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Modeling of Peak Phosphorus

A Study of Bottlenecks and Implications for Future Production

Petter Walan

Abstract

Today's modern agriculture is totally dependent on phosphorus to sustain their large yields. Several studies have recently expressed a concern for a future phosphorus deficiency. These studies are based on data for estimated reserves which have been increased with more than a fourfold since 2010. Some argue that these concerns are unfounded, despite the fact that only Morocco account for the bulk of these new reserves. This report provides new forecast for the world phosphorus production based on the new available reserve data. These forecasts are using bell shaped curve models to examine how individual countries' future production of phosphate rock affects a global production peak. Estimates of the size of several reserves are highly uncertain and it is therefore difficult to make an accurate forecast of future phosphorus extraction.

Despite this uncertainty, a global production peak is likely to occur within this century. The global production will depend largely on China and Morocco's production as they hold a large share of the reserves and the current production. China's production will probably peak in 10-20 years at current production trend. It is uncertain if Morocco can increase production enough to replace China's production in the future. It is not likely that Morocco will be able to produce as much as would be required to meet the highest scenarios. This is mainly due to a number of bottlenecks in production such as water scarcity, increasing proportion of impurities and a decreasing concentration of phosphorus in the phosphate rock.

Keywords: Phosphate rock, peak phosphorus, reserves, production, curve fitting

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Referat

Modellering av Peak Fosfor – En studie av flaskhalsar och konsekvenser för framtida produktion

Petter Walan

Dagens moderna jordbruk är totalt beroende av forsfor för att upprätthålla sina stora skördar. Ett antal studier har nyligen uttryckt en oro för en framtida brist på fosfor. Dessa studier har varit baserade på data för de uppskattade reserverna, vilka har mer än fyrdubblats i storlek sen 2010. Vissa hävdar därför att denna oro är obefogad, trots att endast Marocko står för större delen av dessa nya reserver. Denna rapport ger ny prognos för världens fosforproduktion, baserad på dessa nya tillgängliga data. Dessa prognoser använder klockformade kurvmodeller för att undersöka hur de enskilda ländernas framtida produktion av fosfatsten kan påverka en global produktion topp. Uppskattningar av storleken på flera reserver är mycket osäkra och det är därför svårt att göra en exakt prognos av den framtida fosforutvinningen.

Trots denna osäkerhet, är det sannorlikt att en global produktionstopp kommer att ske inom detta århundrade. Den globala produktionen kommer till stor del bero på Kina och Marockos produktion eftersom de innehar en stor andel av reserverna och den nuvarande produktionen. Kinas produktion kommer antagligen kulminera om 10 till 20 år med nuvarande produktionstrend. Det är osäkert om Marocko kan öka produktionen tillräckligt för att ersätta Kinas produktion i framtiden. Det är inte troligt att Marocko kommer att kunna producera så mycket som skulle krävas för att uppfylla de högsta scenarierna. Detta beror främst på ett antal flaskhalsar i produktionen, såsom vattenbrist, ökad andel orenheter och en minskande koncentration av fosfor i fosfatmineralet.

Nyckelord: Fosfatsten, peak fosfor, reserver, produktion, kurvanpassning

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Modeling of Peak Phosphorus – A Study of Bottlenecks and Implications for Future Production

Petter Walan

Allt form av liv på jorden är beroende av näringsämnen för att växa och frodas. Eftersom en del näringsämnena försvinner från jorden med skörden måste nya näringsämnen tillsättas till jorden för att inte näringsbrist med minskade skördar som resultat ska uppstå. Ett av de näringsämnen som behövs i störst mängd är fosfor och detta tillsätts idag till stor del i form av fosforrikt konstgödsel. Behovet av fosfor har ökat dramatiskt i världen de senaste 50 åren som ett resultat av en växande befolkning och en ökande industrialisering och urbanisering. Utvinningen av fosfor kommer att behöva fortsätta öka i och med att antalet människor kommer att fortsätta öka till mer än 9 miljarder år 2050 och att många människor i tillväxt länder som Kina och Indien äter allt mer kött och mejeriprodukter. Större delen av den fosfor som finns konstgödsel tas i dag från fosfatsten som är en icke förnyelsebar resurs eftersom det tar flera miljoner år för den att bildas. Ekonomiskt utvinningsbara resurser av fosfatsten finns endast i en begränsad mängd i världen och är mycket ojämnt fördelade, med större delen av reserverna koncentrerade i Nordafrika och Mellanöstern.

Fosfatsten utvinns med liknande metoder som inom kolindustrin, ofta i enorma dagbrott med hjälp av mycket stora grävmaskiner. Därefter anrikas fosfaten genom att oönskat material tas bort med olika metoder. Slutligen framställs konstgödsel av fosfaten för att göra fosforn mer lättillgänglig för växter att ta upp. Dessa processer orsakar flera sorters föroreningar som övergödning, koldioxidutsläpp, gruvavfall och framför allt bildas stora mängder fosforgips vid tillverkningen av fosforsyra under konstgödselproduktionen. Detta gips innehåller mycket radioaktivt avfall och måste därmed läggas på hög. Stora mängder vatten och energi används också i flera av processerna i produktionen. Framför allt vattenanvändningen kan bli ett problem i framtiden eftersom större delen av fosfatstensreserverna i världen ligger i länder som har brist på färskvatten.

På senare år har flera studier pekat på att det kan bli brist på fosfor i världen inom en snar framtid eller att fosforreserverna till och med skulle kunna ta slut inom detta sekel. Andra studier menar på att det inte finns någon risk för fosforbrist inom en överskådlig framtid och att fosforn kommer att räcka i flera hundra år till. Att det finns en så stor skillnad beror på att olika metoder används för att göra prognoser samt att det finns en mycket stor osäkerhet över hur mycket fosfor det finns kvar som kan utvinnas i framtiden. De få data som finns på uppskattade reserver ökade dessutom dramatiskt 2010 men en nästan fyrfaldig ökning av reserverna. Framför allt antogs Marocko ha en mycket stor del av världens reserver.

I denna studie används kurvmodeller som tidigare används för att bland annat korrekt förutspå produktionstoppen för oljeutvinningen i USA:s 48 nedre stater. Modellerna bygger på historiska produktionsdata och data för fosfatstensreserverna i världen. Dels gjordes modelleringar för den totala världsproduktionen, men också för de större producenterna som Kina, Marocko och USA. I dessa modelleringar användes olika scenarier med olika uppskattningar på hur mycket fosfatsten som kommer att vara utvinningsbart i framtiden. En undersökning av fosforkoncentrationen i fosfatsten gjordes också både för världen och enskilda länder, men endast USA visade på en klart neråtgående trend i koncentrationen och det gick inte att se något tydlig nedgång för världen i helhet.

Resultaten av modelleringen visar att en global produktionstopp av fosfatsten kommer att ske under detta århundrade med nuvarande produktionstrend, men att fosfatsten kommer att kunna fortsätta brytas inom en överskådlig framtid. Den globala produktionstoppen påverkas mycket av hur snabbt och hur mycket Kina och Marocko kommer att öka sin produktion i framtiden. Kina har haft en mycket kraftig produktionsökning de senaste 10 åren, men denna produktion antas kulminera om 10 till 20 år med nuvarande produktionstrend. Marocko kommer att få en allt större del av den globala produktionen, men det är osäkert hur mycket de kommer att kunna producera med tanke på framför allt begränsningar i tillgång på vatten, men också på grund av ökade energikostnader, investeringskostnaderna som krävs samt att Marockansk fosfatsten ofta innehåller större mängder tungmetaller som kadmium.

Studien visar att peak fosfor problematiken är för komplicerad för att bara använda ihop slagna världsdata istället för att modellera varje land för sig. Vissa länders produktion kommer toppa långt före andra och det gör att vi kan få tillfällig brist om inte andra länder lyckas ersätta dessa produktionsfall.

Contents

List of abbreviations

BGS	British Geological Survey
DAP	Diammonium Phosphate
EFMA	European Fertilizer Manufacturers Association
EROEI	Energy return on energy invested
GPRI	Global Phosphorus Research Initiative
HCSS	The Hague Centre for Strategic Studies
IFA	International Fertilizer Industry Association
IFDC	International Fertilizer Development Center
NPK	Nitrogen (N), phosphorus (P) and potassium (K)
MENA	Middle East and North Africa
MAP	Monoammonium Phosphate
Mt	Million tons
OCP	Office Chérifien des Phosphates
P_2O_5	Phosphorus pentoxide
SSP	Single Superphosphate
TSP	Triple Superphosphate
UNEP	United Nations Environment Programme
UNIDO	United Nations Industrial Development Organization
URR	Ultimate recoverable resources
USBM	United States Bureau of Mines
USGS	United States Geological Survey
USSR	Union of Soviet Socialist Republics
WPA	Wet Process Phosphoric Acid

1. Introduction

With the growing population and rise in urbanization and industrialization in the world over the last 50-years, the demand for phosphorus has increased dramatically (Ashley et al., 2011). This has led to a sharp increase in phosphate rock production and humanity has at the same time become increasingly dependent on the constant supply of phosphorus. The current food production requires access to large amounts of phosphorus fertilizer and a shortage would lead to smaller harvests (Cordell et al., 2009). Phosphorus in the form of phosphate rock is like oil a finite resource and will eventually be exhausted (May, 2011). Reduced phosphorus production would have serious consequences for the global food security unless measures are taken in time to reduce the dependency of phosphorus.

Over the last two decades, there has been a rising concern over a future world scarcity of phosphorus. After a big price peak in 2007-2008, the question of phosphate rock depletion got lots of attention and many reports were written on the subject. There have been a number of studies warning that the existing reserves could be depleted, or that at least the global production of phosphorus will peak within the 21st century (Herring and Fantel, 1993; Steen, 1998; Smil, 2000; Hutton and Meeûs, 2001; Rosemarin, 2004; Déry and Anderson, 2007; Rosemarin et al., 2009; Cordell, 2008; Cordell et al., 2009; Smit at el, 2009; Udo de Haes et al., 2009; Vaccari D, 2009; Mórrígan, 2010).

The phosphorus production was recently estimated by Cordell et al. (2009), to peak around year 2033. This was challenged in 2010 by a report from the International Fertilizer Development Center (IFDC), which estimated the reserves to be more than four times as large that was previously assumed. This changed the picture dramatically and resource shortages seemed no longer as looming as before. Many new reports now estimate that the reserves will last 300-400 years at current production and that there is no indication of peak phosphorus in the nearby future (Van Kauwenbergh, 2010; Cooper et al., 2011; Scholz and Wellmer, 2013). Few scientific articles have therefore been written about phosphorus deficiency since then and there has especially been lacking new studies of when a future peak in phosphorus production might take place. Hence, there is still a common belief that phosphorus will peak around 2035, although the state of knowledge has changed.

Therefore, a new forecast is needed to estimate if the world production of phosphorus is likely to peak in a near future. Another aspect that is totally absent is the potential production peaks of individual countries and their impact on the global peak. Since phosphorus availability is such an important asset to the food production and the large reserves are concentrated to only a few countries, such study may be useful. This would also give a picture of how the future phosphorus production might be distributed, as some countries production are likely to peak before others.

1.1 Objective

The aim of this report is to model the future phosphorus production to examine if there are geological limits of phosphorus in the form of economically recoverable reserves that will result in a global peak in phosphorus production in the near future. This is conducted by using mathematical curve fitting models and historic production and reserve data for the major phosphorus producing countries and for the world as a whole. Another major aim of this report is to conduct a thorough literature review and background on phosphorus depletion.

Other objectives are to study the largest producers' impact on world production and to discuss the potential bottlenecks of the future production. The report will also attempt to answer if the concentration of phosphorus has decreased in the phosphate rock that has been extracted in the world historically.

1.2 Limitations

The mathematical models will only take into account the historical production trends and the estimated ultimate recoverable resources (URR) of phosphate rock. Changes in demand and production bottlenecks will therefore only be discussed and not be included in the models. Only free available public data will be used in the report. Production prognoses will only be implemented to the ten largest producers. The amount of phosphorus will be given in phosphate rock as data of phosphorus concentration is lacking before 1978 and phosphate rock data are available since the beginning of the 20th century (7 ton phosphate rock usually contains around 1 tons of phosphorus (Cordell et al., 2009)).

2. Method

2.1 Previous studies

There are different approaches to forecasting the future availability of a mineral. The simplest and one of the most common model for evaluating phosphate scarcity is to calculate the R/P-ratio (reserve-size/annual-production) which shows how long reserves will last at the current production rate. The model has many shortcomings as neither production rate or reserve size is constant over time due to new discoveries and changes in demands and production (May et al., 2012). It is also unlikely that production would suddenly be interrupted. Instead it is more realistic that it would slowly subside. Scholz and Wellmer (2013) argue that R/P figures can be used to identify possible future shortages and how much time that is available to explore new resources. Smil (2000), Rosemarin (2004), Van Kauwenbergh (2010) and Scholz and Wellmer (2013) are examples of articles that uses the simple R/P-ratio to describe future scarcity of phosphorus are.

Another type of model that has been applied to forecast mineral depletion is exponential production models with a fixed growth rate. These models can be found in a number of articles about phosphorus depletion by Herring and Fantel (1993), Hutton and Meeûs (2001), Smit et al. (2009) and Cooper (2011). The specified growth rate in this model has a major impact on how fast the reserves will be depleted, which means that several different growth rates should be tested (Smit et al., 2009). This model better describes the increase in production, but it fails to describe reduction like the R/P ratio do. Also it is questionable whether a constant exponential growth is reasonable in the long run (Smit et al., 2009, Höök, 2011). Hence, these models do not reflect the future production very well.

System dynamic models have also been used by Van Vuuren et al. (2010) to forecasts on mineral resource depletion. These models are often very complex, using feedback loops and a great deal of in-data (May et al., 2012). Hence, it is much more complicated to develop accurate models with this method and the confidence in the final model can therefore be reduced if the data are uncertain.

Bell-shaped curve models have also been applied by a number of articles focusing on phosphorus (Cordell et al. (2009), Déry and Anderson (2007) and Mórrígan (2010)). The model has the advantage that it better describes the production trend and illustrates when the supply no longer can meet demand. Cordell et al. (2009) estimated that the production would peak at 29 million tons of phosphorus (about 203 million tons of phosphate rock) around year 2033. Their URR (ultimate recoverable resources) was based on production and reserve data from USGS, EFMA and IFA. The peak was later recalculated by the *Global Phosphorus Research Initiative* (GPRI) to occur somewhere between 2051 and 2092 with a mean at 2070 (Cordell et al., 2011a).

Déry and Anderson (2007) and also Mórrígan (2010) argue that the production already peaked in 1989 at 166 million tones. This estimate was based on Hubbert linearization to estimate a URR of 8,000 Mt phosphate rock rather than to base the URR on cumulative production data and available reserves. Data for 2012 show that the cumulative production reached over 7,400 Mt since 1900 and that production is now up to 210 Mt in 2012. Hence, this decline in production after 1988 probably was a result of the collapse of the Soviet Union and a drop in demand in Europe and North America to reduce the problem with eutrophication (Cordell et al., 2009; IFA 2011).

2.2 Peak phosphorus modeling

To predict future peak of phosphate rock production, time series analyses can be used in the form of bell-shaped curve models. This method uses the trend from historic production data and a constraint in URR to predict future production (Höök et al., 2011). In time series of production data, growth of the production is common. Unbounded exponential growth of for example phosphorus production is, obviously, impossible in the long run as the production would grow to infinity. As Earth is a finite planet, there must therefore be a physical limit to this growth. Hubbert was a pioneer in this field by highlighting the limitation of the non-renewable resource; oil. By using a bell-shaped model he correctly predicted the extraction peak of oil in the U.S. lower 48 states (Bardi, 2005). A number of articles have also been published recently on the global production peak of oil. A report by the UK Energy Research Centre (Sorrell et al., 2009) covering over 500 studies on the subject, concluded that a global peak before 2030 is likely and that there is a significant risk that a peak will occur before 2020.

Mineral production almost always results in the form of bell-shaped curves as well (Bardi, 2005). Bardi and Pagani (2008) showed that the bell-shaped curves could be applied for most minerals and that 11 of the 57 minerals investigated probably already had peaked. One of the more uncertain of these minerals was phosphorus, which they wrongly assumed peaked 1989. The model, however, provides a simple method to forecast the future production at a "business as usual" trend and identifies the time frame for a future peak event (May et al., 2012). When talking about oil it is often sad that: *it's not the size of the tank which matters, but the size of the tap* (Aleklett, 2012). This means that what is important is not how large the resource is, but how much of it that can be extracted and at what rate.

The bell-shaped curve has a low production at the start and in the end of production with one or more production maximum somewhere in between (Höök et al., 2011). The area under the curve is equal to the URR and the production peak for a symmetric curve will occur when half of the URR have been extracted (May et al., 2012). The production curve can be both symmetric and asymmetric (Höök et al., 2011).

One major difference between the prognoses of mineral production peaks (like phosphorus) and the production peaks of fossil fuels, is that mineral resources are recyclable and not destroyed when it is consumed (May et al., 2012). There will always be the same amounts of phosphorus in the world regardless how much we use since the phosphorus molecules cannot be created or destroyed. Phosphate rock on the other hand is a nonrenewable mineral as it is formed very slowly. Another difference is that phosphorus can exist in many different concentrations compared with crude oil, which are not graded. This makes it difficult to determine exactly what is possible to extract and what is not (Bardi and Pagani, 2008).

It is known that the cheapest and most easily extracted resources are depleted first, which results in that costs 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. For phosphorus, a lower P_2O_5 content results in more impurities and higher costs (Van Kauwenbergh, 2010). This would eventually lead to excessive costs and therefore a production peak. The same principle can be applied to energy sources, but instead for the cost of money is the energy cost calculated. This is called EROEI, e*nergy return on energy invested*.

2.2.1 Limitations of the peak phosphorus analysis

Bell-shaped curve models are simple and effective models to identify the time frame of a future production peak (May et al., 2012). The model has a number of limitations due to its simplicity. It is based only on information of geological supply and assumes that demand follows the current trend. It is therefore sensitive to fluctuations in both demand and supply. If new technology is developed or the price is increasing, some resources with lower concentration or more difficult extractable phosphate rock may be converted to economically extractable reserves (May et al., 2012). Other factors on the supply side that can change the time of the production peak are discoveries of new larges reserve deposits, changes in the estimations of the reserve sizes, and geopolitical unrest. On the demand side are changes in the world economy, new diets, geopolitical shocks and changes in the use of fertilization possible factors that may change the timeframe of peak phosphorus (Cordell et al., 2009).

One other limitation is the unreliable data available for reserves. As new reserves are discovered, the URR will increase over time. The model also assumes that it is possible to extract all minerals in the reserves, which is probably impossible in reality. To make a proper estimate, it is therefore a good idea to use more than one URR to estimate a time interval where a future peak might take place.

Although a global peak of phosphorus might be far into the future, national peaks will occur earlier in some countries (Höök et al., 2011). This has important implications for the competition between countries in the phosphate rock market. It also supports the countries with useful information about the future development of phosphate mining in the country and can in this way help to transform the economy into other activities, in case of a national imminent production peak (May et al., 2012).

