morocco high URR logistic cases (Figure 4c and 4d) do not reach peaks in production until the next century, and reaches quite remarkable levels of production compared to the current levels, but what is perhaps most notable about these are that the global production becomes increasingly reliant on Morocco and by the second half of this century a majority of the global production comes from that specific country.

The Gompertz model using high URR estimates for Morocco (Figure 5c and 5d) also peaks in a similar fashion as the logistic models, but does not decline as fast after the maximum production is reached. The much slower growth rate of the Gompertz curve makes Morocco, making up most of the reserves grow much slower and not peak until well into the 22nd century. However, the same tendency can be seen as for the other models, that the total production gets increasingly reliant on Morocco with time.

5. Discussion

5.1 Modelling phosphate rock production

The large variations of the results of the aggregated production model with production at peak ranging from around 200 Mt/year to almost 1000 Mt/year and peak years between 2030 and 2131 show how dependent this type of models are on the URR estimates used. Scholz et al. (2013) state that this type of models, as well as R/P ratios, can be used as “early warning indicators”, but should not be seen as predictions. On the other hand, bell shaped-curve fitting models describe more likely production patterns and should be seen as a better early warning mechanism than R/P ratios, since the production

profile assumed in R/P models does not resemble a production trajectory seen historically. However, the actual production profiles could in theory look in numerous different ways. The inherent uncertainties in this type of modelling, as well as the parameters included, should not be seen as a reason not to worry about resource depletion and the fact that the quantities of the resource that will be extracted is unknown does not make it infinite.

To provide an alternative perspective to existing models, a disaggregated model is used in this study to show the production from individual regions. Some of these production curves appear quite odd, with multiple peaks, and many of the cases grow fast to high peaks and fast decline. Few of these cases are very likely to happen in reality, but they can provide insight of what can be expected under certain assumptions of production in different regions. To avoid results that would deplete the reserves at an unrealistic pace, this study uses a 5% maximum depletion rate, meaning that a maximum of 5% of the remaining reserves are allowed to be produced in one single year. The historical production data for China and Egypt show very sharp production hikes over the last decade, with reserve estimates that appear too small to support such trends, and these trajectories appears impossible to model using the depletion rate constraint. The production trajectory of the FSU is also somewhat peculiar, mainly due to a large production collapse in the early 1990s after the fall of the Soviet Union, why this is modelled with multi cyclic modelling using two curves. Multi cyclic curve fitting modelling often results in fast decline, and the only place where the depletion rate constraint actually affects the model is for the USSR logistic model. Although the depletion rate constraint did not affect most of the models, it functioned as an alarm clock that lead to an alternative URR estimate for China being included in the model. The fact that Chinese reserves appear to be underestimated has previously been pointed out in other studies (Cordell et al. 2009).

A very interesting result in the disaggregated model is the fact that very large Moroccan reserves makes the high URR models produce results where the world would be almost completely reliant on Morocco around the second half of this century. The restrained nature of the Gompertz model makes these models reach much lower peak productions, and the most notable difference is for the morocco high URR cases. Perhaps the high URR Gompertz model is a feasible description of how it could look if the production in Morocco is not able to grow as fast as wanted.

The phosphate rock reserves are uncertain and that they can both increase and decrease in the future. For instance, the Chinese reserves appears likely to increase, while it appears questionable if the very large reserve estimates for Morocco, compared to other countries, will be feasible to extract. However, the argument that sea water will ever provide substantial amounts of phosphorus appears unlikely when looking at the amounts of water that would need to be processes to reach significant levels. Sub-ocean mining cannot be completely ruled out, but it appears questionable if significant amounts of phosphate can actually be produced in a practical, economical and environmentally acceptable way.

To account for the uncertainties in reserve estimates, several different scenarios for the URR are used in both the aggregated and the disaggregated model. The low estimate in the aggregated model, using a reserve estimate similar to the one used before the 2010 revision, is deemed relevant to investigate if this outdated reserve estimate appears to low to use as a base for URR in these models, as well as a comparison to early studies, such as Cordell et al. (2009). The use of the Gompertz curve shows that using another type of curve shape can significantly change the results based on these reserve estimates, and also indicate that this reserve estimate appear small. The high case is used to investigate how the results would change if a similar revision to the reserve estimates would happen again. In a similar fashion, the high and low reserve estimates for China and Morocco used in the disaggregated model provide alternative cases to if the Chinese reserves would increase significantly

or the Moroccan reserves would be decreased, for instance due to different types of bottlenecks in production.

This study makes no attempts to project future demand of phosphate rock. Some of the results in the models presented reach phosphate rock production many times higher than current levels, and depending on the development of factors such as global population, diets, efficiency and recycling of phosphorous, the demand of virgin phosphate rock can look very different in the future. This is one of the reasons why both the logistic and the Gompertz functions are used in the modelling. Since the logistic curve has been found to reflect something similar to a free market situation, and Gompertz more restrained developments (Mohr et al., 2011), these two different cases could be seen as high and low demand scenarios.

5.2 Bottlenecks

There are many potential bottlenecks that could limit production flows and these should be addressed in the context of the individual countries where the production is supposed to happen. If countries such as Morocco are expected to increase their phosphate rock production with several times the current production, issues such as local environmental impacts, water availability, access to energy and geopolitical issues should be addressed on a regional level. Also, food producers could become more or less completely dependent on phosphate rock from Morocco due to its large and increasing share of the export market, which could lead to something resembling a monopolistic situation for Morocco in the future with associated risks (Elser and Bennett, 2011).

One important aspect is that the countries responsible for the phosphate rock mining will inevitably face local environmental impacts. Most phosphate rock is mined using large scale surface mining, which tend to have large impacts on the environment as it disturbs local landscape, and a wide range of other local environmental impacts can follow, such as water contamination, air emissions, noise and waste generation (UNEP, 2001).

Both phosphate rock production and beneficiation is highly water intensive, and water scarcity may essentially limit the beneficiation in dry areas (Van Kauwenbergh, 2010). Many countries that produce phosphate rock, such as countries in the MENA region, already suffer from a shortage of fresh water (De Ridder et al., 2012). In Morocco, most water is currently used for agriculture, out of which 30% is taken from the groundwater, often in an unsustainable way, and the groundwater table has fallen by an average of 1.5 meters per year since 1969 (UNEP, 2009). Energy intensive desalination plants are built by the national Moroccan phosphates company OCP to meet their need for water (OCP, 2011).

Access to energy, especially oil, has been pointed out as a potential problem in the future as mining and fertilizer production rely on cheap oil and higher oil prices with associated supply chain effects caused by peak oil could increase production costs (Cordell et al., 2009; Fantazzini et al., 2011; Hanjra and Qureshi, 2010). For individual countries to be able to produce large amounts of phosphate rock, or products based on phosphorus, they will need large amounts of oil.

Geopolitical problems and civil unrest is a potential issue for phosphate rock production. The Arab spring, starting at the end of 2010, affected phosphate rock supply as production fell in several important producing countries in the MENA region, and the protracted conflict in Syria continues to influence supply of phosphate (de Ridder et al., 2012). Although not affected much by the Arab spring, Morocco has seen strikes and protests over employment and wealth equity concerns, but has not experienced any major disruptions in production (Wellstead, 2012). Another issue is that Western Sahara, currently contributing with about 10% of Morocco's phosphate rock production, has been

occupied by Morocco since 1975, creating a ground for potential future instabilities (Edixhoven et al., 2013).

Phosphate rock of different origin varies widely in composition and contains different quantities of impurities, such as cadmium (IFA, 1998). It has been suggested that the high cadmium content in many phosphate rock deposits in Morocco may provide an incentive for declining demand for Moroccan phosphate rock in the future (De Ridder et al., 2012). It should be noted that the modelling in this study does not take account for potential variations in demand for different qualities of phosphate rock or potential cross effects in demand for phosphate rocks from the different countries.

5.3 The future of phosphate rock

The current waste of phosphorus fertilizer causes a great deal of environmental problems, and it is questionable if it is a good idea to extract all the phosphate rock reserves if it would still end up in lakes, streams and the sea. As more and more phosphorus have been added to the ecosystem, many lakes and coasts have seen an increased algae growth (De Ridder et al., 2012), which in some cases have led to serious eutrophication and dead zones due to lack of oxygen (Ashley et al., 2011; Elser, 2012). Carpenter and Bennett (2011) even consider that the planetary boundaries for eutrophication of freshwater due to phosphorus have already been exceeded. It is possible to recycle phosphorus from human excreta, manure and different types of waste products (Cordell et al., 2011b) and efficiency improvements in production and usage of phosphorus could offer a possibility to postpone a potential production peak (Cordell and White, 2013).

The aim of this study is not to provide accurate predictions of future production of phosphate rock, and certainly not to foretell a date of a peak in production. What this study does attempt to show is that large global reserves of phosphate rock do not necessarily mean large annual production and a continued debate on the global phosphorus system is encouraged. Perhaps most importantly, the rather enormous phosphate rock reserves in Morocco is not reason enough to stop attempting to find solutions towards a more sustainable food and energy system. There are simply a wide range of reasons to start using phosphorus resources in a more sustainable way. Using less phosphorus fertilizers, recycling and reusing phosphorus at a higher extent would both limit environmental impacts as well as making the resources available longer.

7. Conclusions

Estimates of future production of phosphate rock vary greatly depending on models used and assumptions made. Simple curve fitting modelling on aggregated global production data constrained by current USGS reserve estimates suggest that global phosphate rock production could reach a peak about 70 years from now, while other models or other reserve estimates used paints widely different pictures. This study proposes an alternative view to commonly used reserve to production ratios or curve fitting models on aggregated global production data, modelling the major producing countries individually in a *disaggregated regional production model*.

The models provide somewhat similar results as a common curve fitting model, but are able to depict what production would be needed from different countries to bring current reserves to market. The results should not be interpreted as predictions of future production of phosphate rock, or the most likely production trajectories in the future, but as a method to investigate production levels in different regions, to be able to indicate potential problems and bottlenecks that are otherwise overlooked.

It is concluded is that the total estimated recoverable amounts of phosphate rock will likely not be the most important limiting factor for the global production in the near future, but what is commonly neglected is that the global supply could come to rely almost completely on one single country, namely Morocco. This means that potential bottlenecks and concerns about phosphate rock production need to be analysed in the context of the individual countries, in particular Morocco. A main question for further research is if it is possible and even desirable, both for Morocco and the importing countries, that production in Morocco should increase as much as are implicitly indicated in some projections for future phosphate rock production. Also, even if the whole Moroccan current reserves estimate is extractable, it is still a risk that global production will experience a peak as a result of the declining production in China.

Future demand, as well as the quantities of phosphate rock available for extraction is highly uncertain, but what is absolutely clear is that the current depletion of phosphate rock cannot go on forever and a more sustainable use of the essential element should be desired for a multitude of reasons. Although the future of phosphate rock production appears uncertain, even the possibility of reaching a “peak phosphorus” calls for a timely transition to a more sustainable use of the resources, with more widespread reuse, recycling and higher efficiency in use of fertilisers as potential mitigation measures to depletion.

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Tables

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**		Linear growth or exponential production growth at a rate of 1.04 to 3%. Stable demand after 2025, 2050 or 2100 in the most optimistic scenarios.
Steen (1998)		60 - 130 years	10– 22.4	Dynamic R/P	2-3 % yearly production growth rate, 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	3 % annual production growth rate.
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	0.7 % yearly production growth rate
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	0.7-2% production growth rate 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**	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 **	System dynamics	Demand-supply model, using price and recovery feedbacks to supply scarcity.
Cooper et al. (2011)		370 years*	65	Static R/P	Continued constant production.
van Enk et al. (2011)		31 – 87 years/ 61 - >200year	15 / 47 **	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 – >200years	15.7 – 53.9 **	System dynamics	Demand-supply model, using price feedbacks and global flow analysis. Recycling postpone depletion.

* Most countries' reserves will be depleted in less than 100 years.

** Reserve base is included in the highest reserve estimations

Table 2. A summary of the main features and the results of the three cases used in the aggregated production model as well as the R/P ratio for the reserve estimates used for comparison.

	Low URR case	Standard case	High URR case
Reserves	23 900 Mt	67 200 Mt	134 500 Mt
URR	30 300 Mt	74 700 Mt	141 900 Mt
Logistic peak year	2041	2084	2114
Peak production for logistic curve	269 Mt	546 Mt	980 Mt
Gompertz peak year	2030	2084	2131
Peak production for Gompertz curve	208 Mt	316 Mt	471 Mt
R/P year 2012	109 years	320 years	640 years

Table 3. Main features and results from the disaggregated production model.