2.2.2 Bell-shaped growth curves

Many different models can be used to estimate a production peak from time series of historic production data. Since the production not necessarily needs to be symmetrical, both symmetric and asymmetric models are applied in modeling of peak minerals. Some of the best known models are; Logistic, Gompertz, Brody and Bertalanffy functions (Höök et al., 2011). All of these curve models are special cases of another more general model called Richards. The models are describing the cumulative production and are formed as an s-shaped curve, so called sigmoid curves. The logistic curve is symmetric and the second derivative of the function (the annual production), peaks when 50% of the URR have been consumed (Eq. 1). The Gompertz is instead asymmetric, whose second derivative peaks when only 40% of the URR is consumed (Eq. 2). Hence, Gompertz curves have a high growth rate, but a lower decline rate. The logistic model describes a free market situation well, while the Gompertz model has a more limited production development. Since the two models are so different to each other and behave so different, they provide a good interval of possible outcomes for the future estimations of production. The curve models are mathematically described as:

Logistic: $$y(t) = \frac{URR}{1+e^{(-k(t-t_0))}} \quad (1)$$

Gompertz: $$y(t) = URR * e^{(-e^{(-k(t-t_0))})} \quad (2)$$

Where y(t) is the cumulative production at time t. The URR is the ultimate recoverable resources, k is the growth rate and t_0 is the year of the production peak.

For some countries is it impossible to fit these curve models to their production trend. This problem occurs in some cases because there is two (or more) production peaks. The problem can be overcome for logistic curves by adding an extra peak (Eq. 3). Logistic double peaks have been used for example in Höök and Aleklett (2010).

Logistic double peak: $$y\,(t) = \frac{URR_1}{1+e^{\left(-k_1\left(t-t_{0(1)}\right)\right)}} + \frac{URR_2}{1+e^{\left(-k_2\left(t-t_{0(2)}\right)\right)}} \quad (3)$$

The URR_1 in this case is the cumulative production at the first peak, $t_{0(1)}$ and the URR_2 is URR - URR_1. The growth factor is k_1 and k_2 for the two different peaks and $t_{0(2)}$ is the year of the second peak.

The major limiting factor to the model that determines when production peaks is the ultimate recoverable resource, URR. To estimate the URR, a calculation of the total cumulative production is required as well as an estimate of how much that will be possible to extract in the future. The cumulative production is obtained by summing together data for the previous production. The URR can be described as the area under the curve obtained from the model. In some cases it is also possible to obtain the URR by applying Hubbert linearization. This method use linearization of the production trend in relation to the cumulative production, to obtain a final URR (see Déry and Anderson (2007) for more information).

Another potentially important limiting factor except the URR is the depletion rate ($d_{\delta t}$), which is the proportion of the annual production compared to the reserves remaining in the ground (Eq. 4). The depletion rate is described as:

$$d_{\delta t} = \frac{P_t}{URR - Q_t} \qquad (4)$$

Where P_t is the annual production at a given time t and Q_t is the cumulative production at the same time.

There is always a limit to how large the depletion rate can become (Höök and Aleklett, 2010). If no maximum depletion rate is used, the curve can behave unrealistically with, for example a steep rise and then a sharp fall in production. Mining activities for other minerals indicates that there is a maximum limit around 3 to 5% for the depletion rate (Vikström et al., 2013). A maximum depletion rate is therefore set to 5% in order to prevent unrealistic results in the modeling, even though the model is mathematically correct.

2.3 Methodology

To estimate when peak phosphorus will occur, similar methodology is applied as in previous studies of Vikström et al. (2013) and Höök and Aleklett (2010). Bell-shaped growth curves are fitted to historic production data for the countries that are examined. The URR and a maximum depletion rate are applied as restraints for the model. The modeling is conducted using numerical and least square methods to fit the growth curve to the production curve. This is done in Excel with help of the add-in Microsoft Excel Solver, which finds the minimal sum of the least squares for every year by changing two variables: the peak year (t0) and the growth factor (k). Some years can be given a larger impact by multiply the least squares for the year by a two or three order of magnitude. This is conducted for the last year in this report to make the modeled production for this year to correspond well with the past year's known production.

3. Phosphorus background

3.1 Terminology

Phosphorus is often referred in different ways depending on the context. It is important to understand the difference between the different expressions as they mean different things. The word *phosphorus (P)* is most often used in contexts where it is described as an element or a nutrient and consists of a single element P. Since phosphorus is mostly found in the form of *phosphate* (PO_4^{3-}), this is also a common name, especially when it comes to phosphorus ecological function. The main source of phosphate is found in phosphate rock from sedimentary and igneous deposits (Kauwenbergh, 2010). The size of production, resources and reserves is described almost exclusively in tons of *phosphate rock*, which does not have a fixed concentration but may vary between different sources. Other words for phosphate rock are *phosphorite* and *rock phosphate*. Fertilizer and phosphate rock grade are usually expressed as *phosphorus pentoxide* (P_2O_5), which has a phosphorus content of about 44% (Cordell and White, 2011). Phosphorus pentoxide will be used in this report to describe the phosphorus content in phosphate rock. Some publications, such as the British Geological Survey (BGS) mineral statistic summaries report the phosphate rock grade in tricalcium phosphate, $CA_3(PO_4)_2$. There are many different expressions for tricalcium phosphate including; “bone phosphate of lime”, “tricalcium phosphate”, “triphosphate of lime” and “tribasic phosphate of lime ” (Krauss et al., 1986). One ton of tricalcium phosphate is equal to 0.4576 ton of P_2O_5 or 0.1997 ton of P (Van Kauwenbergh, 2010; Krauss et al., 1986).

Often in articles about the extraction of phosphate rock or other minerals, the word production is frequently used, although the minerals in this case is not created but is extracted from the ground. The word production is also applied in this report as it is the commonly used terminology in this area, although it may sound strange to talk about production of an element or production of a mineral that is created in the ground. Production refers in this report to either extraction or manufacturing of something.

3.2 The importance of phosphorus

All forms of life on earth need some form of energy to live. Humans and animal need energy in the form of food, which requires water, sunlight and nutrients for growth. One of these nutrients is phosphorus that is a vital element of all sorts of life. In animals and humans, most of the phosphorus can be found in bones and teeth’s in the form of hydroxyapatite, $Ca_{10}(PO_4)_6(OH)_2$ (Smil, 2000). It is also an important part in structure components in the nucleic acids in DNA and RNA as well as a vital part of the cells energy carrier, ATP. Without phosphorus there can be no proliferation and no animals or plants can grow and reproduce and therefore is phosphorus an essential nutrient for both plants and animals. A person needs roughly about 0.8 g/person per day (adults over 24 years old and children) and to be healthy. Young adults need about 1.2 g/person, but a typical consumption of phosphorus is about 1.5 g/person, hence it is very unusual with phosphorus deficiency (Smil, 2000).

Phosphorus is also associated with many positive growth factors for plants such as stimulation of root development, improvements in crop quality and growth as well as an increased resistance to plant diseases (Griffith, n.d.). Phosphorus is one of 16 essential nutrient elements that are required for crops to grow. Phosphorus together with nitrate (N) and potassium (K) are the nutrients that are utilized in the largest amounts by crops and therefore needs to be added to the soil in large quantities as fertilizers to gain high yields. Lack of one of these tree nutrients is usually the limiting factor for plant growth. There is a huge imbalance globally between the different soils with some that have a major shortage of phosphorus like the sub-Sahara region and Australia, while other areas such as the Western Europe and North America have phosphorus rich soils after decades of intensive fertilization (Cordell et al., 2009).

Of the three most important nutrients, nitrogen is the one that is required in the greatest amount. As 78% of the air in the atmosphere consists of nitrogen it is also one of the most abundant elements on the planet. Natural gas is often used as energy source to synthesize nitrogen-rich ammonia from nitrogen gas in air as nitrogen in its stable phase is not available to most plants (IFA/UNEP, 1998). Other energy sources such as coal can also be used for production of nitrogen fertilizers and it is also possible to absorb nitrogen from the air to the soil with nitrogen-fixing plants and bacteria. Potassium is the third most important nutrient for plants. It is a more abundant element in the earth's crust than phosphorus and is also required in much smaller quantities. Potassium is gained from various mined salts that contain potassium often called potash.

As a consequence of the phosphorus importance as a nutrient, about 82% of the extracted phosphate rock goes to fertilizer production (Schröder et al., 2009). About 7% is for animal feeds, about 1-2% for food additives and the remaining 8-9% of the phosphorus is needed in a wide range of industrial applications such as detergents, matches, fireworks, food and beverages, flame-retardants, water based paint, paper coating, the processing of various ceramic products and to chemically polish aluminum (Phosphate Forum of the Americas, 1996). The proportion of phosphorus in detergents has declined in recent years as a result of the new regulations imposed in many countries to limit the problem of eutrophication (Schröder et al., 2009).

3.3 Geochemistry

Phosphorus is the 11th most abundant element in the earth's crust with an average concentration of 0.10 to 0.12 percent (Krauss et al., 1986) and the 13th most common element in seawater (Smil, 2000). Unlike nitrogen it does not occur in its elemental form in nature and rarely in gaseous state. Therefore is it always combined with other elements in various forms of orthophosphates and it only exists adsorbed on particulate matter in the atmosphere (Pierriu U, 1976). Despite its importance to plants and animals, biomass is not a major source of phosphorus as the phosphorus only accounts for 0.025% on average of the biomass in the forest compered to coal that accounts for 45% (Smil, 2000). The main reservoirs of phosphorus are found in bedrocks, soil and sediments (Ruttenberg, 2003). Phosphorus is mostly found in nature as phosphate because of its highly reactive characteristics. Apatite, a group of phosphate minerals, is the main source of phosphate and is found in sedimentary, igneous, metamorphic and biogenetic environments. About 95% of all the phosphorus in the earth crust is estimated to be bound in different forms of phosphate apatite minerals of which there are more than 200 forms known (Krauss et al., 1986). In general, phosphorus occurs with all the elements in the periodic table. Phosphate minerals mostly consist of different types of calcium phosphate apatite, of which fluorapatite, ($Ca_{10}(PO_4)_6F_2$), hydroapatite ($Ca_{10}(PO_4)_6OH_2$) and chlorapatite ($Ca_{10}(PO_4)_6Cl_2$) are most common (Smil, 2000). Concentrations of phosphate in phosphate rock are generally low and economical extractable phosphate in high concentrations is only found in large quantities in a few countries.

3.4 The phosphorus cycle

Phosphorus moves through the lithosphere, hydrosphere, and biosphere in what is called the phosphorus cycle (see figure 1). Unlike other biochemical cycles such as for nitrogen and coal, the atmosphere does not play a significant role in the phosphorus cycle, since production of phosphine gas only occurs in specialized, local conditions (Ruttenberg, 2003). The cycle begins with a volcanic activity or an uplift of phosphorus rich sediments, which makes the phosphate minerals exposed to physical erosion and chemical weathering. Although the phosphate rock is poorly soluble, this result in a release of dissolved phosphorus in both organic and inorganic forms that is transported out to soils, rivers and seas. On land, plants take up phosphorus from the soil in the form of various phosphate ions. The phosphorus is returned to the soil by decomposition of dead plants and animals or from animal feces.

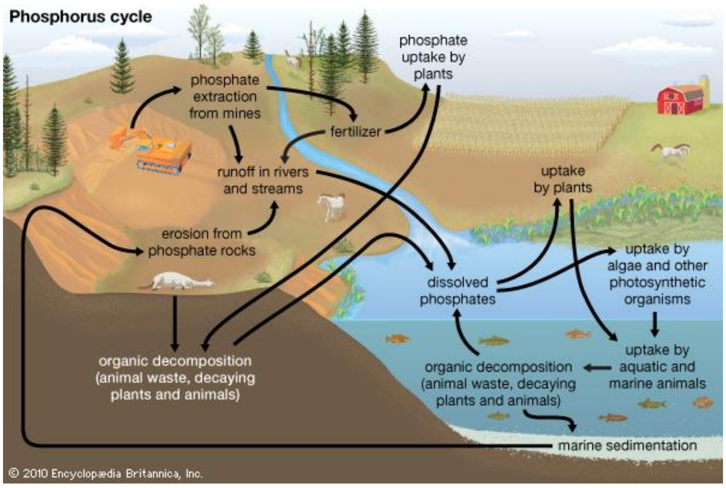


Figure 1. The phosphorus cycle (Encyclopedia Britannica).

Much of the phosphorus ends up in lakes and oceans where it is taken up by photosynthetic organisms. Unfortunately, because of human activity and reduced return of phosphorus to the fields in the form of human excrement, increasingly more of the phosphorus has ended up in the oceans. Death and decomposition of marine organisms return some phosphorus to the water. Phosphorus rich shells and other hard parts fall to the ocean floor and become a part of the marine sediments (Goldhammer, 2009). After 10 to 100 millions of years, movement of crustal plates uplift the seafloor and the phosphates become exposed to erosion and weathering once again (Smil, 2000). The phosphate rock deposits usually only occur during some special conditions in some specific areas as a result of the phosphorus cycle (Krauss et al., 1986). Phosphate Rock deposits can mainly be found in regions outside the old shield area and in old folded mountain areas. A large amount of phosphate rock was also created during specific periods when the conditions were particularly favorable for the formation of these deposits (Krauss et al., 1986; Ruttenberg, 2003).

3.5 Different types of deposits.

Today almost all phosphorus that is extracted in the world is from phosphate rock deposits. Phosphate can also be extracted form guano (mainly bird droppings from islands and coast) and bones from animals, but this only account for a very small proportion of phosphorus production and the reserves are small. The two main deposits of phosphate rock is sedimentary and igneous rock, each with different mineralogical, structural and chemical properties. Phosphate rock deposits vary not only in type and concentration it also have a great variation in the size of area and depth. The depth for instance can range from only a few meters up to more than 100 meter (UNEP/IFA, 2001).

Marine sedimentary deposits account for the major part of the world production, with 80% of the phosphorus market. The sedimentary phosphate rock deposits are formed as a result of biological and chemical precipitation of phosphorus in coastal areas that are close to the equator and with strong cold upwelling currents of phosphorus-rich water from great depths resulting in a high biological productivity (Ruttenberg, 2003). Sedimentary phosphate rock has a P_2O_5 around 30-35% (Krauss et al., 1986). The higher the phosphorus content is in the sedimentary phosphate rock, the lower is the level of contamination usually. Examples of areas with large sedimentary deposits are North Africa and Middle East (the MENA region), where large phosphate rock producers such as Morocco, Tunisia, Algeria, Egypt, Jordan, Syria and Israel are located (Krauss et al., 1986). U.S. and China also have large sedimentary layer of phosphate rock.

Igneous deposits are formed by differentiation of minerals in partly melted magma. Igneous rocks are low in grade with a P_2O_5 content that often are less than 5%, but this can be upgraded through beneficiation to 35-40% or even higher (Van Kauwenbergh, 2010). The igneous deposits are generally freer from certain types of pollutants such as radionuclides and heavy metals. The igneous phosphate rock deposits only accounts for about 20% of the phosphate rock in the world and these deposits can mainly be found in countries like Russia, Brazil, South Africa and Finland.

4. Supply and demand

4.1 Supply

Since phosphorus is one of the most abundant elements in the world, one could imagine that the availability of phosphorus should not be a problem. However, phosphorus is only profitable to extract if the concentration is high enough, the content of heavy metals and other pollutants is low enough and the phosphate is available in sufficient quantities that are economically and technically extractable. There are many different sources to phosphorus that can be used in agriculture such as; bones, guano, animal and human manure, organic waste, slaughter waste, fish waste and phosphate rock (Mårald, 2000). In other words, all that somehow originate from animals or plants have potential as a source of phosphorus. Today, most of the phosphorus comes from phosphate rock minerals and only a small proportion of the total amount of phosphorus that is produced comes from organic sources of phosphates as manufacture for these are more expensive per nutrient content (Van Kauwenbergh, 2010).

4.1.1 Classification

There are many different terms to describe the size of the mineral assets. Terminology to describe the available reserves include; *reserves, resources, reserve base, recoverable resources, economic reserves, ore reserves, proven ore reserves* and *proven mineral reserves.* All these expressions have different meanings. It is therefore crucial to understand the implications of these and not to confuse them, which commonly happen. There are also several different classification systems in the world. USGS have their own system with many different classifications, but only reserves are compiled currently in the annual releases apart from an estimate of the total amount of resources in the world (USGS, 2013). Before 2010, they published an estimated reserve base for some countries, but they stopped with this due to lack of sufficient information which made these estimates of the reserve base too uncertain (USGS, 2013). Other classification concepts include; the Australian *JORC code* that are used in many other countries, the South African *SAMREC*-system, *Crirsco* that are based on the JORC code and the *National Instrument 43-101*. The different systems use similar terminology, but differ in some aspects which can lead to confusion at times when data is collected from different areas.

The two most common classifications of deposits are reserves and resources, which will be used in this report. The two definitions are often applied by other authors and have relatively clear definitions. Yet, these two words are frequently confused with one another. The most common terms that are applied to phosphate rock is described below.

Resources are a concentration of minerals in the earth´s crust in such a form and amount that economic extraction is currently or potentially feasible.

Reserve base are the part of an identified resource that reach the minimum criteria for current mining and production practices, such as grade, quality, thickness and depth.

Reserves are the part of the reserve base that that could be recoverable profitably at current market conditions but extraction facilities does not need to be in place and running.

Economic reserve is the part of the reserve where profitable extraction has been established, proven by analytically demonstrations or can be assumed with reasonable certainty.

Ultimate Recoverable Resources (URR) is the total amount of mineral that will ever be extracted and produced. The ultimate recoverable resources can for instance be obtained by summing up the cumulative production and the available reserves and the resources that are assumed to be recovered in the future, which also include assumed new discoveries.

Reserves were earlier described by the United States Bureau of Mines (USBM) as the phosphate rock that could be produced at a cost less than US $40/ton, while the reserve base was described as what could be produced for less than $100/ton (Van Kauwenbergh, 2010). Many different factors have an impact on whether a deposit is economically recoverable. One important factor is the concentration of P_2O_5 in the phosphate rock. Other factors that is important for extraction is the economic demand, available technology, social and political factors. This can cause the size of the reserves to change from one year to another (Cordell and White, 2011). This could be seen after the price increase 2007/2008 when prices rose sharply and since then stayed at a price much higher than before. This price increase resulted in that many countries greatly increased the magnitude of their estimated reserves. The size of the reserves also changes naturally with time, because of new discoveries and depletion of others. This makes it almost impossible to make accurate estimates of resources and reserves. There are also other bottlenecks for production due to ecological, geopolitical, social and legal limitations. This can mean that available resources or reserves might be much smaller in reality than predicted.

4.1.2 Data for reserves and resources

There are limited data for both reserves and resources of phosphate rock. One of the problems is that much of the data are produced by the companies in the mining and fertilizer industry, which have no interest in making it publicly available. Some data are available from private companies but at a very high cost (Cordell and White, 2011). The only free available data that was found was from the United States Geological Survey (USGS) and a report from 2010 by the International fertilizer Development Center (IFDC). The USGS is the only organization that has publicly available annual reserve data for global minerals and metals. The data, however, rely on historically reported reserves and resources stated by companies and other reports. Although companies report proven reserves, the total size of the reserves and resources in the world will not be known as the exploration of new reserves is expensive and this only made if the layer is believed to be taken in production in the near future (Scholz and Wellmer, 2013). This means that the data for reserves may not be changed for many years, despite new advances in technology, higher prices and increasing or constant production (figure 2).