Country	Cum. prod.	Reserves	URR	Prod. 2011	Peak year.	Peak prod.	Depl. rate at peak	Peak year.	Peak prod.	Depl. rate at peak					
											Logistic model			Gompertz model	
											[Mt]	[Mt]	[Mt]	[Mt]	[%]
China low	924	3 700	4 624	81.2	2024	135	5.7	2021	111	3.9					
China high	924	7 400	8 324	81.2	2032	215	5.1	2030	129	2.4					
Morocco low	1 056	5 700	6 756	28.0	2048	83	2.4	2039	60	1.4					
Morocco high	1 056	50 000	51 056	28.0	2109	513	2.0	2139	202	0.6					
United States	2 289	1 400	3 689	28.4	2001	42	1.8	1989	45	2.2					
USSR*	1 072	1 500	2 572	13.7	1981	32	1.5	1980	30	7.8					
					2043	24	2.6	2029	43	-5.5					
Major producers**	991	3950	4941	28.7	2061	48		2062	44						
Rest of the world***	809	6450	7259	16.8	2098	43	1.2	2093	26	0.6					

* Includes: Russia, Kazakhstan and Uzbekistan.

** The merged production from: Jordan, Brazil, Tunisia, Egypt, Israel and Syria

*** The production for all countries, excluding; USA, China, Morocco, the former USSR and the major producers.

Figures

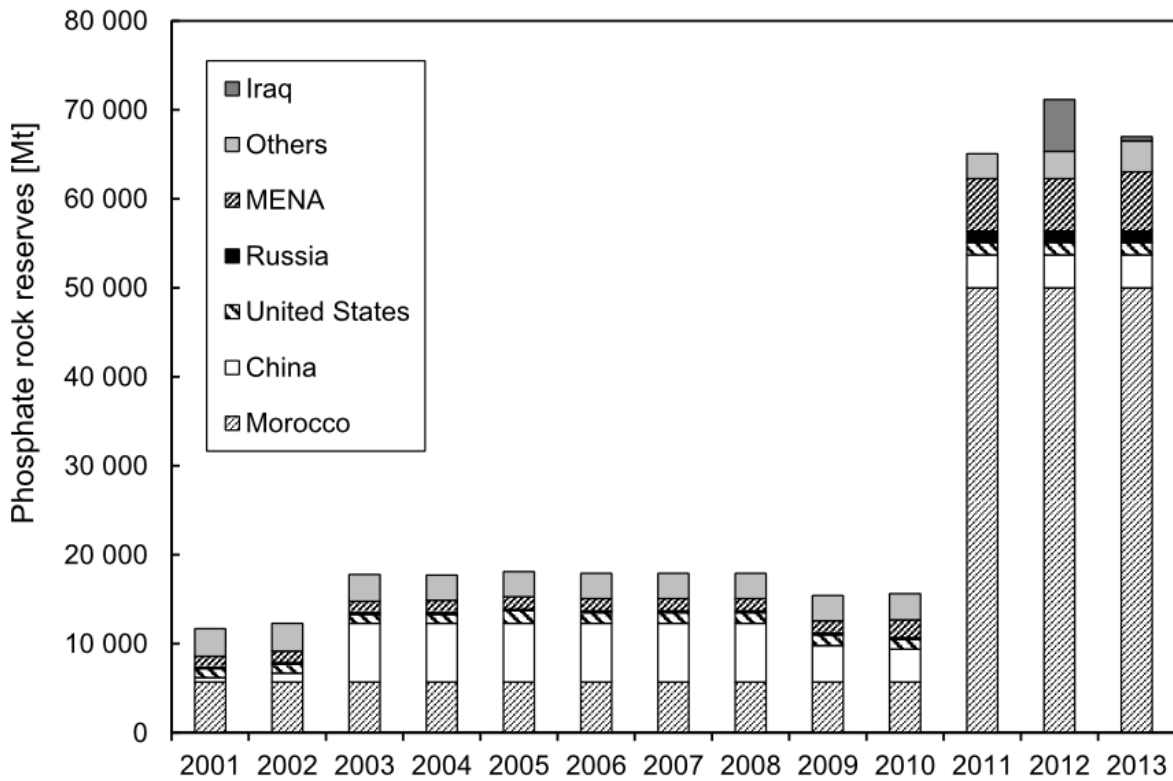


Figure 1. The size of USGS reported reserves from 2001 to 2013 in thousand metric tons of phosphate rock ore (data from Jasinski (2013a)).

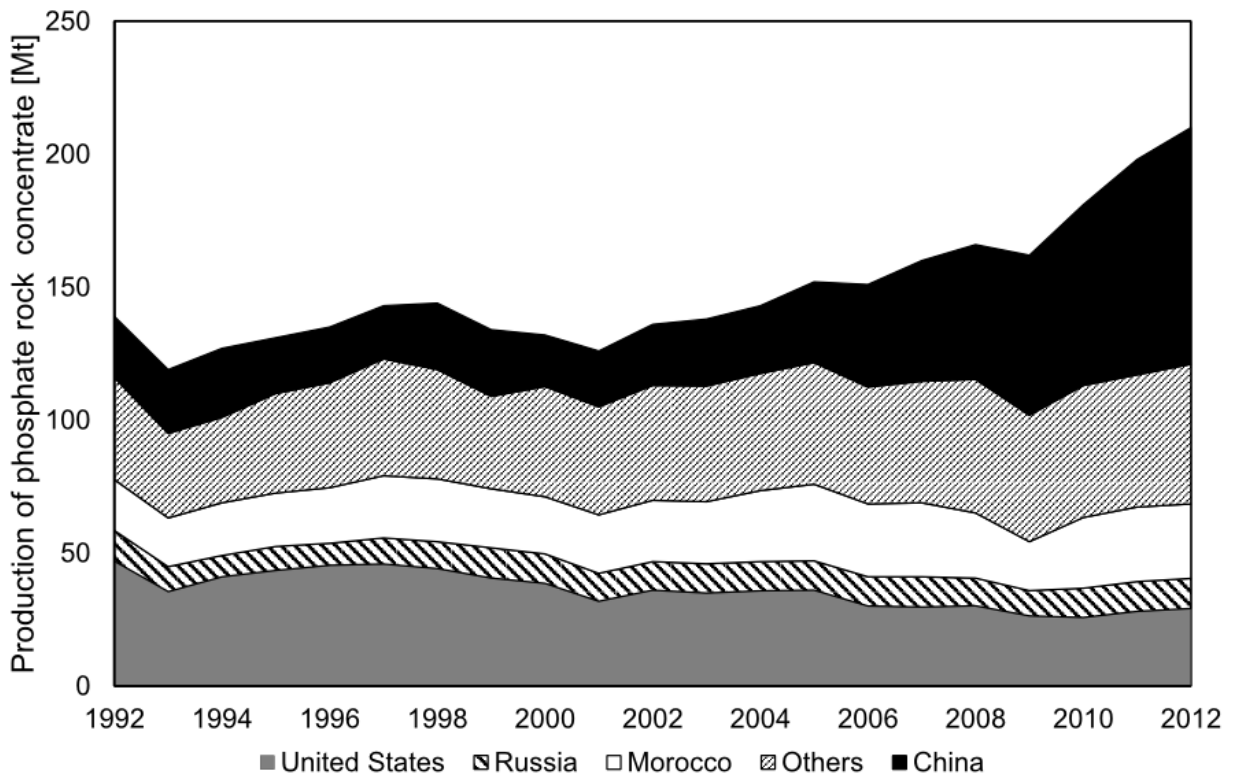
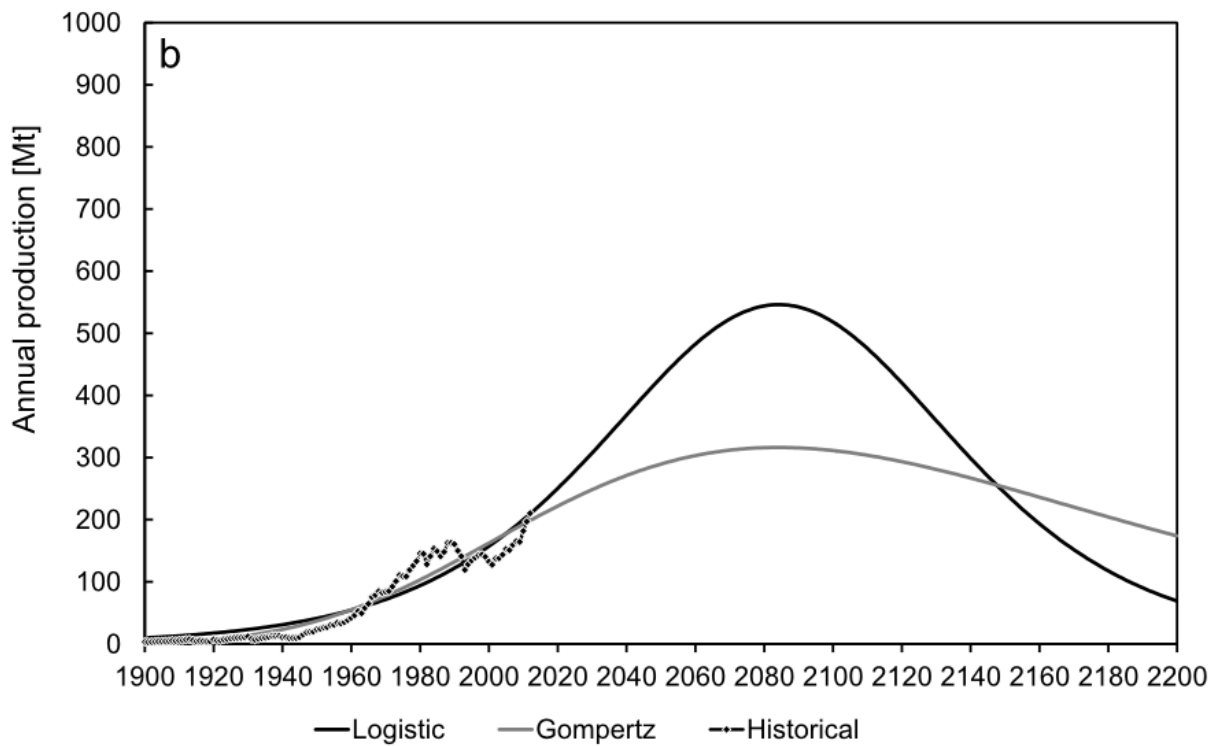
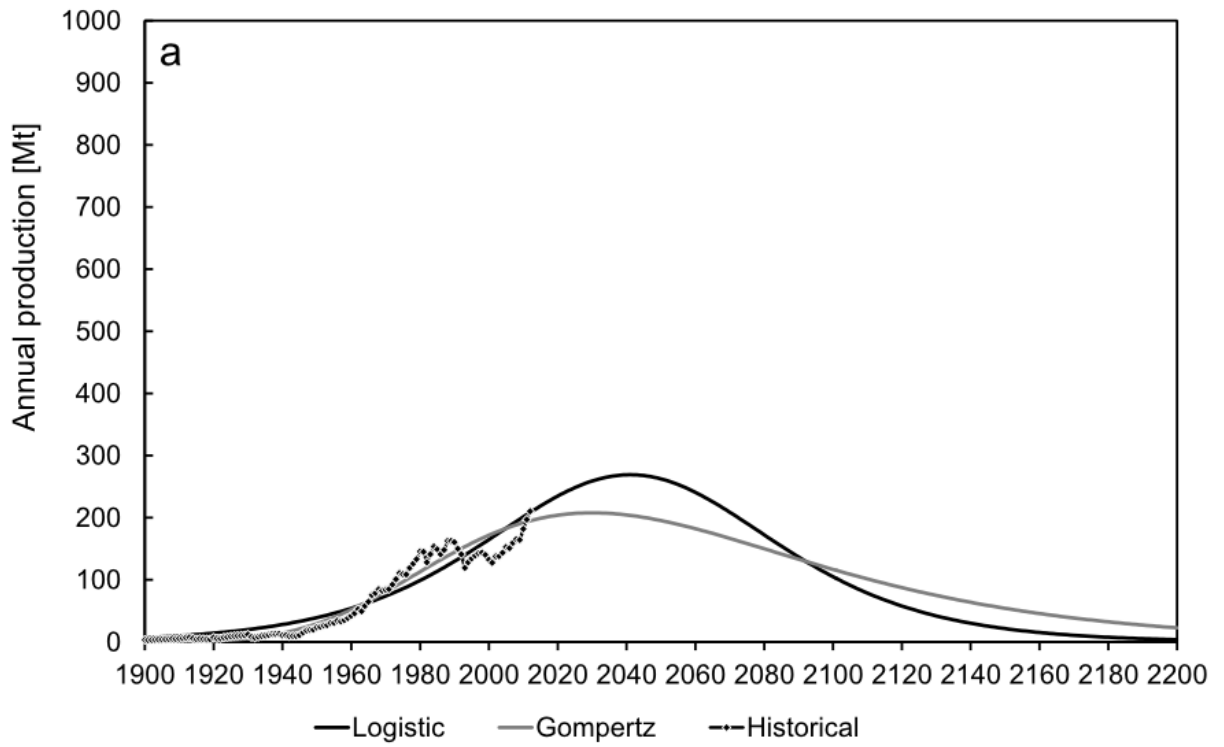