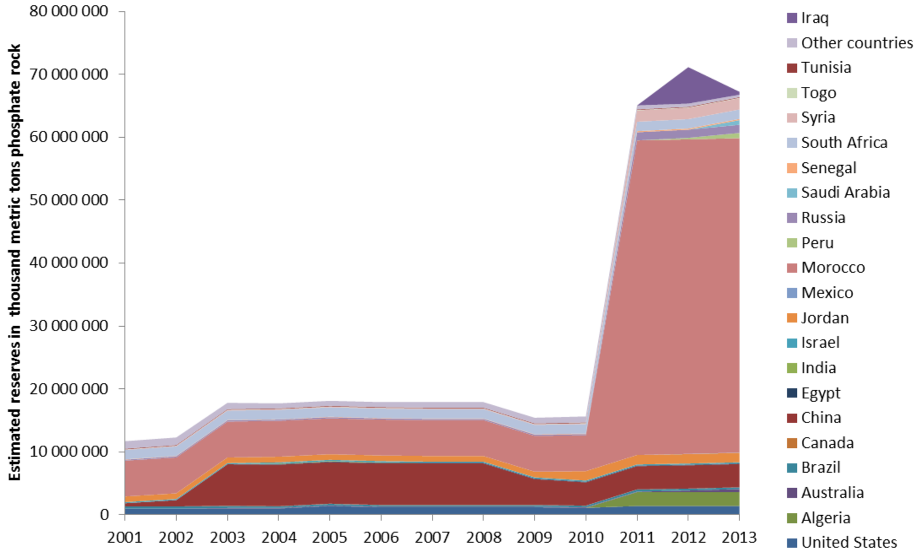


Figure 2. The size of USGS reported reserves from 2001 until 2013 in thousand metric tons of phosphate rock (data from Jasinski, 2013).

Reserve data

The total estimated reserves in the world according to USGS in January 2013, was 67 billion metric tons phosphate rock. The size of the estimated reserves in USGS annual publications has remained constant for many countries for several years despite their continuous production, while other countries have made significant changes in the size of their estimated reserves (see figure 2). One of the most dramatic changes in given reserves was made 2011 when USGS upgraded Morocco's reserves from 5.7 billion tons to 50 billion tons, based on new information from Moroccan producers and a report from the International Fertilizer Development Center (Van Kauwenbergh, 2010). The new numbers made the USGS estimated world reserve to increace from 16 to 65 billion ton from 2010 to 2011 (Jasinski, 2013). Although the data are based on secondery literature and it is not known if all this phosphate rock is truly recoverable at today's costs and prices (GPRI, 2010). Since mining companies do not put money on expensive exploration of potential reserves that they do not plan to use in many decades to come, Morocco's reserves and resources is not yet fully explored (Van Kauwenbergh, 2010).

Other reserves that have been revised significantly over the last years is the reserves of China (2003), Syria (2011), Russia (2011) and Iraq (2013) (figure 2). Countries with reserve estimation that have been constant for a long time in USGS data and still not not changed include a number of countries; Israel whose estimated reserves at 180 million tons have not changed since 1996, reserves for Tunisia (100 million tons) and South African (1,500 millon tons) that have not changed since 1999 and Egyptan reserves (100 million tons) that have not changed since they were included in the publications in 2004. Since all of these countries except South Africa is among the ten largest producers in the world and that the reserves despite that is not updated for such a long period, it is reasonable to assume that the stated reserves are not consistent with the actuall amount that is extractable. IFDC's figures for these countries also differ with lower estimated reserves for Tunisia and Egypt, and much lower for South Africa while Israel is assumed to have slightly larger reserves (see table 1).

Resource data

The U.S. Geological Survey does not specify any estimates of resources for individual countries but gives an estimate of the total amount of resources in the world to more than 300 billion tons of phosphate rock (Jasinski, 2013). This is consistent with the 290 billion tons identified resources what Van Kauwenbergh estimated in his report for IFDC 2010 were he also estimated the resources for some of the largest producers in the world, see table 1 (Van Kauwenbergh, 2010). Morocco is believed to have by far the largest share of the world's resources. Van Kauwenbergh (2010) estimated Morocco to hold more than half of the resources with approximately 170 billion tons of identified phosphate rock and that this might amount to around 340 billion tons if hypothetical resources also are considered. Other countries that hold large reserves are United States and China. A large amount of exploration projects are planned in various countries, which will likely increase the size of several countries estimated reserves and resources in the future.

Table 1. Estimation of reserves and resources in million metric tons of phosphate rock by the IFDC and the USGS (data from Van Kauwenbergh, 2010 and Jasinski, 2013).

Country	USGS Reserves 2010	IFDC Reserves 2010	USGS Reserves 2013	IFDC Resources 2010
United States	1,100	1,800	1,400	49,000
Australia	82	82	490	3,500
Brazil	260	400	270	2,800
Canada	15	5	2	130
China	3,700	3,700	3,700	16,800
Egypt	100	51	100	3,400
Israel	180	220	180	1,600
Jordan	1,500	900	1,500	1,800
Morocco	5,700	51,000	50,000	170,000
Russia	200	500	1,300	4,300
Senegal	80	50	180	250
South Africa	1,500	230	1,500	7,700
Syria	100	250	1,800	2,000
Togo	60	34	60	1,000
Tunisia	100	85	100	1,200
Other countries	950	600	4 656	22,380
Total	15,627	59,907	67,238	287,860

Large resources have also been found on the continental shelf and seamounts in the Atlantic and Pacific Ocean. Some of these areas, which are located in not too great depths, are planned for exploitation. Because of mainly environmental reasons, it is uncertain whether these areas will be developed in the future.

Another hypothetical resource for phosphorus is the oceans. In terms of the huge volume of the world's oceans, seawater is basically an infinite resource. If new technology for low-cost renewable energy would be developed in the future it would perhaps be possible to extract phosphorus from seawater according to IFA/UNEP (1998). The concentration of phosphorus in seawater is only 0.088ppm at 3.5% salinity (Anthoni, 2006), but the total volume of the ocean is approximately $1.3324*10^9$ km^3 (Charlotte and Smith, 2010). This means an additional 117 billion tons of phosphorus. This is about 14.5 times more than the world total estimated reserves (approximately 8.069 billion tons of phosphorus).

4.1.3 Distribution of reserves

The phosphate rock layers in the world are unevenly distributed. The bulk part of the reserves can be found in the MENA region, where more than 85% of the world's resources can be found (Jasinski, 2013). According to the latest data from the USGS almost three quarters of the world's phosphorus reserves are found in Morocco (see figure 3). Unfortunately, because of future depletion of existing reserves in many countries, Morocco is likely to gain an increasing share of production given their huge reserves. Hence, the world might see oligopolistic or monopolistic tendencies in the future because of this misallocation of the world's phosphate rock reserves (HCSS, 2012).

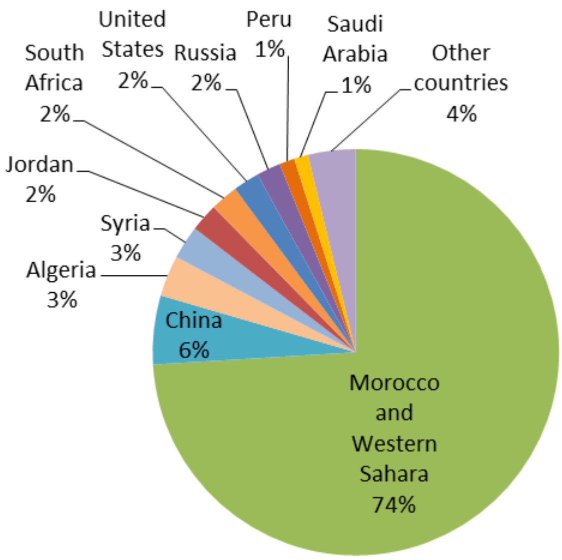


Figure 3. Reported reserves in 2013. Data from U.S. Geological Survey (Jasinski, 2013).

4.2 Demand

As phosphorus is one of the essential nutrients plants need to grow and give high yields, the world's agriculture is totally dependent on enough phosphorus to feed a growing population. The world population will exceed 9 billion in the year 2050 and later surpass 10 billion in the year 2100 according to the United Nations (2011). Because of the rapid increase in world population and more and more people in the developing world eat meat and dairy products, the food production will have to increase by 70% until 2050 according to FAO (2009). This requires a substantial increase in yields of the crops, since the availability of unexploited arable land is very limited without damaging valuable ecosystem. Large areas of cropland is also lost every year because of expanding cities, depletion of aquifers and overuse of irrigation water as well as degradation of agricultural land due to land mismanagement with results as salination and soil erosion (Worldwatch Institute, 1996). The global phosphorus supply will need to increase with 50 to 100% by 2050 to keep up with the world's demand for food (Cordell et al., 2009). Lack of chemical fertilizers is in many locations a constraint on food production and availability of fertilizer could therefore increase crop yields significantly in these areas. The phosphate rock production has over the past five years increased by an average of almost 5 percent, while prices have increased sharply. The world consumption was projected by U.S. Geological Survey in 2012 to continue grow at a rate of 2.5% annually during the next five years (USGS 2012a). Although, the growth for 2013, was as much as 7% and prices are still high.

4.2.1 Phosphate rock consumption

According to IFA data for phosphate rock consumption, Asia was using half of the produced phosphorus in the world 2010 as seen in figure 4. Especially South and East Asia have gained greater purchasing power which has led to an increase in their phosphate consumption as more people have been able to afford meat and dairy products. China, whose consumption and production both increased sharply in recent years, imposed a 135% tariff on phosphate in order to keep exports down and secure domestic supply for the future. Meanwhile other parts of the world instead still lack access to phosphate fertilizers due to low purchasing power. This is specially the case for many of the sub-Saharan countries, which at the same time belongs to a part of the world that have the most phosphorus-deficient soils (Cordell et al., 2009).

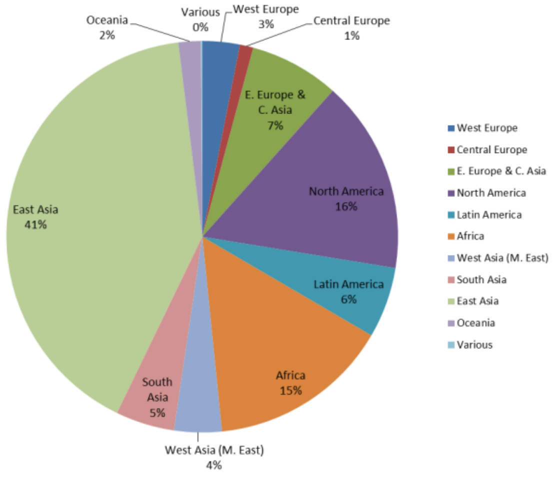
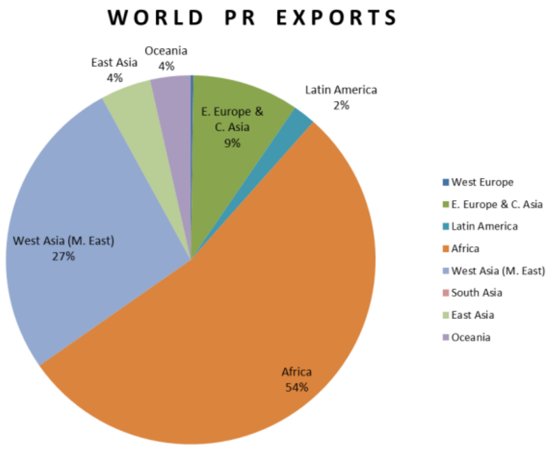


Figure 4. The total world phosphate rock consumption in 2010. Data from IFA's *production and trade statistics* (IFA, 2012).

As a result of the increasing demand from Asia and at the same time a tighter supply of phosphate rock, the price increased drastically from $40 to $460 at the price peak at the end of 2008 (USGS, 2008). This huge increase in price was also caused by a weaker dollar and high freight rates and energy costs due to the high oil prices at that time. The price recovered to a price around $90 at the time of the finance crisis, but has since then risen again and stabilized around $185. To increase the production takes time and requires a large amount of capital. In the United States for example, it may take 5-10 years to get a permit to build a new mine (Van Kauwenbergh, 2010). This may lead to shortages and high prices. There might also be a limit to how high prices farmers are willing to pay for phosphorus.



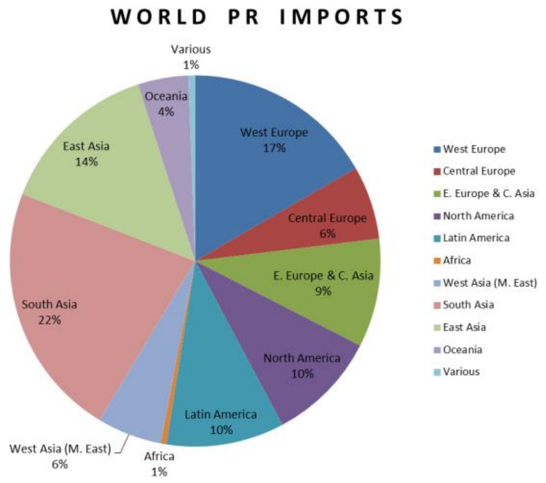


Figure 5. Export and import of phosphate rock in the world in 2010. Data from IFA's *production and trade statistics* (IFA, 2012).

4.2.2 Exports and imports

Although most of the produced phosphorus (about 79%) is consumed locally (PotashCorp, 2009), a large part of the world such as South Asia and Europe are highly dependent on imports. The tree largest producers, China, United States and Morocco, accounts for two thirds of the world production. China and United States consume most of their phosphate domestically and their reserves will be depleted in 50 years at current production rate. Morocco on the other hand exports most of their production and provides 42% of the export market with phosphate (PotashCorp 2009). With their goal to increase production from todays 27 million ton to 55 million ton phosphate rock by 2020, Morocco's share will probably increase a substantially (OCP, 2010). The rest of the export comes mainly from Middle East and the rest of Africa (figure 5).

4.2.3 Biofuel

Biofuels is often seen as part of the solution to peak oil and climate change, and production of biofuel is therefore expected to increase in the future. For example, the EU stated a target in 2009 that 10% of the fuel in the transport sector shall come from renewable energy resources in 2020 (Eurostat, 2009). This target has recently been reduced to 5% to avoid competition between food and fuel (Fox, 2012). Biofuels from agriculture requires a large amount of water, energy, land and fertilizers, which all are limited and instead could be used for food production. In addition, the corn-based biofuel have an EROEI (energy return on energy invested) around 1:1 (0.8-1.6:1) according to some studies, which means that corn-based ethanol barely gives any net energy at all to society (Murphy and Hall, 2010). Sugarcane ethanol can achieve an EROEI of up to 10:1. If the world's sugarcane production would be used for ethanol production, this would only replace 2.5% of the fossil fuels in the transport sector and at the same time would it be a lack of food in the world (Johansson et al., 2010). Another alternative source to biofuel could be micro algae. Micro algae have the advantage of producing more oil and that it can be grown on small surface areas that not need to be suitable for agricultural use (Demirbas, 2011). The water consumption is also smaller, but instead are the need for fertilizer much larger. A study by Rösch et al. (2011) found that it takes between 29 to 145 grams of phosphorus to produce one liter of biodiesel depending on condition, but at the same time ten times more nitrogen is consumed. About 48 to 93% of this phosphorus could be recyclable, however. Another report by Beal et al. (2011) studied the EROEI for microalgae and got an EROEI of only about 0.001 during experiments. This was estimated to increase to between 0.013 and 0.36 during more optimal conditions. Biofuel from micro algae is still only at an experimental stage and it is still unclear how high EROEI that can be achieved in the future. One of the major disadvantages for production of microalgae is also that they have a very low biomass concentration, which makes it expensive and hard to upgrade to commercial large scale production (Demirbas, 2011). With development of new technology, biomass from cellulose might play a more prominent role for the production of biofuel in the future (Johansson et al., 2010).

5. Production

5.1 Historic phosphorus production

Phosphorus was discovered by the German alchemist Hennig Brandt around 1669 in his search for the philosophers' stone when he tried to make gold from human urine (Ashley et al., 2011). At first pure phosphorus was seen as a mysterious source of light and was called *cold fire* as it was glowing in the dark. The name phosphorus comes from the Greek words for light and bearer (Ashley et al., 2011) and it was at first mainly used for questionable medical purposes. A century later, phosphorus was discovered in bones at higher concentrations than urine, which made it possible to produce larger amounts of phosphorus. In the 19th century, the main use of phosphorus was in matches due to its flammable qualities and later also as an element in war. In 1840, Justus von Liebig found that phosphorus and other minerals such as nitrate were essential for plant growth.

For thousands of years, animal manure has been returned to the fields to increase yields in China. This had also been done in Western and Central Europe since the Middle Age. In China, it has also been known for at least 5,000 years that human excreta has a fertilizing effect on soils, and it was therefore always returned to the fields (Ashley et al., 2011). Human excreta have also been recycled in Japan since the 12th century but this never happened to any great extent in Europe, although attempts were made over a few decades from the middle of the 19th century (Cordell et al., 2009; Mårald, 2000). The recycling system was abandoned in Europe at the beginning of 1900 for sanitary linear systems where wastewater instead was released into rivers, lakes and coastlines (Mårald, 2000). This was primarily due to health benefits, difficulties in dealing with latrine and economic unprofitability compared to chemical fertilizers which had become increasingly common on the market. This became a sanitation revolution which led to great health benefits, but also increased water pollution (Ashley et al., 2011).

The first fertilizer that was commercially applied was crushed bones in the beginning of the 19th century (Mårald, 2000). During this time, new better methods of cultivation with crop rotation arose, as well as new technologies and particularly new crops that could fix nitrogen from the air. These improvements meant that the agriculture in Europe could recover from the famines that had been a big problem during the 18th century (Cordell et al., 2009). Later guano started to be applied as fertilizers from islands along the Peruvian coast in the middle of the 19th century (Mårald, 2000). Production increased rapidly and peaked in the late 19th century and included at that time also islands in the Pacific Ocean. Unfortunately, because of lack of fertilizers and the small amounts of bones and guano that were available, attempts were made to find other sources of phosphorus. The new source needed was found in apatite rich phosphate rock that seemed to occur as an unlimited resource. In 1867 mining operations of phosphate rock started for the first time in South Carolina for the manufacture of phosphate fertilizers (Van Kauwenbergh; 2010). This new phosphate source had a higher nutrient content than what was found in animal manure, and it increased even more when methods were developed to separate the calcium sulfate to form double and triple phosphate fertilizers.

In the beginning of the 20th century, new complex NPK fertilizers were created that not only contained phosphoric acid but also ammonium nitrate and potassium chloride (UNEP/UNIDO/IFA, 2000). The green revolution that started after the World War II led the production to begin to grow drastically (se figure 6). With the help of pesticides and good water irrigation, this led to high increases in yields that could sustain a large population growth in the world (Cordell et al., 2009; IFA/UNEP, 1998). This also made the agricultural system increasingly dependent on external supply of fossil fuels, fertilizers and fresh water, all of which could be in short supply in the future. The production for phosphate rock grew quickly and appeared to peak in production once in 1988 at 166 million ton. The peak was largely because of decreasing demand and production as a result of the fall of the Soviet Union as well as an increased awareness in the western world about eutrophication (IFA, 2011; Cordell et al., 2009; IFA/UNEP, 1998). Production has increased in recent years due to a growing population and a sharp increase in the consumption of meat and dairy products in developing countries as China and India, as well as an increased biomass production for biofuel (Cordell et al., 2009). This trend is expected to continue while there also will be 2-3 billion more people to feed in 2050. The world is therefore totally dependent on an increasing production of phosphate rock to be able to feed the world in the future.

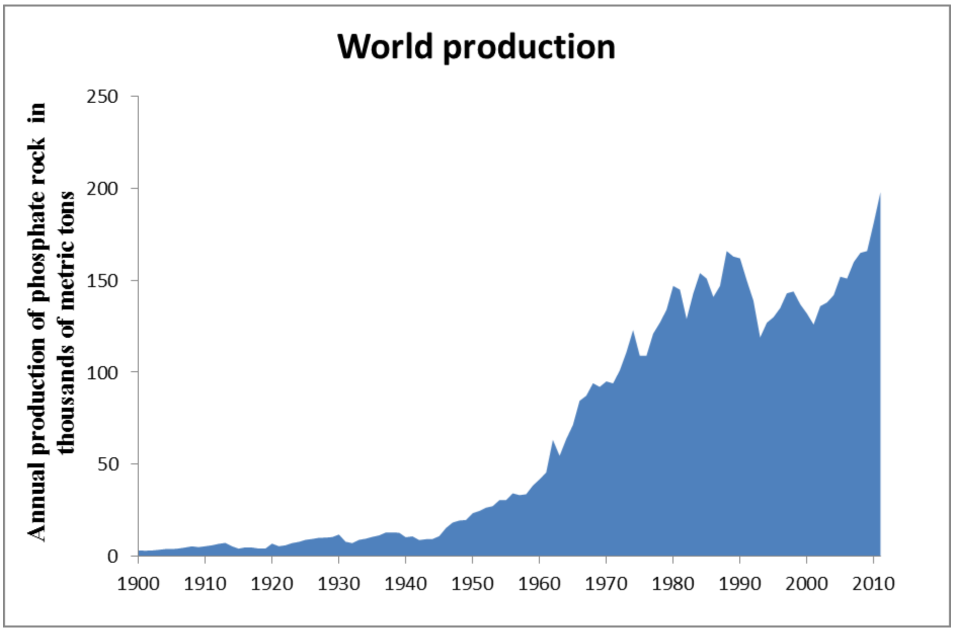


Figure 6. The phosphorus production over time since 1900 (Cordell et al., 2009).

5.2 Current production

Even though the phosphate rock reserves might be large, it doesn't matter if the extraction can't be done at the rate desired and the phosphate can't be refined into fertilizers for food production (Cordell et al., 2011b). These limitations may be due to bottlenecks in the production line or in the transport chain.

5.2.1 Production of phosphate rock

Phosphate rock is produced in more than 30 countries around the world, but only a few of them are major producers (EcoSanRes, 2008). U.S. has historically been the largest producer of phosphate rock, but their annual production peaked in 1980 at 54.6 million tons and has since then fallen to almost half of this. Also the former Union of Soviet Socialist Republics (USSR) have previous been a large producer, but their production collapsed as a result of the dissolution of the Soviet Union in the end of 1991 and they are now only producing a little more than 5% of the world production (se figure 7). China accounts for most of the sharp increase in production that has taken place since 2000 as seen in figure 8. Hence, China is now by far the major producer in the world holding 43% of the total production with 89 million tons of phosphate in 2012 (see figure 8). The other two largest producers today are the USA and Morocco with 14% of the production each at 29.2 and 28 million tons in 2012 (Jasinski, 2013). Other major producers are primarily found in the MENA region and consist mainly of Tunisia, Jordan, Egypt, Israel, Syria, Saudi Arabia and Algeria. The whole MENA region holds more than a quarter of the world production if Morocco is included.

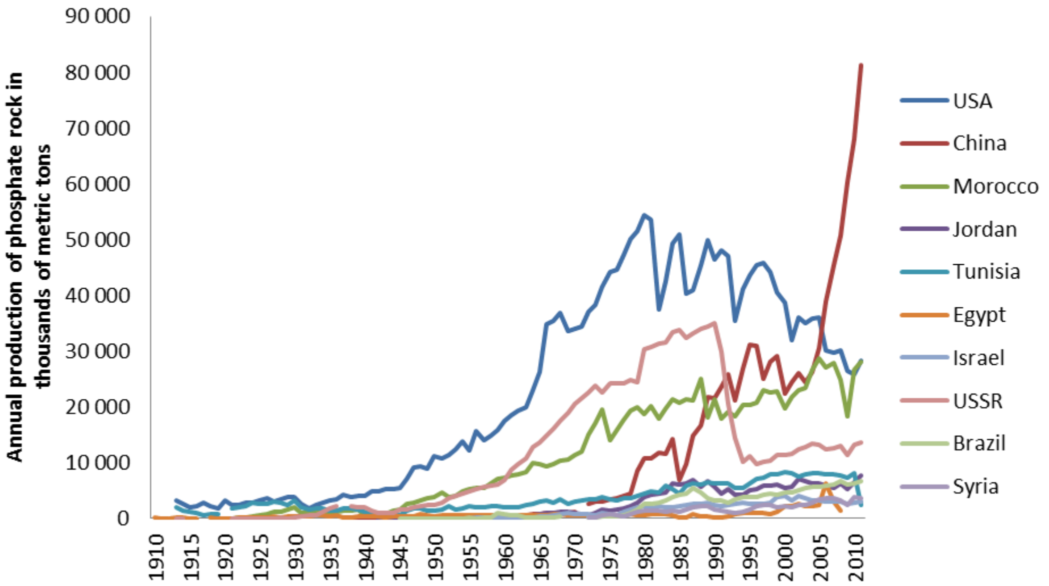


Figure 7. Production for the ten largest producers of phosphate rock (data from BGS).

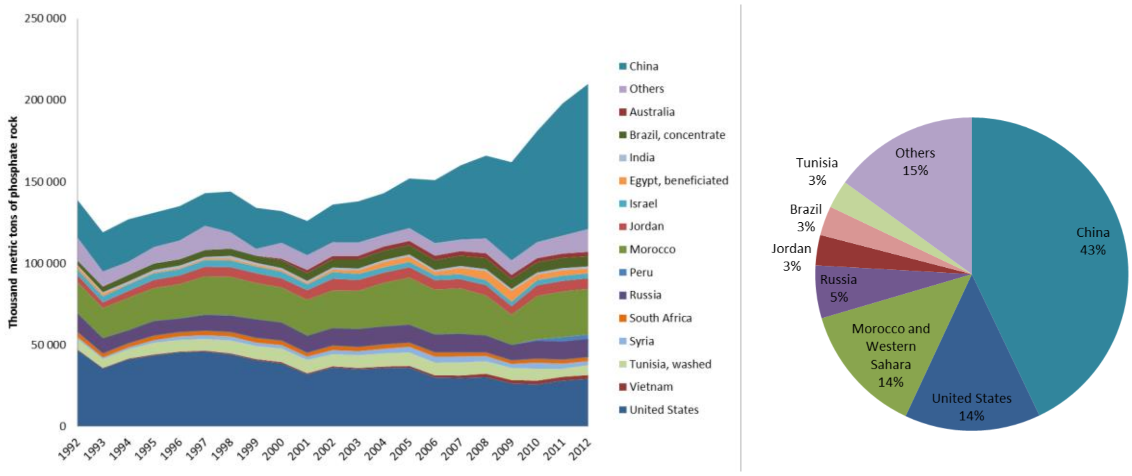


Figure 8. Left picture; the total phosphate rock production for the countries with the largest production (in thousand metric tons), Right picture; the distribution of the production for the top producers in 2012 (%). Data from U.S. Geological Survey (Jasinski; 2011, 2013).

5.2.1 Production of fertilizers

The fertilizer industry is for phosphate rock what the refinery industry are for oil. It makes it possible to refine raw materials into better products which have higher qualities than the untreated raw material. The distribution is similar as for the phosphate rock production with the largest part in East Asia, North America and Africa (see fig 9). The production in East Asia had increased more than six times in 2010 since 1999 while North America's share of production had decreased from 43% to 21% of world production. Still North America holds a large share of the fertilizer production and exports, but they are at the same time one of the major importers of phosphate rock. Also Europe and South Asia have a larger share of the fertilizer production than the amount of phosphate rock they produce as they barely produce any phosphate of their own. Africa and the Middle East that are larger net exporters processes only a part of their phosphate rock into fertilizer production and export the rest untreated.

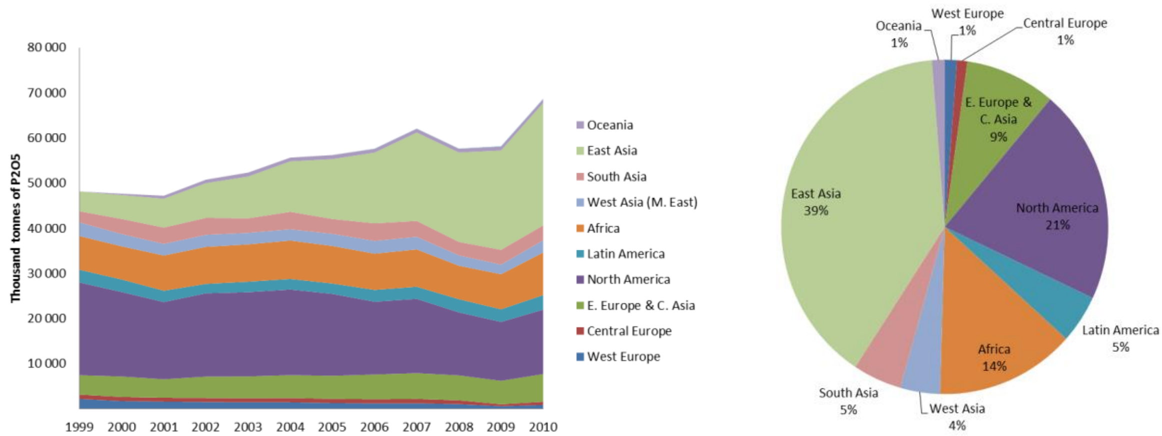


Figure 9. Left picture; the total fertilizer production for different regions (in P_2O_5), Right picture; the distribution of the production for the regions in 2010 (%). Data from IFA's *production and trade statistics* (IFA, 2012).

5.3 Geopolitical issues

The Arab Spring notably lead to reduced phosphate rock production in Tunisia due to political turmoil and also in Syria has production fallen as a result of the civil war and sanctions from the EU that previously imported about 40% of Syrian phosphate rock (Wellstead, 2012). Other phosphate producers like Morocco and Jordan were also affected by the Arab Spring, but their production was only disrupted to a minor extent (HCSS, 2012). Still, there are political contentions in the occupied West Sahara that might disrupt the production in the future. West Sahara accounts for about 10% of Morocco's production of phosphate rock, which therefor provides an incentive for the occupation. Most of the area has been controlled by Morocco since 1991 when the United Nations brokered a ceasefire to the long lasting conflict. The separatist movement Polisario Front wants independence for West Sahara, which Morocco opposes.

Although Africa accounts for more than four-fifths of the world's total reserves and is by far the largest exporter of phosphate rock, it is also the continent that suffers from the largest food shortage (Jasinski, 2013; Cordell et al., 2009). The concentration of reserves to only a few countries in the world means that large parts of the world are totally dependent on imports of phosphate. This including: India, Europe, South East Asia, Australia and Pakistan. Other parts of the world instead lack access to phosphate fertilizers due to low purchasing power. This is specially the case for many of the sub-Saharan countries, which at the same time are one of the parts of the world that have the most phosphorus-deficient soils (Cordell et al., 2009).

5.4 Production data

Compared to data of reserves, availability for the production data for phosphate rock is significantly better. Production data for United States and the world as a whole was found from 1900 in USGS historic phosphate rock statistics (Buckingham and Jasinski, 2012). Production data for total world was also found from 1920 in the British Geological Survey (BGS) mineral statistics archive (BGS, 2013). Data for most of the phosphate rock producing countries in the world was found from 1913 in the BGS archive and from 1929 in archive from U.S. Bureau of Mines and USGS (USBM, 1932-1993). The compilation of data from USBMs archive was done manually by visual assessment of the numbers that often were hard to decipher. The annual summaries often stated production for the past five years, which meant that the data could be confirmed by comparing one year's production data in subsequent annual compilations. In cases where production differed between years, data from the latest publication where used, since this data were assumed to be the most recent corrected and thus the most accurate. The data from BGS data archive were much easier to decipher and the data for individual years did not vary as much. Although, lack of publications for a couple of years (especially 1968-1971), made some data more uncertain. Soviet and China lack data for a number of years and these have therefore been estimated by the U.S. Bureau of Mines.

Data from U.S. were mostly given in metric tons of phosphate rock but in annual summaries between 1954 and 1966 were long tons used and after that short tons until 1977. The same problem existed also with data from the British survey which used long tons before 1970 and metric tons after that. Data given in short and long tons were therefore converted to metric tons to be consistent with each other (one long ton is about 1.016 metric ton and one short ton is about 0.907 metric ton). Production given in phosphorus pentoxide (P_2O_5) could be found for most countries in the USGS mineral yearbooks since 1990 and from USBM´s archive since 1978. The phosphate content given in "Tribasic phosphate of lime" can also be found in BGS´s Statistical Summary of the Minerals Industry for the years between 1941 and 1971. USGS generally have much more data for production in the U.S. than other countries and these data could be found for the U.S. from the mid 40's and data could also be found for the crude ore production since the early 50's (Jasinski, 2011; USBM, 1932-1993). By using the USGS data for P_2O_5 and converting the "Tribasic phosphate of lime" in the BGS data to P_2O_5 and divide it with the phosphate production, the proportion of P_2O_5 in phosphoric rock could be obtained.

Production data for phosphate rock and phosphorus pentoxide could also be found in the International Fertilizer Industry Association's production and trade statistics (IFA, 2012). There is also data for some of the most traded fertilizers, including Phosphoric acid, diammonium phosphates (DAP), monoammonium phosphates (MAP) and triple superphosphate (TSP). Data for individual countries were not publically available and therefore not used. Only public data for different regions and the world as a whole were therefore used from this source. This database also included information on export, import and consumption. A limit of the easy available data was that there were no data included beyond 1999 except some data for the world and East Asia from 1960 in an IFA report (IFA, 2012; IFA, 2011).

A comparison of world production data that show the difference between the sources as can be seen in figure 10. A compilation of the data from the BGS and USGS for the ten largest countries can be found in Appendix 1.

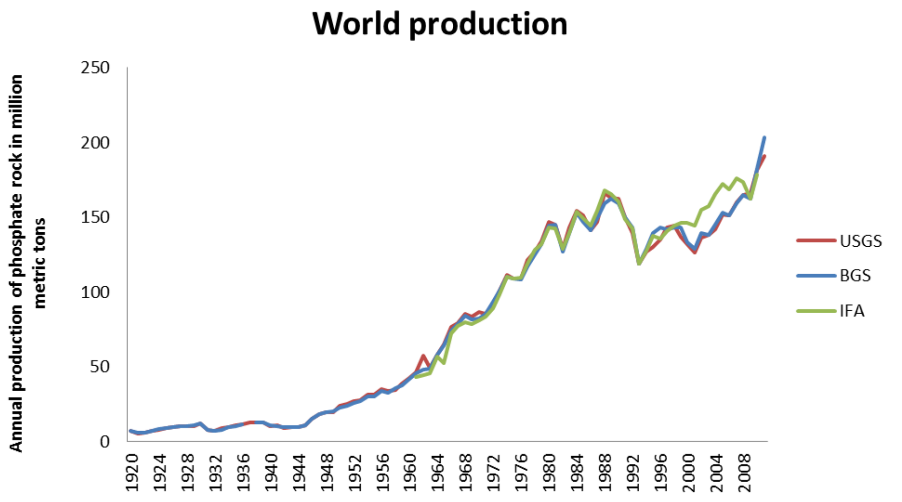


Figure 10. World production, according to various sources (data from USGS, BGS and IFA).

5.5 New developments

Since the phosphate price increased in 2007, a number of new deposits have been investigated to boost production. One of the major mining projects is found in Morocco where four new mines are opening that expect to increase the production capacity by almost 100% to 55 million tons by 2020 (OCP, 2010). To support this increase in production they are also building a 235 km long sludge pipeline from the mining area in Khouribga to the city of Jorf Lasfar at the coast. There are also plans to increase the fertilizer production from 3.6 million to 10 million tons.

Outside the Namibian coast at a depth of 185-300 meters under the sea, there is a large reserve of 1.8 million tons with a P_2O_5 content of 18-19% (Creamer, 2012). Mining companies want to mine this reserve but the proposed removal of the seabed has become much disputed because of environmental reasons since marine mining has never been done before and the impacts on the marine life and the environment might be serious (Hartman 2012). A number of other mining developments are taking place at the moment in other parts of the world as well. A similar project as in Namibia is taking place in New Zealand and 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) (HCSS, 2012).

5.6 Production processes

5.6.1 Prospecting and exploration

There is a long and expensive process before mining processes can start in a new area. The first thing that is needed is to locate potential reserves. To do this, direct observations and aerial and satellite imagery can be used to identify areas with the right geological structure to find phosphate rock (Encyclopædia Britannica: mining, 2013). When a potential deposit is found, samples are taken by drilling several probe holes and apply geophysical and geochemical prospecting of the soil in these. The long process and high price of exploring makes it a risky investment, as projects may be canceled due to environmental, technical or political reasons (HCSS, 2012). As a consequence of the long process, the phosphate rock price is very inelastic.

5.6.2 Mining

As the deposits vary in type, concentration and size, many different methods are applied when mining phosphorus. Similar methods and equipment are used as in coal mining, se figure 11 (Van Kauwenbergh, 2010). There are two main types of phosphate rock mining: surface mining and underground mining. The methods that are used range from very mechanized to low tech and labor intensive. Transport of ore and products are done by trucks, conveyor belts and in slurry pipelines or by train. The methods applied depends on the individual mine, distance, infrastructure, water availability and other factors.

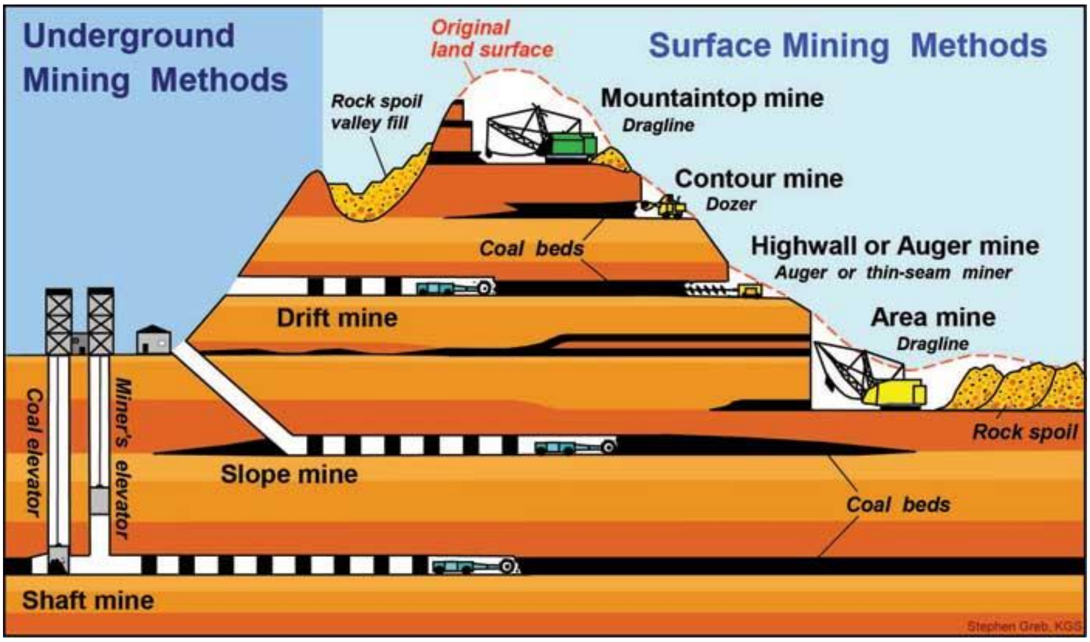


Figure 11. Mining methods for coal (picture from Kentucky Geological Survey).