Figure 2. The total phosphate rock concentrate production for the countries with the largest production (in thousand metric tons). Data from U.S. Geological Survey (Jasinski, 2013a, 2013b).



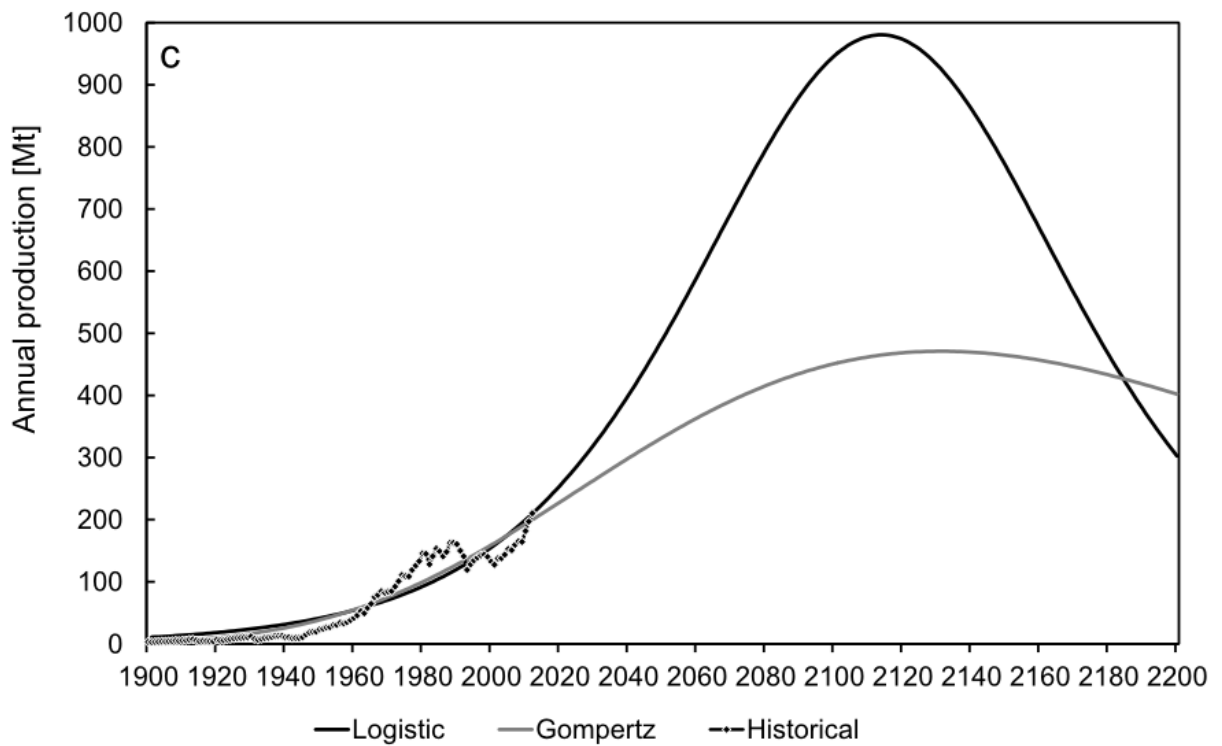
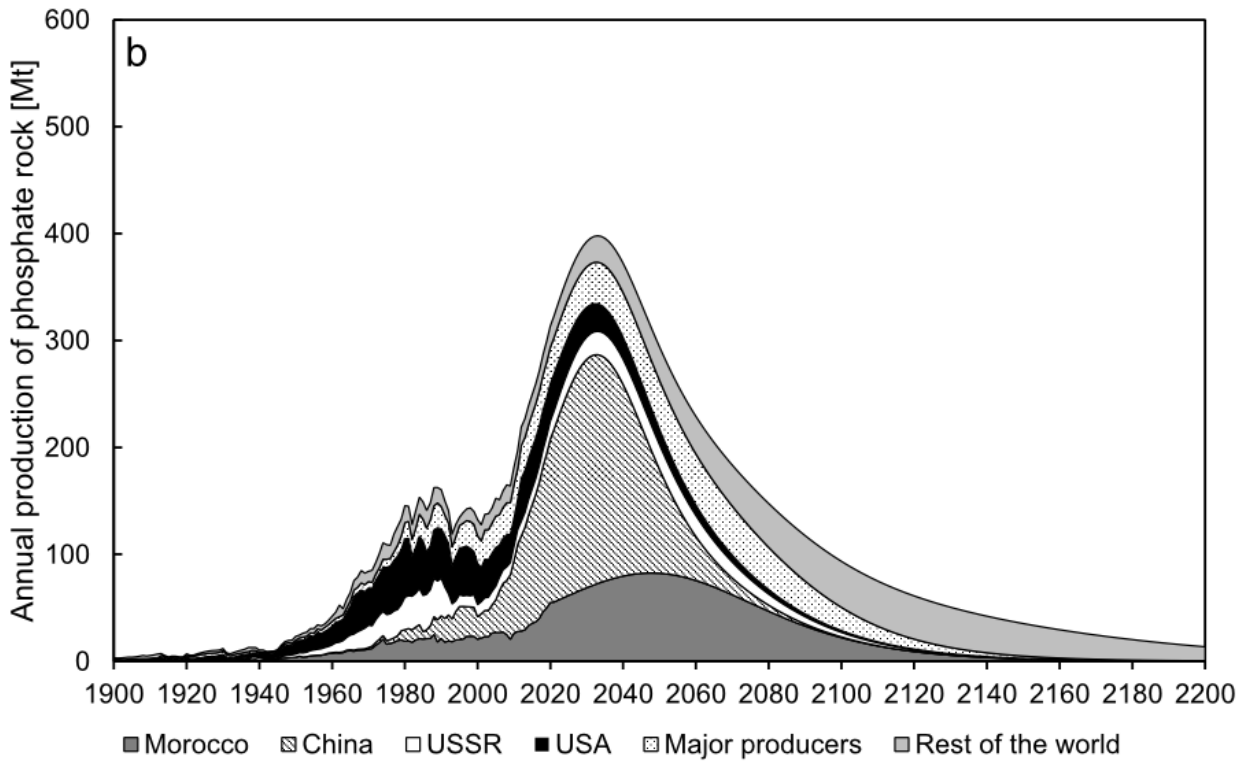
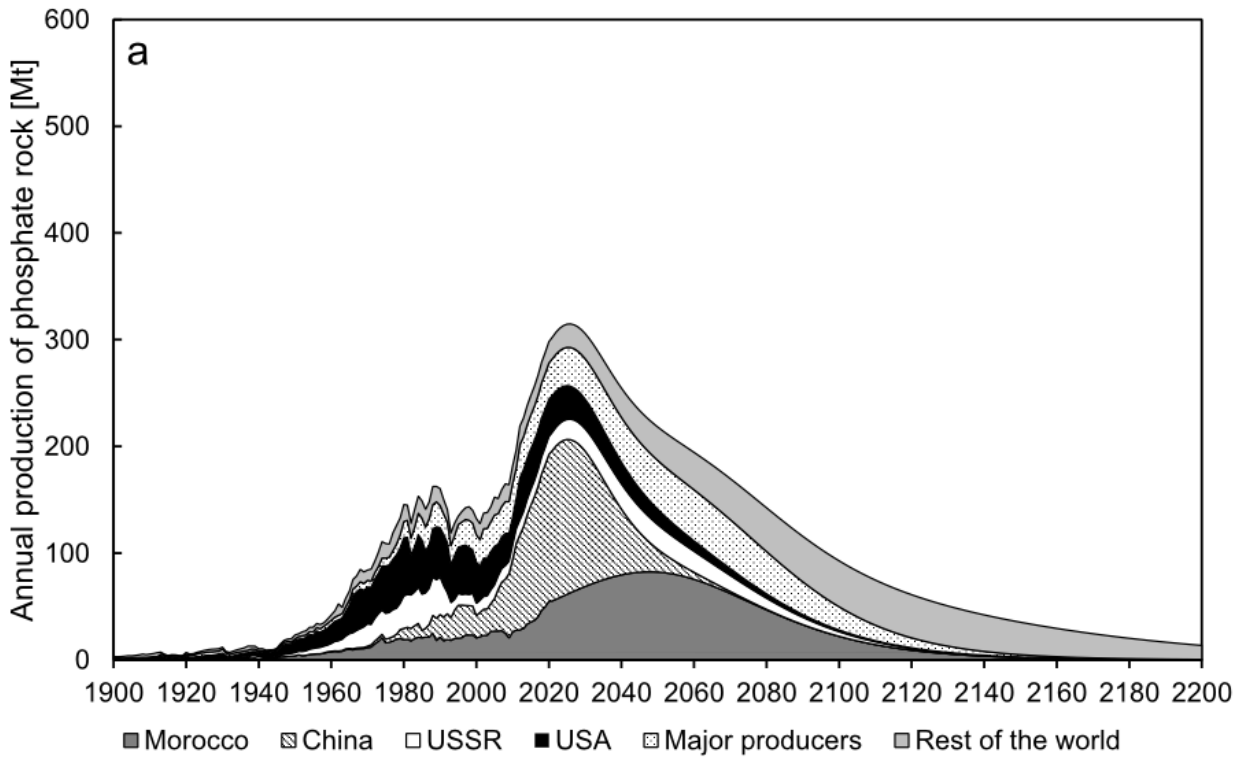


Figure 3. Phosphate rock production outlooks in the aggregated production model. a) Low URR case, assuming that Morocco's reserves are much smaller than current reserve estimates. b) Standard case with an URR estimate based on current reserve estimates. c) High URR case, assuming that the recoverable amount of phosphate rock is two times the current estimates.



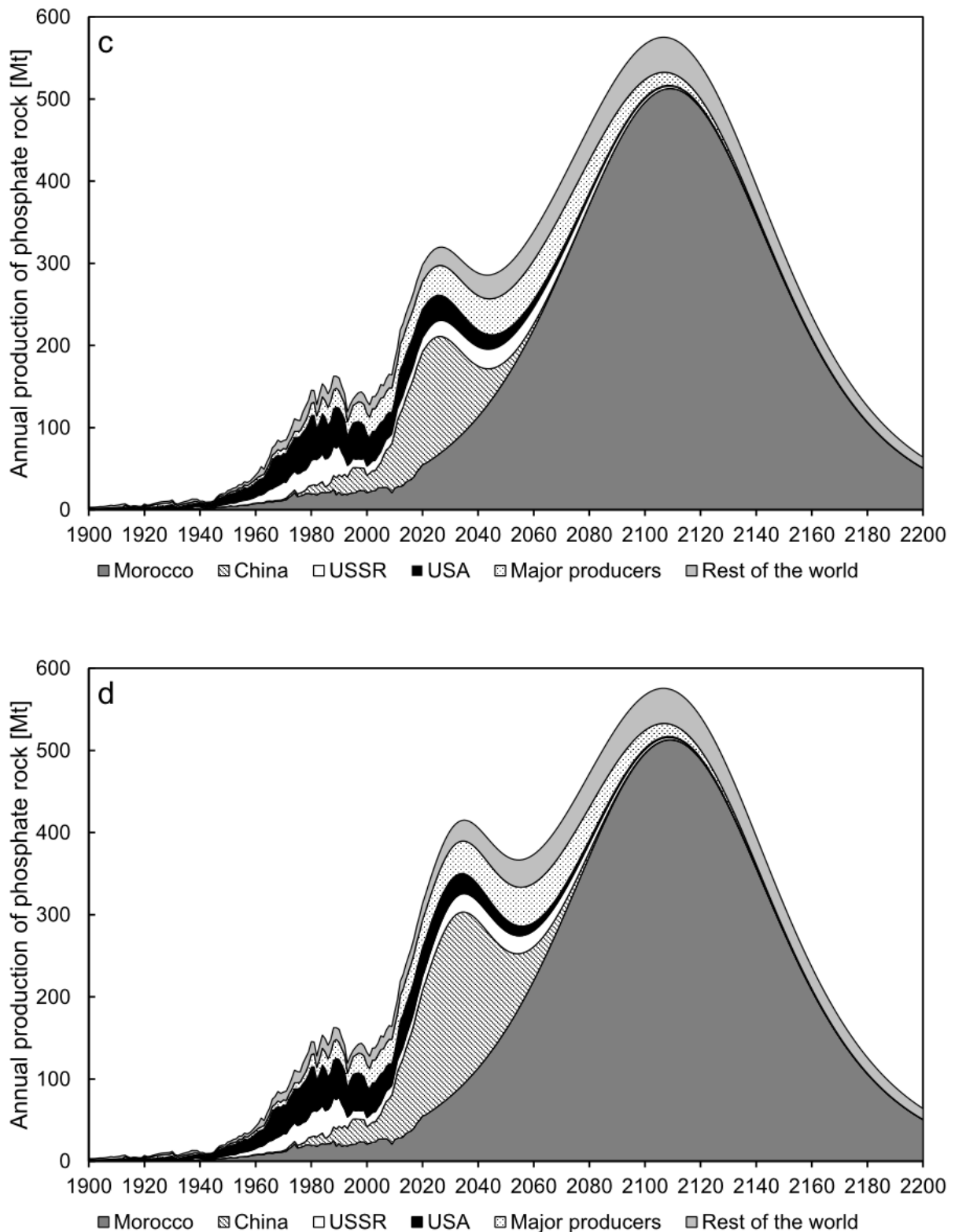
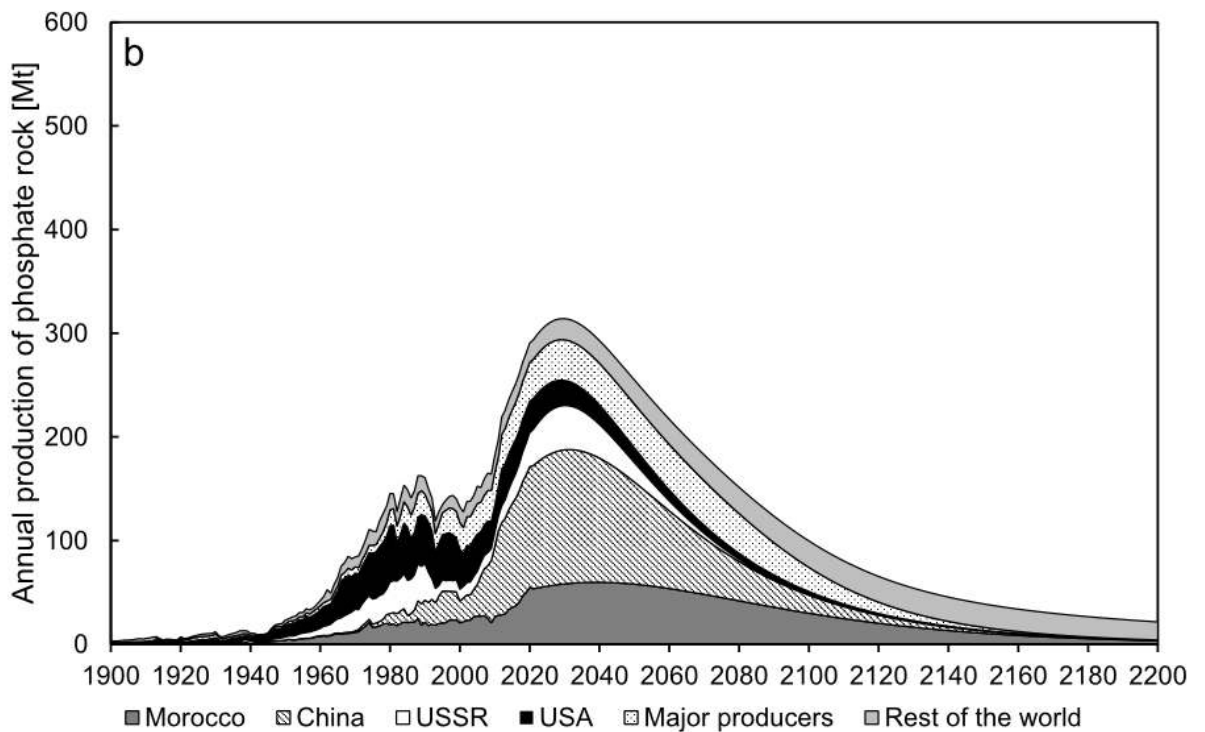
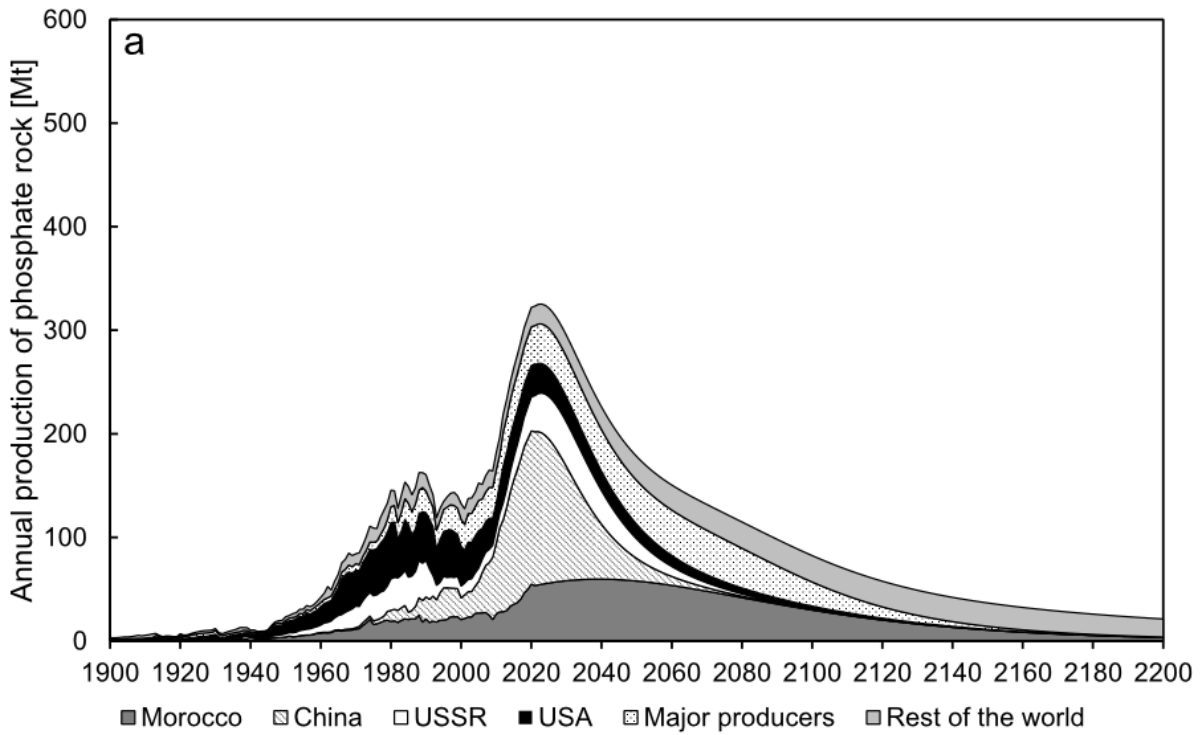