Surface mining

Surface mining is by far the most common method for mining phosphate rock deposits and are typically less costly than underground mining in large scale (Van Kauwenbergh, 2010). For phosphorus mining two different types are applied; strip mining and open-pit mining. The first one is done by first removing the top layer of the soil by large electronic draglines, large shovels or similar excavators (Encyclopædia Britannica: mining, 2013). This method is suitable for flat and shallow deposits. Open-pit mining, or opencast mining as it also is called, typically result in a large hole divided into horizontal layers that is called benches where mining is done by large shovel machines. For this type of mining are large bucket wheel excavators very useful to remove large volumes of materials. These machines are one of the world's largest types of vehicles that ever been constructed. Open-pit mining is used for deposits near the surface but makes it possible to reach down to all the minerals in thick or less shallow deposits. As an open-pit gets deeper, more and more of the surrounding rock have to be stripped away to keep the walls at a safe angle. This makes it increasingly expensive to mine deeper and at some point the cost of the mining will exceed the revenue from the extracted phosphate rock. The amount of waste rock produced per ton of mined phosphate ore is usually between 2 and 7 ton (Krauss et al., 1986). If the amount of waste rock exceeds this, underground mining have to be considered. Countries that currently use surface mining methods for phosphate rock are Morocco, USA and Russia for instance (UNEP/IFA, 2001).

Underground mining

Many different methods are applied for underground mining. A common method is room and pillar mining where some of the ore are left as pillar for roof support (Van Kauwenbergh, 2010). Another method that also has been used is what is called longwall mining that use hydraulic supporters instead of leaving pillars of ore. Continuous miners or drum shearers are used for this type of mining method. Underground mining is applied when ore layer is located a substantial distance under the surface, as the large volumes of waste rock that have to be removed out of the mine makes surface mining unsuitable (Encyclopædia Britannica: mining, 2013). The method is still much more expensive than surface mining as the mining cannot be done on the same scale and smaller machines have to be used, hence the amounts of produced ore is much lower per worker shift. Underground mining therefore plays a smaller role of the total world production. The concentration needs to be higher for this underground mining, but the higher grade the ore have, the more expensive mining methods can be applied. Countries that currently use underground methods in phosphate rock mining are Morocco, Tunisia, Mexico and India (UNEP/IFA, 2001).

Dredging

If the ore deposit is below the normal groundwater level or the sea level, dredging methods can sometimes be applied for the mining. This method use a floating plant to operate from and dredging technics like bucket-ladders or clamshell dredges that dig up the ore from the seabed (Encyclopædia Britannica: mining, 2013).

The world's oceans contain an enormous reserve at the seabed at the continental shelves. The major part is found at depth of more than 300m under the sea which makes it difficult and expensive to mine. The phosphate from the shallower water might be easier to recover, but there is instead a risk for significant environmental damage. Hence, environmental impacts have to be carefully examined before mining can begin there (Scholz and Wellmer, 2013). Marine phosphate mining has never been done in the world so far and no one knows the real impact intensive dredging of ocean surface sediments could have on the marine life.

Seawater

The low concentration means that it would take more than 280,000 km^3 of seawater to produce the phosphorus that is currently mined in the world in one year (approximately 26.8 million tons of phosphorus in 2011). Vikström et al. (2013) investigated the possibility of extracting lithium from seawater, which has almost twice concentration of lithium than of phosphorus. Lithium is also produced in much smaller amounts (28.100 tons in 2011) and at a higher cost (2,000-8,000$/ton) than phosphorus (Vikström et al., 2013), which is produced at a cost of 25-70$/ton (Van Kauwenbergh, 2010). Lithium extraction form seawater was considered to not be feasible in the imminent future due to the large water flow and the process additives that are needed for a high production. Hence, it will probably not be feasible to extract phosphorus form seawater in the future.

5.6.3 Beneficiation

To separate impurities from the phosphate rock, beneficiation methods to increase concentration have to be applied for most ores. The phosphate rock ore can contain natural impurities like organic matter, clay, sand, limestone, siliceous and quartz depending on the type of deposit, the containing minerals and the weathering (UNEP/IFA, 2001). Removal of finer impurities is usually conducted by a combination of crushing, grinding, water washing, wet screening and/or hydrocyclones. If the water supply is inadequate, dry screening might be effective as well if the ore characteristics are of the right qualities (Van Kauwenbergh, 2010). For ore that contain larger impurities like sand or siliceous, an additional froth flotation stage has to be used to separate the particles. The flotation processes use differences in the surface wettability for minerals and intensive aeration to make impurities hydrophilic so that they adhere to the air bubbles and forms froth (Encyclopædia Britannica: mineral processing, 2013). Phosphate rock with a low P_2O_5 content has a high content of impurities, which leads to higher costs for mining and processing. If the P_2O_5 content is to low, there can be problems with the processing which can lead to bad products.

Many phosphate rock deposits contain large quantities of calcite ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) (Van Kauwenbergh, 2010). To remove these carbonates, calcination of phosphate ore is needed (UNEP/IFA, 2001). Calcination is conducted by heating the material to a very high temperature (below melting point) which makes carbon dioxide turn into gas (Eq. 5). This is followed by slacking the remaining oxide with water to form calcium hydroxides that can be removed by using hydrocyclones (Eq. 6). Due to the high energy cost this method is used where natural gas is cheap (Van Kauwenbergh, 2010).

$$\mathrm{CaCO_3(s) \rightarrow CaO(s) + CO_2(g)} \qquad (5)$$

$$\mathrm{2CaO(s) \ + \ H_2O \rightarrow \ 2Ca(OH)_2} \qquad (6)$$

It is also possible to remove carbonates by flotation, but this is difficult because carbonates have similar characteristics as phosphate minerals (Van Kauwenbergh, 2010). Hence, flotation is not widely used despite the fact that less energy is required and that significant amounts of research on the method have been made. Today the method is only applied to treat igneous rock in Finland and Brazil.

5.6.4 Manufacture of fertilizers

Today almost all the phosphorus fertilizer is made from phosphate rock (Van Kauwenbergh, 2010). Phosphate rock can be applied directly as fertilizer if the phosphate content is high enough, but it is hard for plants to absorb phosphate ion from the apatite rock. To increase the content of phosphorus and make it more water soluble, different processes are used to produce several different types of phosphate fertilizers (see figure 12). Most of the fertilizer production uses phosphoric acid as phosphorus source since phosphorus is much more concentrated and available to plants in this form (UNEP/UNIDO/IFA, 2000). Some of the acid can also be found in a number of industry processes as well as in cola beverages. The phosphoric acid is produced today mainly through wet processes where phosphate rock is mixed with sulfuric acid (UNEP/UNIDO/IFA, 2000). Thermal processes can also be used but are much more expensive because of the high energy use. The wet phosphoric acid (WPA) process consumes large amounts of phosphate rock and sulfuric acid for every ton of phosphoric acid that are produced and leave large amounts of gypsum as byproduct. With the addition of ammonia, phosphoric acid can be used to produce NP-fertilizers as diammonium phosphates (DAP) and monoammonium phosphates (MAP). Multi nutrient fertilizers (NPK-fertilizers), containing phosphorus, nitrogen and potassium can also be produced by mixing phosphate rock with nitric acid and ammonia to produce nitrophosphates or by mixing the nitrophosphates with phosphoric and sulfuric acid. If potassium salt and micronutrients are added, complex multi nutrient fertilizers can be made. To produce phosphate fertilizers without the addition of ammonia, phosphate mineral can be treated with phosphoric acid (triple superphosphate), sulfuric acid (single superphosphate) or both (double superphosphate).

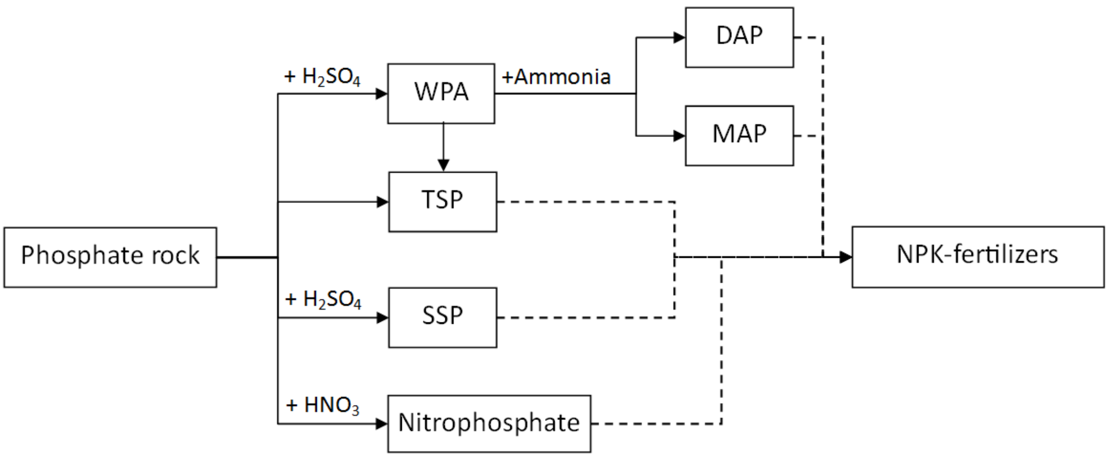


Figure 12. Different phosphorus fertilizers and their relation to each other (based on figure in World phosphate rock reserves and resources, Van Kauwenbergh, 2010).

6. Environmental issues

6.1 Eutrophication

When talking about phosphorus it is often seen as a pollutant that has to be treated to reduce eutrophication. All major civilizations have been affected by eutrophication as consequence of increased population. The problem increased in the 19th and 20th century as population grew and phosphorus rich wastewater was discharged into lakes, rivers and oceans instead of being returned to land. The problem grew further after World War II with the increased use of chemical fertilizers and introduction of phosphorus-rich detergents (Ashley et al., 2011). The growing use of phosphorus fertilizers in agriculture to increase crop yields have led to an increasing amounts of phosphorus that has been released into surface water through runoff from cropland, largely because of overuse of fertilizers. As more and more phosphorus have been added to the ecosystem from the phosphate rock reserves, many lakes and coasts have seen an increased algae growth (HCSS, 2012). This has in some cases led to serious eutrophication and dead zones due to lack of oxygen (Ashley et al., 2011). Therefore it has become necessary with costly wastewater treatment to overcome this problem. Another important measure that has been implemented was that phosphate were banned or regulated in detergents in many places (Ashley et al., 2011; IFA/UNEP, 1998). With help of these measures, the inputs of phosphorus to waterways were reduced. Despite decisive actions in both Europe and the United States to reduce the eutrophication problem by improved sanitation, sewage treatment and reduction of the overuse of phosphorus fertilizers, eutrophication is this still a growing problem in the world and more and more phosphorus is lost as a pollutant.

6.2 Impacts from mining

Phosphorus does not only have a negative impact on the environment at the consumption stage as eutrophication. Phosphate rock production also affects the environment in a variety of ways and at all stages during a mine's life cycle from the exploration of the deposit until the closure of the mine (UNEP/IFA, 2001). The largest effects of phosphate rock mining are seen in the extraction and beneficiation stages. Surface mining methods tend to have larger impacts on the environment than underground mining methods, as it totally changes the landscape of a large surface area. The extraction process also cause carbon dioxide emissions and can affect the ground water level. The major effect of the beneficiation phase is that large volumes of waste as contaminated process water and tailings of sand or clay is produced. Another environmental issue is the large amounts of fresh water that is needed for beneficiation processes such as washing and flotation. In almost all stages of the mining, large amounts of dust are generated and there is often a risk for water pollution due to run-off, leaching and leakage. Hence, before approval of a new mine these environmental issues have to be taken into account.

6.3 Impacts from fertilizer production

The manufacture of phosphate fertilizers also has large effects on the environment. For every ton of P_2O_5 in the produced phosphoric acid is 4.5-5 tons of phosphogypsum generated (CPCB, 2012). The gypsum consists mainly of calcium sulfate but also of fluoride and water, see chemical reaction (Eq. 7) (UNEP/UNIDO/IFA, 2000). Slurry with gypsum is pumped out to large ponds where the gypsum settles and the clear water is recycled in the process. Phosphogypsum is currently mostly stockpiled primarily because of the content of the radioactive radium that accumulates in the gypsum. Other impurities like arsenic, cadmium, lead and phosphoric acid can also be found in the phosphogypsum stack which makes it important that there is no leakage from it (CPCB, 2012). Previously it was common to pump the gypsum in to the sea for coastal-near fertilizer factories (UNEP/UNIDO/IFA, 2000). This is in some cases still permitted if the cadmium concentration is low, but this could have a severe impact on the sea life in areas without strong currents. Phosphogypsum have on the other hand also many positive qualities and can be used in cement, plaster, plasterboard, in agriculture and as road making material but high moisture content and the amounts of impurities prevents most of the time the usage. The gypsum is also a potential source of sulfuric acid that is possible to extract, but at a higher cost than other sources (UNEP/UNIDO/IFA, 2000).

$$\mathrm{Ca_{10}F_2(PO_4)_6} + 10\mathrm{H_2SO_4} + 10\,\mathrm{x}\,\mathrm{H_2O} \rightarrow 6\mathrm{H_3PO_4} + 10(\mathrm{CaSO_4 x\,H2O}) + 2\mathrm{HF} \qquad (7)$$

$$\text{Rock phosphate} + \text{Sulphuric acid} + \text{Water} \rightarrow \text{Phosphoric acid} + \text{Gypsum} + \text{Hydrogen Fluoride}$$

6.4 Impurities

Another environmental concern is the natural content of radioactive materials and heavy metals in phosphate rock such as radium, uranium and cadmium. The major problems with radium are found in the phosphogypsum where most of the radium ends up and the problem with the gypsum are therefore strongly connected with radium. Some of the radium could also end up in fertilizers that are not based on phosphoric acid such as superphosphate (Cioroianu et al., 2001). If the phosphate rock has high radium content should therefore this preferably be converted to DAP or MAP instead. Radium produces radon through radioactive decay whose radiation is unhealthy and increases the risk of lung cancer (WHO, 2009).

Another radioactive material is uranium that is found in various amounts in phosphate rock of sedimentary origin. Unlike other radionuclides such as radium, most of the uranium in the phosphate rock remains in the phosphoric acid product and only a small percentage can be found in the phosphogypsum. The total amount of uranium in all phosphorous acid produced each year is actually a significant amount compared to the amount of uranium produced and therefore constitutes a potential uranium resource (Astley and Stana, 2012). Much of the uranium can be separated from the phosphoric acid by using solvent extraction processes (Khan, 2011). The production is highly dependent on the cost for uranium which has mostly been very low during the last decades and this method is therefore not used today at any larger extent (Astley and Stana, 2012).

A more serious threat is the natural content of cadmium especially in sedimentary phosphate rock deposits. As the best reserves with low cadmium content runs out first, it is likely we will see a trend towards higher content of cadmium in phosphate rock in the future (HCSS, 2012). Cadmium is added to the soil through atmospheric deposition of airborne cadmium with addition of calcium containing phosphate fertilizers where it is accumulated in plants and organic organisms and is transmitted to humans (Järup and Åkesson, 2009). Cadmium is primarily taken up through food consumption but can also be absorbed by smoking cigarettes, which means that smokers belong to a particularly vulnerable group. Cadmium accumulates mainly in the liver and kidneys, which can eventually lead to kidney failure, decreased bone mineral density and cancer (HCSS, 2012). The amount of cadmium in phosphate rock varies greatly between different deposits. Igneous phosphate rock often contains almost no cadmium while sedimentary deposits varies from low to higher amounts of cadmium, which the latter can be found in countries like Morocco.

6.5 Water usage

Phosphate production is water intensive. Mining and beneficiation in Florida for example, use between 8 and 15 tons of freshwater to produce each ton of phosphate rock, however, most of this water is reused (Van Kauwenbergh 2010). Especially in the beneficiation of phosphate rock is much water needed for washing, screening and the use of hydrocyclones and flotation (UNEP/IFA, 2001). Water scarcity may especially limit the use of flotation in dry areas. Water use can be reduced by using dry screening if the phosphate rock has the right characteristics and saltwater may also be used for washing, screening and flotation (Van Kauwenbergh 2010). Many countries that produce phosphate rock have a shortage of fresh water including most countries in the MENA region (HCSS, 2012). This region holds 85% of world's phosphate rock reserves and important producers such as Morocco, Jordan and Tunisia (Jasinski, 2013).

With increasing population and growing economic development, the global water usage has increased more than twice as much as population growth over the last century, which has led to an increased pressure on existing water reserves (UN Water, 2006). Irrigation of agriculture usually accounts for the major part of water use in a country and accounts for approximately 70% of the water demand (Cordell et al., 2009). Water is therefore also the limiting factor for food production in many places. In addition, climate change is altering precipitation patterns in many parts of the world which will further exacerbate water availability in countries that already suffers as serious water constraints (UNEP, 2009). Many phosphate rock producers will therefore be faced with an ever decreasing availability of water in competition with agriculture and the general population. In order to reduce the water usage in agriculture is often water-saving technology applied such as advanced drip irrigation systems. In many areas that are severely affected by water scarcity have also often energy-intensive technology been built to desalinate seawater in large desalination plants (HCSS, 2012). Desalination plants have been built in many countries that are major producers of phosphorus such as Tunisia, Algeria, and Israel, and others are under construction in countries like Morocco. This technology may increase the costs and energy use for the mining industry in the future.

Morocco is one of the countries that facing major challenges due to water shortage. The country has to deal with competing demands between the agriculture and the phosphate mining industry as well as to deliver fresh drinking water for a growing population (HCSS, 2012). About 80-90% of the fresh water is used for agriculture out of which 30% is taken from the ground and often in an unsustainable way. Hence, the groundwater table has fallen by an average of 1.5 meters per year since 1969 and some wells therefore pumps water from more than 200 meters depth. As a consequence of climate change is also assumed that precipitation will decrease in some parts of the Atlas Mountains, which accounts for a large part of the water supply in Morocco (UNEP, 2009). The country also has relatively large resources of oil shale, which would need large amounts of water in case of recovery (Dyni, 2005).

6.6 Energy usage

Energy consumption for the production of phosphate fertilizer out of phosphate rock is considerably smaller than the energy required for the production of nitrogen fertilizers, which is about 93% of the total energy used by the fertilizer industry (IFA/UNEP, 1998). The wet phosphoric acid process is the most energy intensive process in the phosphate fertilizer industry, as seen in Table 2. Globally the fertilizer industry only accounts for less than 2% of the energy consumption in the world. The food production is yet totally dependent on the supply of energy for mining and manufacture of fertilizers as well as for the transportation of fertilizers and food across the globe (Cordell et al., 2009). Every year, about 30 million tons of phosphate rock and more than 16 million tons of phosphate fertilizers are transported across the world (IFA, 2012). Also the modern agriculture is highly dependent on fossil fuel such as oil and natural gas to produce food (Johansson et al., 2010; Cordell et al., 2009).

Table 2. Energy usage for the fertilizer industry in United States in 1995 (UNEP/UNIDO/IFA, 2000).

Fertilizer	Energy use	
Phosphoric acid	138.0 kWh/ton	(100% H_3PO_4)
Sulphuric acid	21.3 kWh/ton	(100% H_2SO_4)
DAP	34.3 kWh/ton	
TSP (granular)	58.5 kWh/ton	
Phosphate rock	73.5 kWh/ton	

6.7 Losses in production and distribution

A constraint for the phosphorus consumption is that a large amount of the phosphorus is lost between the extraction of phosphate rock at the mine and the consumption of food. Phosphorus losses occurs partly due to technical limits that make some phosphorus is lost in the production. Other losses occur due to physical limitations that make the plants incapable of absorbing all the nutrients in the soil. Much of the phosphorus instead finds its way into nearby streams where it pollutes the water (Cordell and White, 2011). About 80% of the phosphorus in the extracted phosphate rock is assumed to be lost before it is consumed.

6.8 Recycling and substitution

Often when discussing solutions for mineral scarcity there might be possibilities to substitute or replace the mineral, but there is no substitute to phosphorous. On the other hand is it possible to recycle phosphorus from human excreta, manure and different types of waste products (Cordell et al., 2011b). In this way is it might be possible to close the phosphorus loop reduces the effects of phosphorus scarcity.