Figure 4. Resulting production from disaggregated model using logistic curves. a) Case 1 with low URR estimate for China and Morocco. b) Case 2, low URR estimate for Morocco, high for China. c) Case 3: High URR estimate for Morocco, low for China. d) Case 4: High URR estimate for China and Morocco.



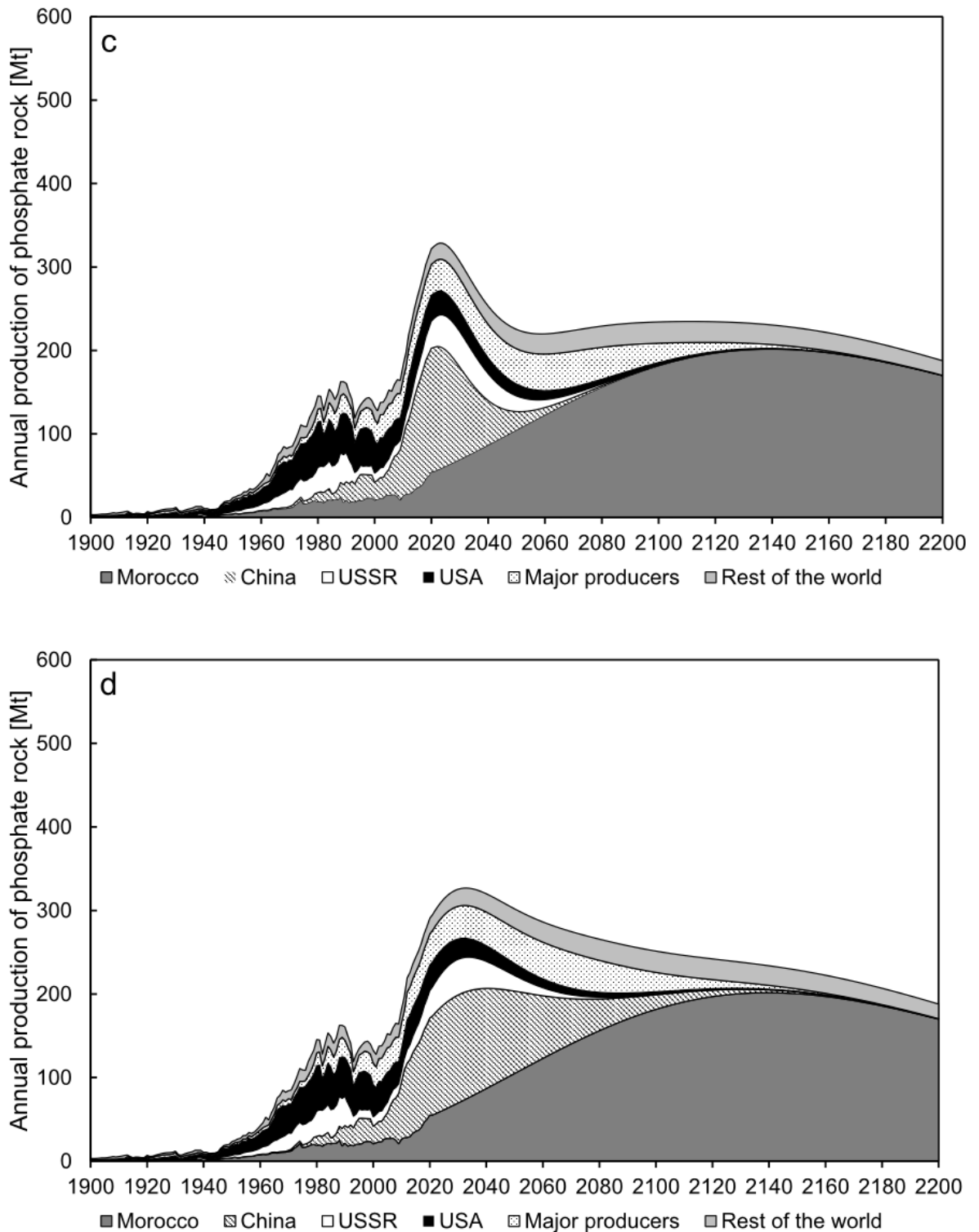


Figure 5. Resulting production from disaggregated model using Gompertz curves. a) Case 1 with low URR estimate for China and Morocco. b) Case 2, low URR estimate for Morocco, high for China. c) Case 3: High URR estimate for Morocco, low for China. d) Case 4: High URR estimate for China and Morocco.