7. Production modeling

7.1 Model testing

Logistic and Gompertz curves are tested on the former phosphate rock exporter Nauru to examine how well the models are fitting to the phosphate rock production. Nauru is examined because it is one of the few reserves with sufficient amount of data whose production is expected to have peaked. Data for Nauru exist from 1930 with a production break for six years at the Second World War. Both curves provide a good fit to the production, although the logistic curve is considered to have a better fit to the production data (see figure 13).

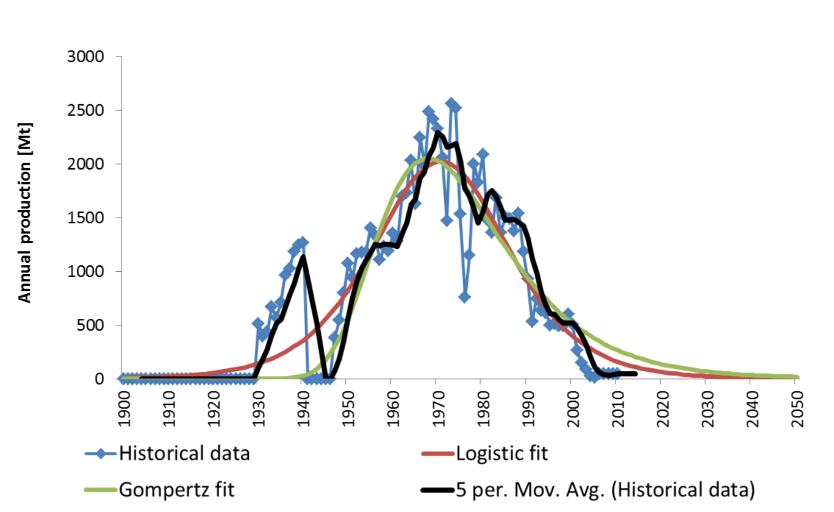


Figure 13. Curve models for Nauru.

7.2 Best guess-URR

The URR is obtained by summing up the cumulative production with the recoverable reserves that are believed to remain in the ground. The mean of the annual production data from USGS/USBM and BGS is used for calculation of the cumulative production for the ten largest producers in 2011 (see table 4). The USSR is hard to estimate due to the dissolution of the Soviet Union. The cumulative production consists of data for USSR until 1991 and later of data from Russia, Kazakhstan and Uzbekistan, which are all available. The reserve data on the other hand is only available for Russia (1300 million ton), but not for Kazakhstan and Uzbekistan. The latter two must therefore be estimated. As the "*other countries*" (which include those not mentioned) in the USGS reserve estimations only amounts up to 390 million ton, it is assumed the Kazakhstan and Uzbekistan have half of these reserves, which means only about 200 million ton. Since the uncertainty of other reserves is so large is assumed that such an estimate could be made. The reserves used for all other nine countries are those estimated by the USGS. All countries except the four largest one are also merged into one group called "*Other countries*" (see table 5) China and Morocco are given one low and one high URR. The world is given three different URR for the three scenarios as seen in Table 6.

Table 3. Calculated cumulative production and URR for the ten largest producers 2011.

Country	Cumulative Production [Mt]	Reserves [Mt]	URR [Mt]
China*	924	3,700	4,624
USA	2,289	1,400	3,689
Morocco*	1,056	5,700	6,756
USSR**	1,072	1,500	2,372
Jordan	205	1,500	1,705
Brazil	156	270	426
Tunisia	365	100	465
Egypt	76	100	176
Israel	115	180	295
Syria	74	1,800	1,874

* Low estimate
** Includes Russia, Kazakhstan and Uzbekistan.

Table 4. Other calculated cumulative productions and URR.

Country	Cumulative Production [Mt]	Reserves [Mt]	URR [Mt]
China*	924	7,400	8,324
Morocco*	1,056	50,000	51,056
Other Countries**	1,833	10,400	12,233

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

Table 5. Calculated cumulative production and URR for the world.

Country	Cumulative Production [Mt]	Reserves [Mt]	URR [Mt]
World low case	7,351	22,938	30,289
World standard case	7,351	67,238	74,704
World high case	7,351	134,476	141,827

The larger portion the cumulative production data have of the URR, the more accurate the model becomes. Hubbert suggested that to get an accurate fit, the model should only be applied at times when the cumulative production have exceeded one-third of the URR (May et al., 2012). Better fits are also obtained if longer time series are used.

7.3 Scenarios

As data is scarce and unreliable for reserves and can change over time, is it difficult to estimate the actual magnitude of these. It is also very difficult to know how much of the resources that will be converted to reserves in the future. Hence, it is better to produce a time interval in which a future peak can be expected. Different scenarios will therefore be developed based on different data for future recoverable reserves. The first three scenarios are made for the world with aggregated data as previous have been conducted by Cordell et al. (2009), to estimate a timeframe for a future peak. Secondly, four scenarios are made to provide a more detailed understanding of how the world production will be divided between the countries over time.

7.3.1 Modeling of aggregated world data

The three scenarios presented here are developed to investigate the range in which a future world production peak of phosphate rock is likely to occur.

Low case scenario: The URR is based on the total reserves in 2013, but Morocco's reserve is assumed to be exaggerated and instead be 5 700 million as they believed to be in 2009 (Morocco would still have the largest reserves in the world). The URR for this case is 30 289 million tons of phosphate rock, which is equal to about 4327 million tons of phosphorus. That is somewhat more than the URR in Cordell et al., 2009. The R/P-rate for this scenario is 109 years. Morocco is in this case assumed to be unable to recover all of their huge reserves due to environmental, political and physical constraints and no new large reserve are assumed to be found.

Standard case scenario: The URR for this scenario is based on the USGS estimated total reserves of 67 238 million tons of phosphate rock, leading to a total URR of 74 704 million tons of phosphate rock. The R/P-rate for this scenario is 320 years. The recoverable reserves are in this case assumed to be equal to the USGS estimated reserves in 2012 and without any constraints will appear as well as no increase in reserves will take place.

High case scenario: The reserve is for this case assumed to be twice as large as for the standard case. This scenario assumes that all current estimated reserves will be recovered, many new reserves will be found and that much of the currently known resources will be converted into reserves. The URR for this scenario is 141 942 and the R/P-rate is 640 years.

7.3.2 Modeling the world peak of production based on individual countries

There are also four scenarios presented for the world production based on individual countries. Since China and Morocco have by far the largest reserves and China yet is likely to have slightly larger reserves than what have been reported, these countries are assumed to be those that have the greatest impact on future world production. For China and Morocco, one high and one low estimate are given to their estimated reserves, while other reserves are the same in all scenarios. This is conducted to examine how the forecasts may change with different size of these reserves. The different combinations can be seen below (table 3).

Table 6. The four different scenarios

	URR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
China low	4,624 Mt	x		x	
Morocco low	8,324 Mt	x	x		
China high	6,756 Mt		x		x
Morocco high	51,056 Mt			x	x

Scenario 1: In this scenario is Morocco's production limited due to constrains in production and Chinese reserve is assumed to be in line with USGS assumptions.

Scenario 2: In this scenario is Chinas reserves double the size of USGS current assumptions. Morocco's production is assumed to be limited.

Scenario 3: Morocco's reserves are in this scenario assumed to be totally recoverable while Chinas reserves are no larger than USGS estimations.

Scenario 4: Both reserves are in this scenario assumed to be very large and fully recoverable. Hence, they will both have a large impact on the future production.

8. Results

8.1 The concentration of P_2O_5 in phosphate rock

First a study is made of how the concentration of phosphorus has changed over time in the extracted phosphate rock. If phosphorus is decreasing in the mined phosphate rock, it would show that the best phosphate rock is already used and that poorer rock now needs to be mined. This is examined for the world as a whole and for the United States and the nine other major producers. Data of the annual amount of minded phosphate rock and P_2O_5 is available from USGS and USBM. Particularly comprehensive data is available for the U.S.

8.1.1 USA

The large amount of data from USBM and USGS for the U.S. makes it possible to conduct a thorough investigation of how the concentration of phosphorus has changed over time in in this country. The study of the P_2O_5 concentration in phosphate rock shows a decline rate of 0.05% for P_2O_5 in phosphate rock per year since 1945 (see figure 14). The r-squared value shows that the correlation is very good for the P_2O_5 concentration in phosphate rock with the linear decline of 0.05%. For the U.S., there are also figures of how much crude ore that is extracted each year to produce phosphate rock. This makes it possible to study the phosphate rock content in mined crude ore. The concentration of phosphate rock in mined crude ore varies more from year to year, but indicates an average declining rate of 0.15% per year.

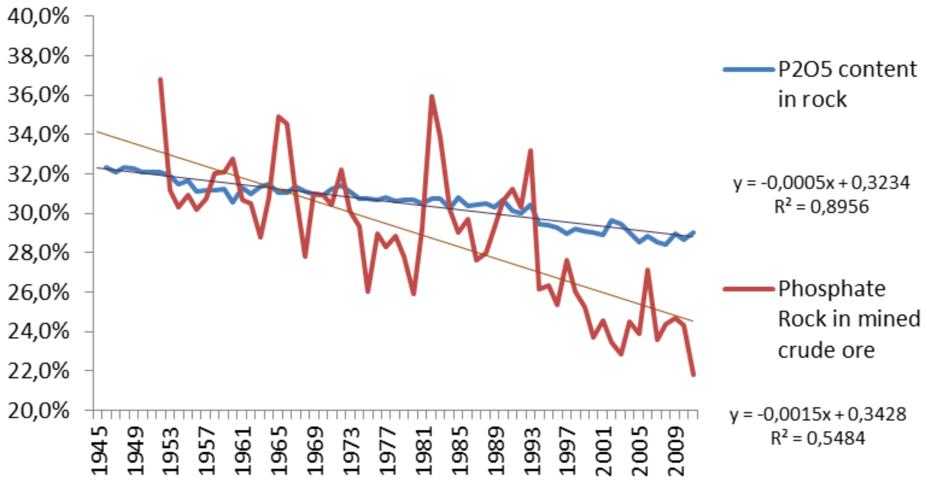


Figure 14. Percent of phosphate rock in mined crude ore and percent P_2O_5 in phosphate rock (based on data from USGS and USBM for mined crude ore, phosphate rock and P_2O_5).

8.1.2 The world

According to Cordell et al, the concentration of phosphorus in phosphate rock decreased from 15% in the 1970s to less than 13% in 1996 (from about 34% to about 29.5% P_2O_5). No detailed research appears to have been made to strengthen this claim. Therefore, an investigation of the phosphate concentration in phosphate rock is conducted by using data from the USGS and USBM. Data on the amount of P_2O_5 produced in the world is only available in USBM archives since 1978. Although the BGS had data for the amount of phosphorus in phosphate rock for individual countries between 1931 and 1971, data are missing for the total world production. The resulting graph shows a large variation over time with a slightly decreasing average concentration, but there is almost no correlation to a linear trend line (see figure 15).

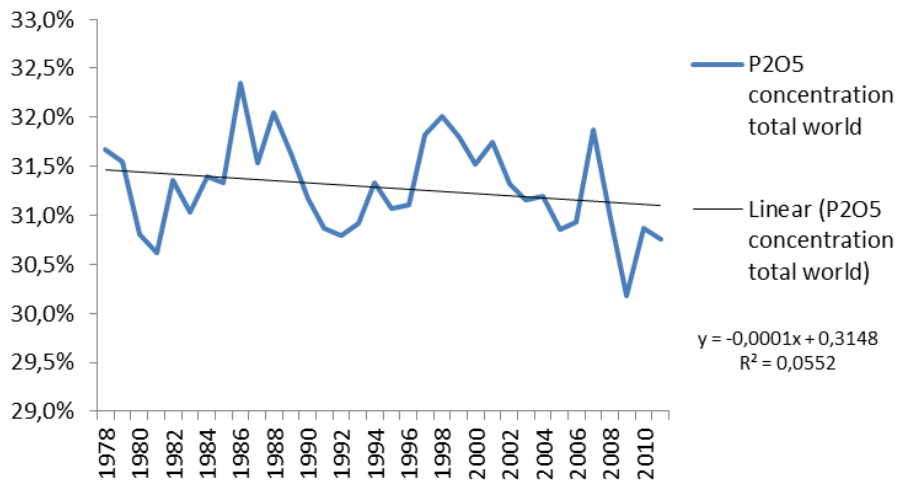


Figure 15. The change in the concentration of P_2O_5 in the world's phosphate rock since 1978 (based on data from USGS and USBM for mined phosphate rock and P_2O_5).

8.1.3 The ten largest producers

The change in the concentration of P_2O_5 for phosphate rock is also investigated briefly for the top ten phosphate rock producers. Only the U.S. showed a decreasing concentration of P_2O_5 and many of the countries have concentrations that vary substantially over time. The blue lines show production and the red lines the change in concentration (see figure 16).

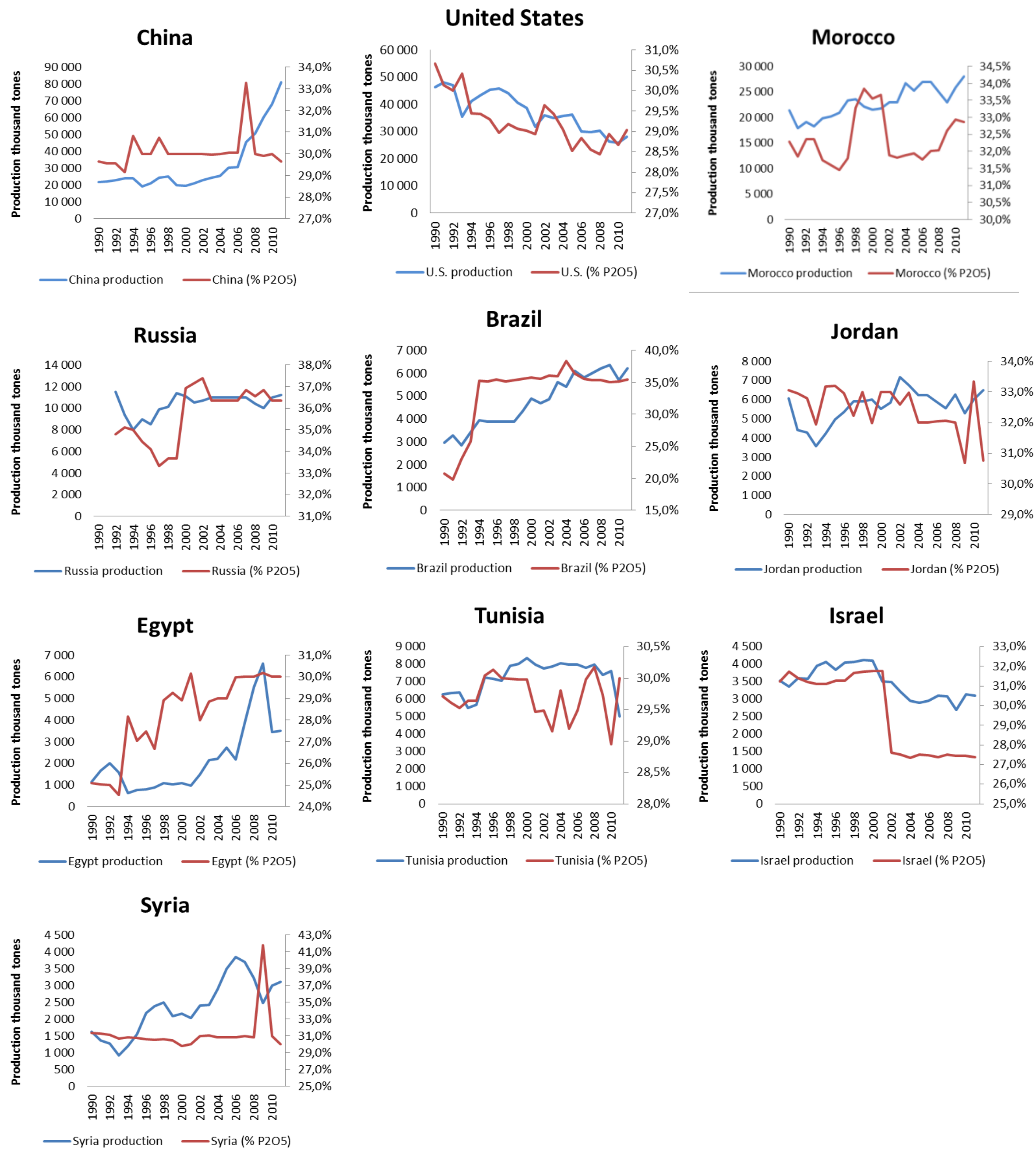


Figure 16. Production and the P_2O_5 concentration in the produced phosphate rock for the ten major phosphate rock producers (based on data from USGS and USBM for mined phosphate rock and P_2O_5).

8.2 Production prognosis for the three major producers

For all the ten largest phosphate rock producers production curves are modeled. Only the three largest will be reported here as they account for more than two thirds of the world production and therefore are considered to be the most interesting.

8.2.1 USA

United States is a good example of a country whose production already has peaked and which has a good correlation to the curve models. The U.S. has long been the largest producer of phosphate rock, but their production peaked already in 1980 at 54.40 Mt and is has since then decline to almost half of the maximum production (see figure 17). The somewhat poor fit to the historical data may be because the United States had used half of their estimated URR first in 1998 and not at the production peak year in 1980. A better fit would be obtained if the reserves where assumed to be smaller.

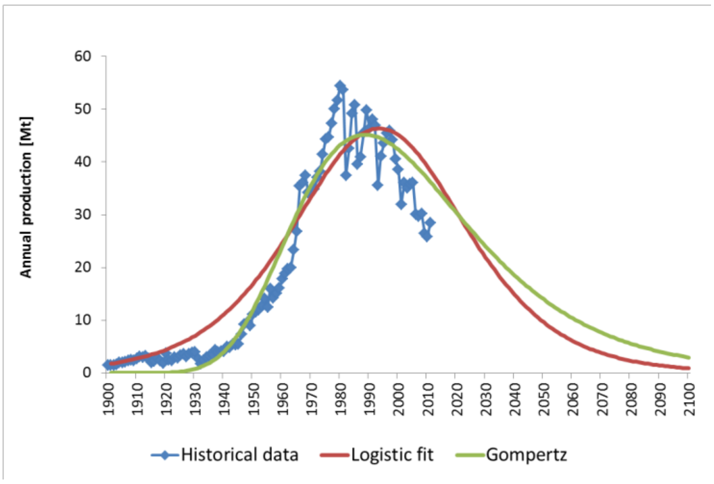


Figure 17. Logistic and Gompertz curves plotted to the U.S. production.

8.2.2 China

In the last 10 years, China has more than triple their production and has become the largest producer of phosphate rock in the world. The historic production is therefore very steep the last ten years. The low scenario that is based on current estimated reserves is impossible to fit with a limited depletion rate, but it is possible for the high case scenario. The modeling of the low and high estimate of the Chines reserves can be seen in figure 18, and 19.

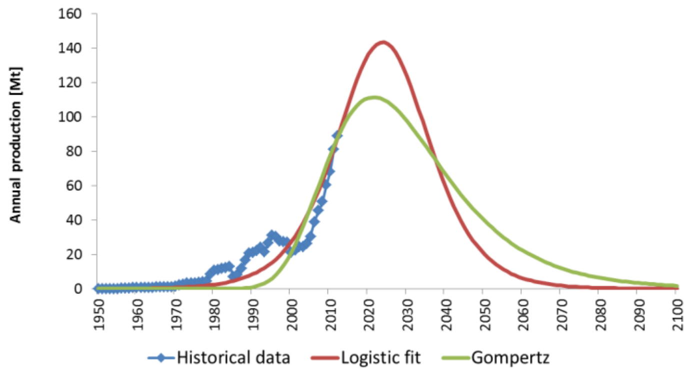


Figure 18. Logistic and Gompertz curves plotted to China's production and the low estimation of China's URR.

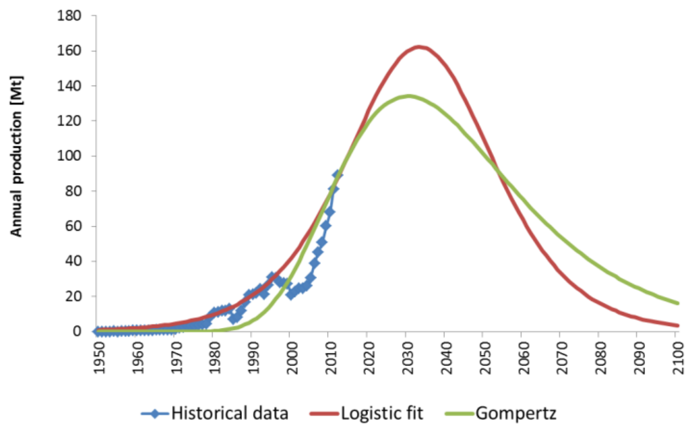


Figure 19. Logistic and Gompertz curves plotted to China's production and the high estimation of China's URR.

8.2.3 Morocco

Morocco's production has steadily increased over the years and now amounts to 28 million ton annually. The planned increase in production of 55 million ton to 2020, have been included in the historical production data. Almost one order of magnitude distinguishes between URR estimates that are used for Morocco, which means that there are large differences between the two models. The modeling of the low and high estimate of the Moroccan reserves can be seen in figure 20, and 21.

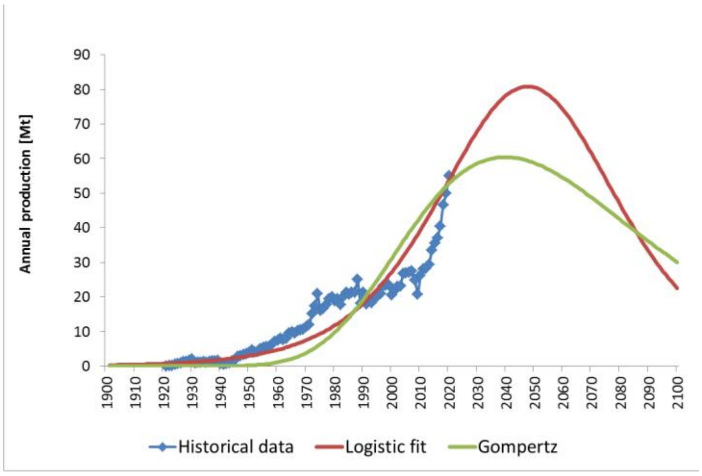


Figure 20. Logistic and Gompertz curves plotted to Morocco's production and the low estimation of Morocco's URR.

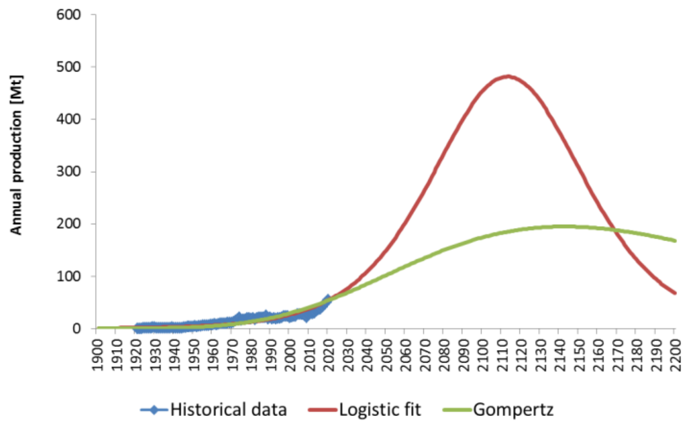


Figure 21. Logistic and Gompertz curves plotted to Morocco's production and the high estimation of Morocco's URR.

8.3 World prognosis

8.3.1 Modeling the world peak of production based on aggregated world data

The Gompertz and logistic curves are plotted to historical data for the three scenarios (see figure 22-24). The estimated future growth in phosphate fertilizer demand is plotted from 2011 and the next five year at a growth rate of 2.5% (USGS, 2012).

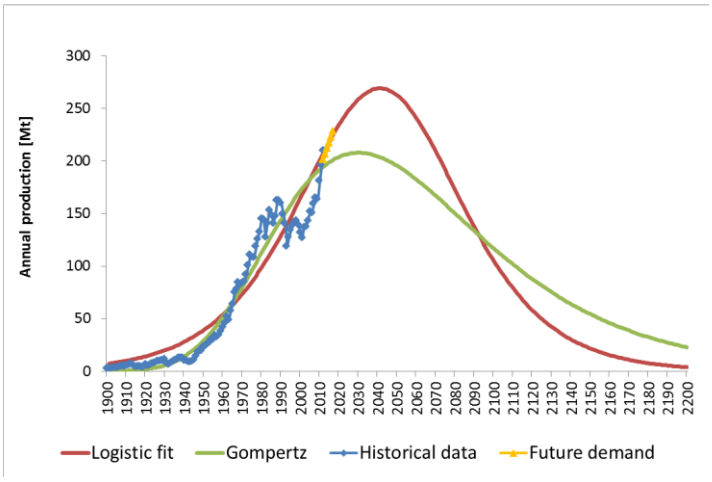


Figure 22. World production for the low case scenario. Logistic: peak in 2041, Gompertz: peak in 2030.

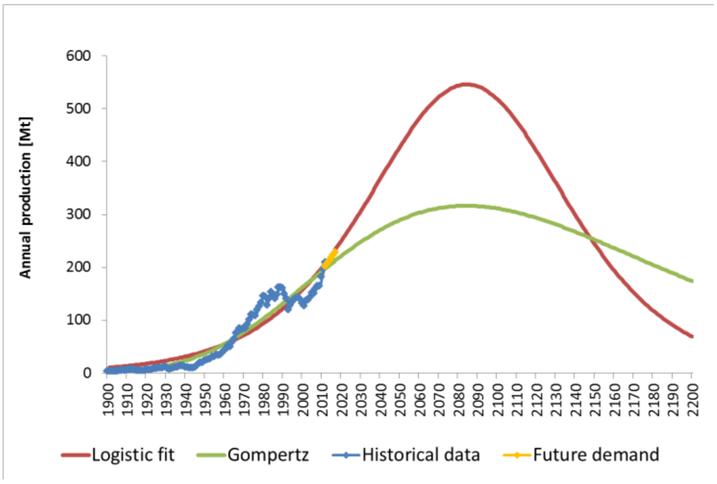


Figure 23. World production for the standard case scenario. Logistic: peak in 2084, Gompertz: peak in 2084.

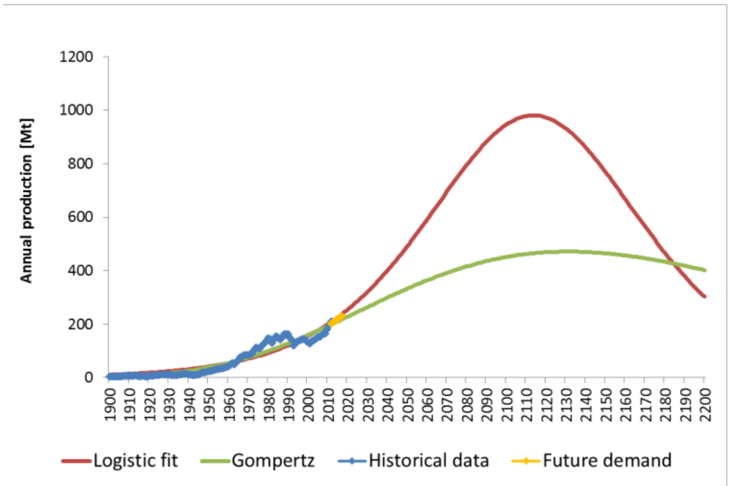


Figure 24. World production for the high case scenario. Logistic: peak in 2113, Gompertz: peak in 2131.

8.3.1 Modeling the world peak of production based on individual countries

The world production is modeled with logistic curves to investigate which countries that have the greatest impact on production in the future. Logistic curves are used as they are considered to fit best to the historic data based on the Nauru fit. USSR is modeled with a double peak because of the large production fall in the early nineties, but it is impossible to get a good fit with a maximum depletion rate limit. The same problem is found for China and Egypt, which both have very sharp increase in production over the last decade but small reserves to support such a production trend. No such limitation is therefore applied for any of these three countries. A depletion rate limit was needed only for Chinas high estimated URR curve. A compilation of the results from the logistic curve models can be seen in table 7. All charts can be found in Appendix 2.

Table 7. Modeled production peaks of phosphate rock for the different countries.

Country	URR [Mt]	Peak year	Peak prod. [Mt]	Prod. In 2011 [Mt]	Depletion rate at peak [%]
China low	4,624	2023	136.88	81.22	5.61%
China high	8,324	2033	162.16	81.22	3.49%
Morocco low	6,756	2047	80.85	28.00	2.31%
Morocco high	51,056	2113	481.85	28.00	1.86%
United States	3,689	1993	35.50	28.40	1.71%
USSR*	2,572	1981	30.70	13.68	9.12%
		2043	23.56		-2.71%
Brazil	426	2018	7.07	6.42	3.10%
Jordan	1,705	2056	17.64	7.07	1.97%
Egypt	176	2020	4.79	3.70	7.65%
Tunisia	465	2000	8.32	5.00	4.20%
Israel	295	2015	4.05	3.11	2.41%
Syria	1,874	2070	24.57	3.39	2.52%
Other countries**	12,233	2062	97.94	45.46	0.83%

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

The modeling of the ten largest countries indicates that the four largest producers, the U.S., Morocco, USSR and China are the ones that have the greatest impact on production as seen in figure 25. Therefore are all the other countries in the world merged into one group called *other countries*.

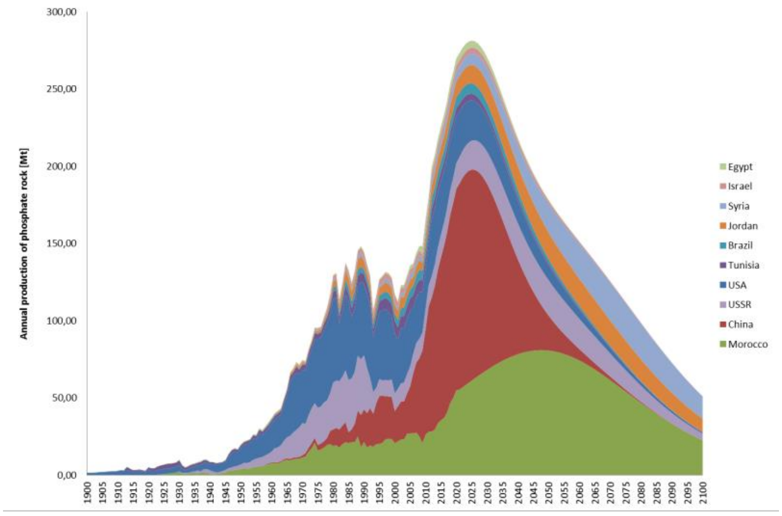


Figure 25. Scenario 1 for the ten largest producers.

China and Morocco's impact on world production can be seen in the following four scenarios. The four scenarios should not be viewed as credible outcomes of production, but they should rather demonstrate how China and Morocco might affect future production at the current trends (Figure 26-29).

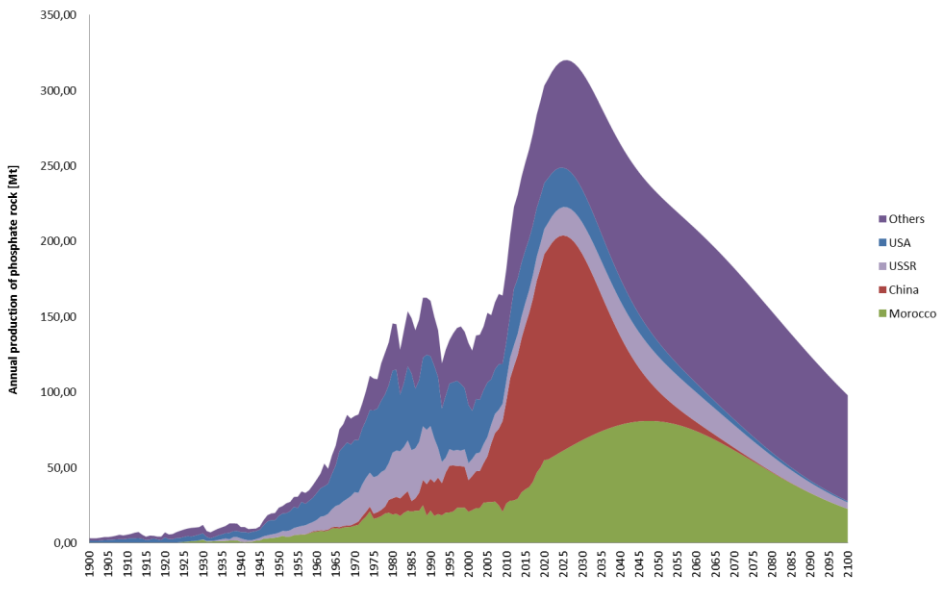


Figure 26. Scenario 1. China low estimate, Morocco low estimate.

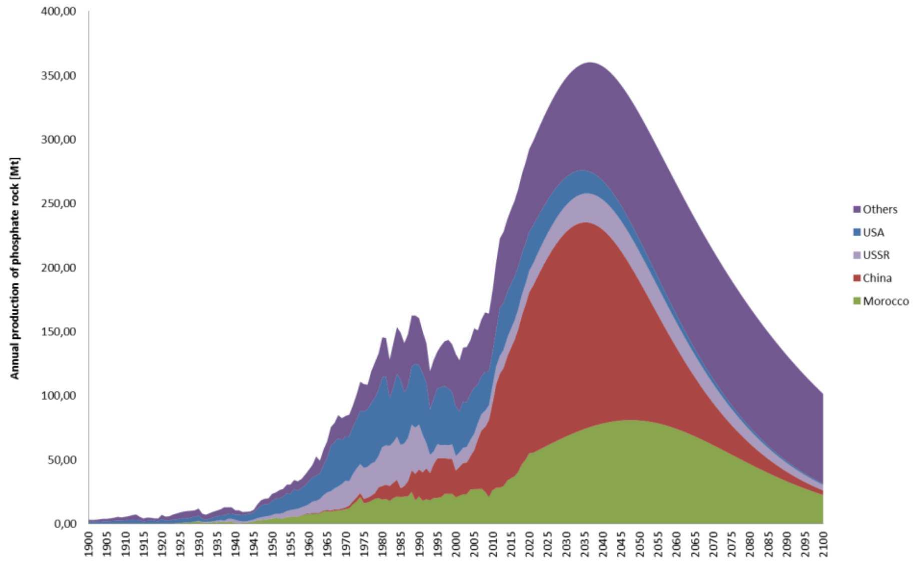


Figure 27. Scenario 2. China high estimate, Morocco low estimate.

In Figure 26, the production peaks in 2026 at 320 million tons and in Figure 27 between 2036 and 2037 at 360 million tons. That is only a few years after Chinas peaks (low: 2023 and high: 2033). These scenarios provide similar outcomes as Cordell et al. (2009) despite the fact that both the URR are significantly higher in these scenarios. The URR for scenario 1 is 29,874 million tons phosphate rock (equal to 4,268 million tons phosphorus) and in scenario 2, the URR is 33,574 million tons phosphate rock (equal to 4,796 million tons phosphorus). This can be compared to the estimations made by Cordell et al. (2009) that are based on a URR of only 3,240 million tons of phosphorus.

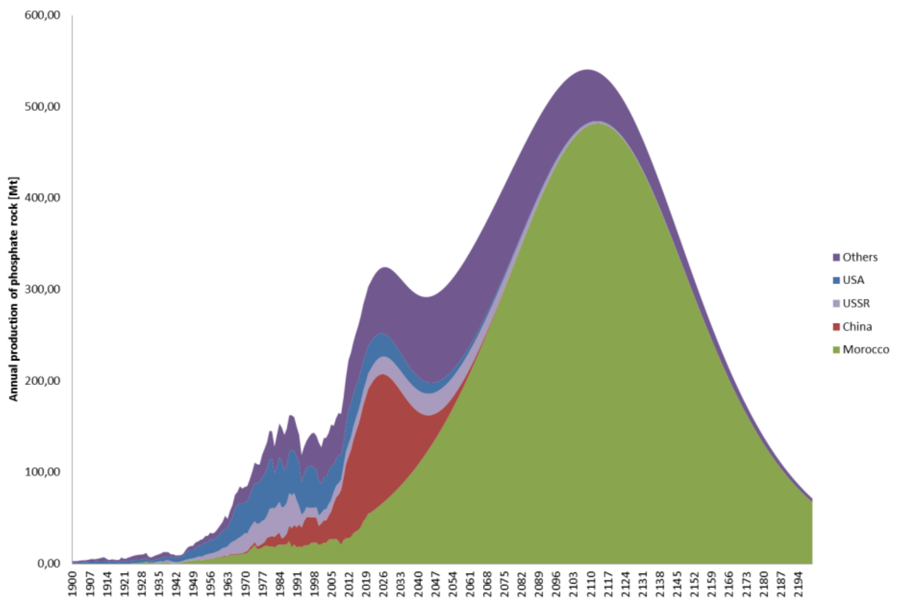


Figure 28. Scenario 3. China low estimate, Morocco high estimate.

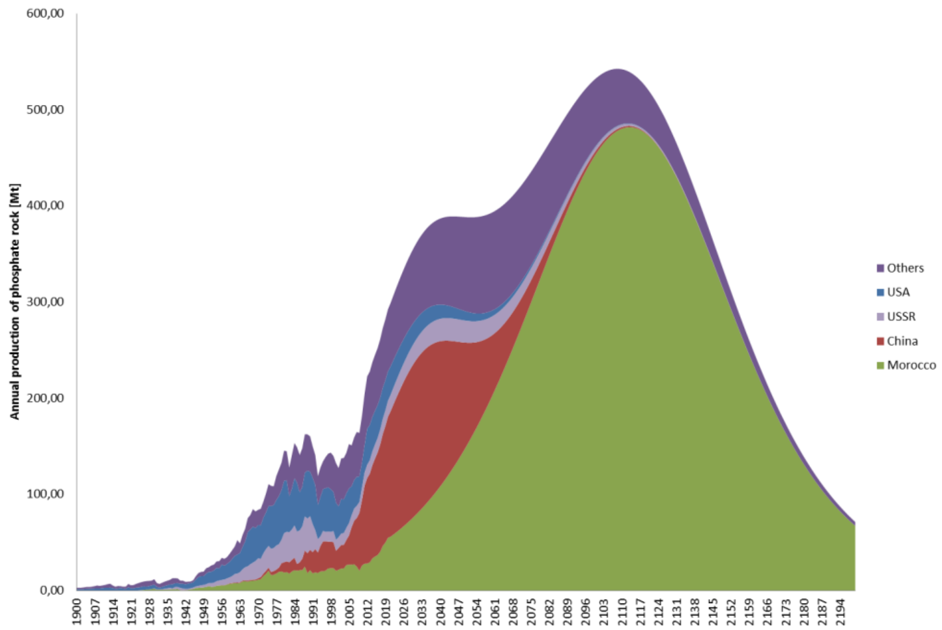


Figure 29. Scenario 4. China high estimate, Morocco high estimate

In figure 28 and 29 we see that even if the whole Moroccan current reserves estimate is extractable, is a risk that global production will have a small production peak as a result of declining production in China. The Figures also show that Morocco in these cases would have a very large share of world production far into the future. It is debatable whether an annual output over 500 million tons will be necessary in the future. The URR is 74,174 million tons of phosphate rock for scenario 1 and 77,874 million tons for scenario 2.

9. Discussion

9.1 Data

One hundred years of historical production data for phosphate rock is available for many countries and data does not differ much between the different sources. The data for the size of the reserves, however, are highly unreliable. The uncertainty in the data for reserves can be seen in the substantial changes made in the estimates of reserves for many countries and that many of them have not changed anything for years despite constant production, which can be seen in figure 2. Hence, it is therefore hard to make reliable predictions.

The declining concentration of P_2O_5 in the phosphate rock and the decreasing amount of phosphate rock in the ore mined in the United States are clear signs of that the best reserves already have been used there. Any reduction of the P_2O_5 concentration in the world or any other country is, however, difficult to see (as shows in figure 15 and 16). The data for produced P_2O_5 seems to be unreliable for most countries except for the U.S., although some increases in concentration may be due to the opening of new mines.

It may also be noted that although today’s estimated reserves will last for more than 300 years with today's production rate, there could be a scarcity of phosphorus much earlier than that. First, production is expected to continue increasing in the future and in addition, there are many obstacles and bottlenecks that means we can get a temporary shortage of phosphorus in the future because of declining production in some places in the world (such as China). Since price sensitivity is very inelastic because of the lengthy processes required for exploration and opening of new mines, an abrupt production shutdown may therefore lead to a long shortage of phosphate rock.

9.2 Peak phosphorus modeling

The modeling of aggregated production curves from different countries, demonstrates the problem of modeling the future phosphorus production only based on aggregated world data. China and Morocco have been shown to have a major impact on the future production for the world. As can be seen in the four scenarios, China’s production peak will have a huge impact on the world production in the near future and it is a significant risk that a production peak will occur globally as a result of the Chinese peak. This risk has not previously been recognized in earlier studies. The reason for this is that aggregated world data simply missed such details. It is unclear whether Morocco can increase production quickly enough to compensate for the reduced production that eventually will happen in China. The global production peak of phosphate rock will also be extremely dependent on how much and how fast Morocco can increase their production.

In the modeling, there were problems to fit the curves to the historical data for three of the countries as the depletion rate became extremely high. For USSR, this was due to the difficulty to find a curve that could describe the extreme fall in production that occurred after the collapse of the Soviet Union. A logistic double-peak-curve was applied in this case to provide a decent model for USSR, but the production fall was too steep to be able use a depletion rate limit in this case. The other two countries were Egypt and China, which both have had an extremely strong growth in the past decade and neither of them has estimated reserves that would make it possible to continue the trend much longer. This may be an indication of that the reserves actually are larger in reality for these countries. Another interesting thing that can be seen in the modeling is that most of Tunisia's URR (which is based on USGS estimated reserves) is exhausted, which would mean that production have peaked and soon will fall sharply if the estimated reserves are correct. More likely is that the reserves are larger than in the USGS estimations.

The high case scenario for the world production is seen as the least likely of the three scenarios for the world production. This is because that would mean that all the reserves and a significant amount of the resources would be possible to extract in the future. There are many bottlenecks such as water and energy use, the infrastructure needed, the increased concentration of cadmium and other impurities as well as a decreasing concentration of P_2O_5 in the phosphate rock.

9.3 Future outlook

First of all, phosphorus is not running out as it is an element, hence it cannot be destroyed. Phosphorus in the concentrated form of phosphate rock is a finite resource that most likely is going to peak at a global scale within the 21st century, provided that production trends follow similar patterns as seen in exploitation of other natural resources. Some countries phosphate rock production seem to have peaked and others to be not far from peaking. United States production has clearly peaked as the production is declining, phosphorus concentrations are decreasing and reserves are much smaller than the URR. U.S. still accounts for a large share of world production, which means that other countries must continue to compensate for the decline in the U.S. production in the future.

Chinas' production has increased dramatically over the last ten years but this trend will be difficult to maintain much longer and the production could therefore peak in 10 to 20 years with current trend. The production might reach a plateau phase instead at for example 100 Mt since a doubling of 2011 years production in ten years might not be possible.

Morocco will probably gain an increasing share of the world production in the longer run. Although, it is unlikely that they will be able to increase their production more than seventeen times the amount of phosphate they produced in 2012, as in the high estimations. This is mainly due to the bottlenecks in production such as the scarcity and competition for water and energy. Climate change is expected to reduce rainfall in Morocco, which will increase the already large water shortages further more (UNEP, 2009). To get enough water, it is likely that Morocco therefore increasingly needs to rely on desalination plants and that competition increases for the water that is left in the ground.

Another great issue is the geopolitical problem that much of the world would become dependent on one single country for the supply of phosphate fertilizers that is needed for food production. As there are still political contentions going on in West Sahara, such dependence would not be good for the world food security and also if Morocco would have a too large share of the production, an oligopolistic or monopolistic situation could appear in the market. There is also a problem with the high cadmium content in much of the phosphate rock deposits that may provide an incentive for declining demand for Moroccan phosphate rock in the future (HCSS, 2012).

The production increase of phosphorus has been strong the past ten years but the price of phosphate rock is much higher than the previous normal price of 40$/ton. There are therefore many indications on a continuing high demand due to a continued population growth and an increased consumption of meat and dairy products that require more phosphorus in the manufacture (Cordell et al., 2009). Another factor is biofuels, which are likely to increase in the future. An increased biodiesel production from agriculture cannot, however, replace any significant proportion of the fossil fuel used in the transport sector due to lack of available land and water and the competition with food (Johansson et al., 2010). Biodiesel from microalgae is often seen as a solution to future shortage of liquid fuels, but this is still only at an experimental stage and many problems remain to be resolved for this to be economical to use in the future. Microalgae are far from giving a net energy production so far and much fertilizer is also needed in the production (Beal et al., 2011). To produce a liter of biodiesel 29-145 g of phosphorus is estimated as necessary and ten times more nitrogen, although much can be recovered (Rösch et al., 2011). Hence, phosphorus might be a constraint in the future for biofuel if it only will rely on phosphate rock.

10. Conclusions

10.1 Concluding remarks

The compilation of this study show that the peak phosphorus problem is too complex to only use aggregated world data as some countries production will peak before others. The scenarios presented in this report illustrates the impact China and Morocco will have on the world production in the future. With the current trend China's production is expected to peak within 10 to 20 years. Chinas future production will therefore have a large impact on the total world production in the coming decades. The only country that has sufficient reserves to replace China's production is Morocco, but it is uncertain whether Morocco will be able to increase production enough to replace a declining production in China in the future. It is unlikely that Morocco will be able to produce as much as they are expected to do in the most optimistic scenarios. This is due a number of bottlenecks, especially water scarcity, but also the increasing proportion of impurities in phosphate rock, a reduced concentration of P_2O_5, greater energy needs and huge investments required for the development of infrastructure and mining. Because of unreliable data it is not possible to draw clear conclusions whether the concentration of phosphorus in phosphate rock is declining in the world or not. Although it is clear that the concentration decreases in the U.S., data for the world's phosphate rock concentration are highly uncertain.

The data for estimated reserves are also uncertain and it is therefore hard to make an accurate forecast of the future production. Better information is needed about the size of China and Morocco's reserves and how much phosphate rock that might be possible to produce at a maximum rate, given the bottlenecks for production. Despite the uncertainties in the data it is possible to conclude that phosphorus production is likely to peak within this century. A smaller production peak may occur before this because of a declining production in China.

10.2 Recommendations

A reduction of the use of phosphate rock would in many ways be desirable. This would in particular reduce the eutrophication of our lakes and waterways. New phosphorus is added continuously to the ecosystem by the use of phosphate rock. If the phosphorus instead could be returned to agriculture in a much higher extent than today and the losses of phosphorus in the food chain could be decreased, these two actions would not only reduce the eutrophication but also reduce the many environmental problems that are associated with phosphate rock mining and fertilizer production. Phosphorus deficiency could thus also be postponed until later into the future. A transition to a more sustainable use of phosphorus is especially a good idea to improve the food security for areas such as the EU, which imports most of the phosphorus from other countries.

Some of the USGS listed reserves might need to be revised, such as for Egypt, Tunisia and maybe China. Their reserves have remained constant for many years and gave strange results in the modeling. The reserves are probably larger for these countries.

10.3 Scope for future work

There is much that could be further studied in this field. More thorough investigations of how much that will be recoverable in the future in China and Morocco would be useful for the estimation of future phosphate rock production and a possible future shortage of phosphorus. A study of water supply in Morocco in relation to an increasing phosphate rock production could provide a picture of a possible maximum limit on the annual production for the country.

How geopolitical problems could affect the phosphate rock production and thus the food security is something that could be investigated further. Another interesting thing that was only covered briefly in this study and could be studied much more is the total energy consumption for mining, fertilizer production, transport and fertilization. It would also be interesting with a study over a likely long term demand of phosphorus in the future. More models could have been applied than logistic models for the different countries and even more countries could have been included in the study, but due to time constraints this was not done in this study.

Similar studies that was made for phosphorus in this case, could also be made for other important nutrients such as nitrogen, potassium and sulfur. It is not unlikely that one of them could constitute a constraint for food production in the future as well.

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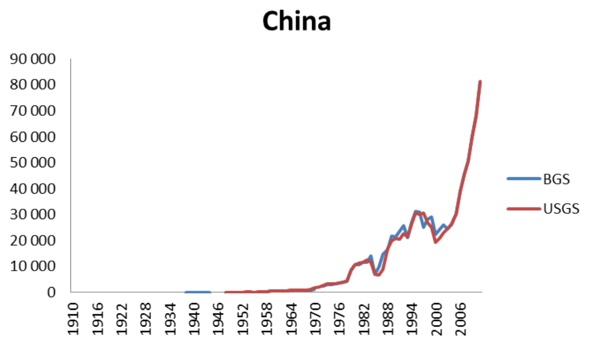
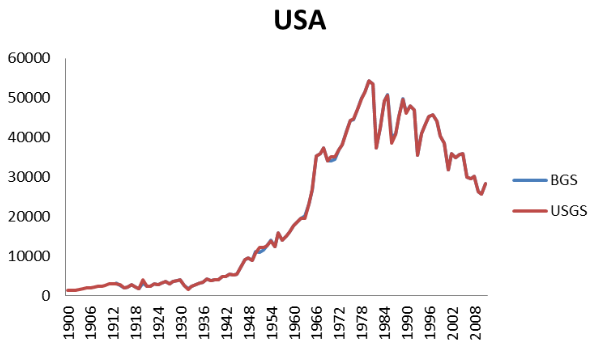
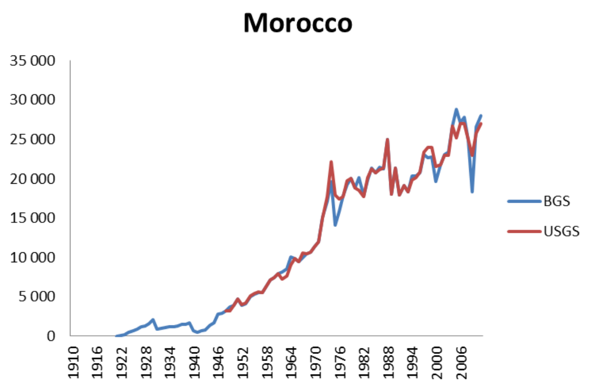
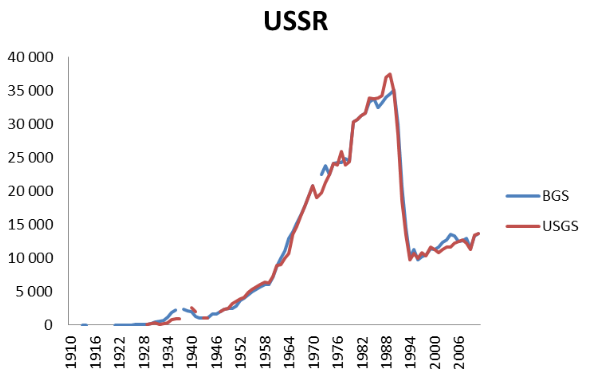
Appendix 1. Production data

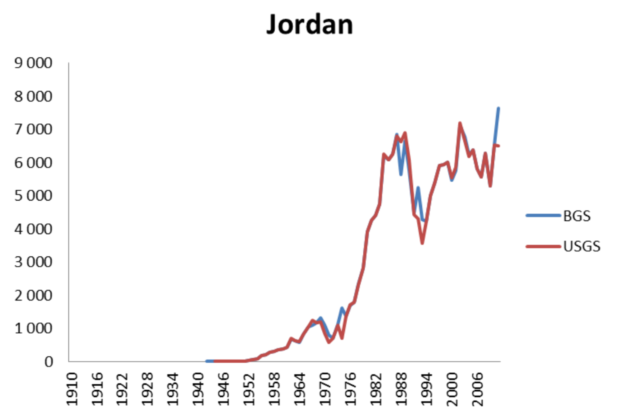
The following charts show the production of phosphate rock in thousands of metric tons for the ten largest countries in 2011. Data collected from both the U.S. Geological Survey and the British Geological Survey. All data are between 1910 and 2012, except USA that had data available from 1900.

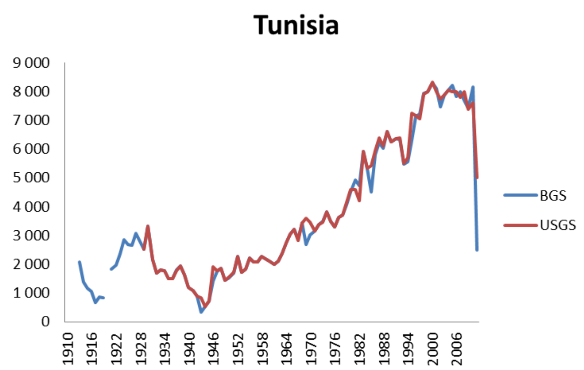


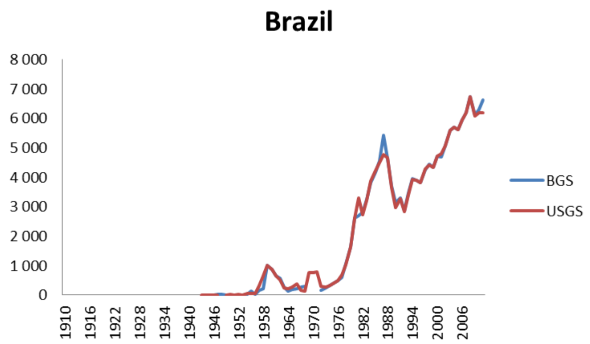


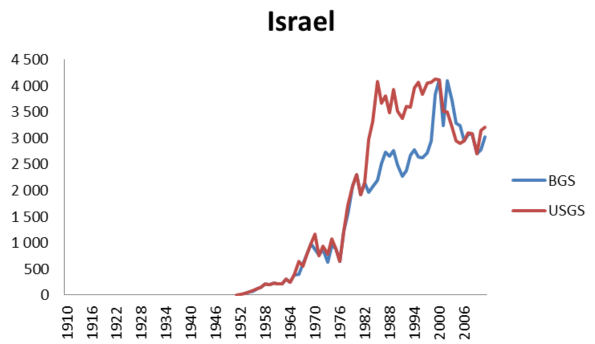









Brazil
8 000
7 000
6 000
5 000
4 000
3 000
2 000
1 000
0
1910 1916 1922 1928 1934 1940 1946 1952 1958 1964 1970 1976 1982 1988 1994 2000 2006
BGS
USGS


Israel
4 500
4 000
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1 500
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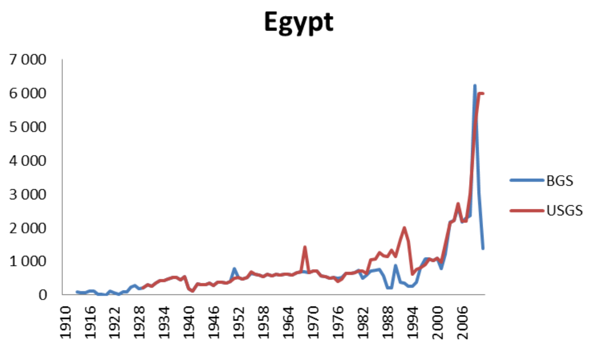
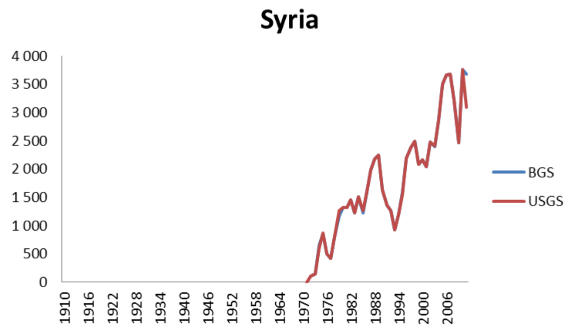
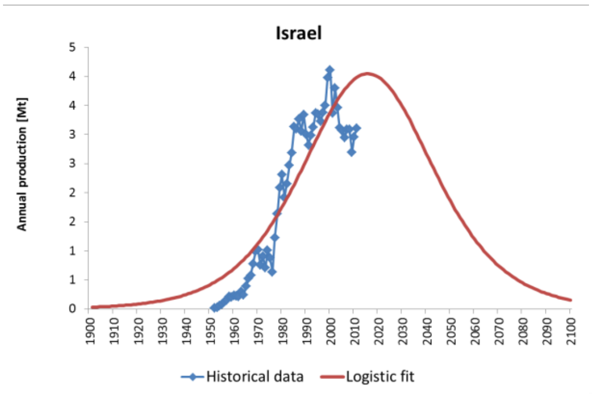
0
1910 1916 1922 1928 1934 1940 1946 1952 1958 1964 1970 1976 1982 1988 1994 2000 2006
BGS
USGS

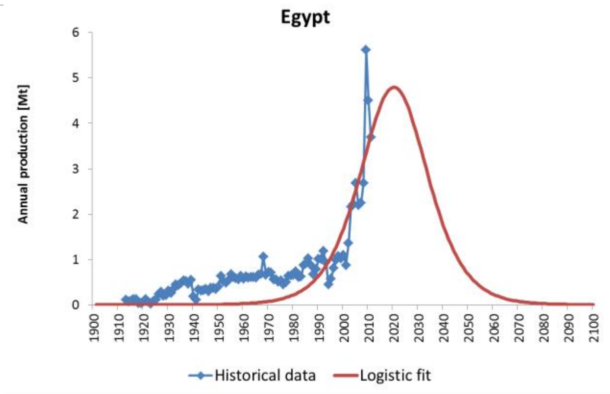

Egypt
7 000
6 000
5 000
4 000
3 000
2 000
1 000
0
1910 1916 1922 1928 1934 1940 1946 1952 1958 1964 1970 1976 1982 1988 1994 2000 2006
BGS
USGS

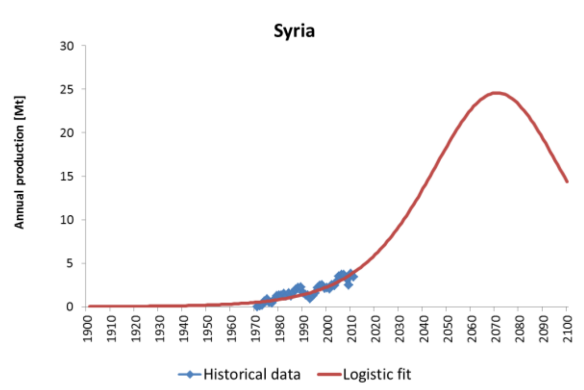

Syria
4 000
3 500
3 000
2 500
2 000
1 500
1 000
500
0
1910 1916 1922 1928 1934 1940 1946 1952 1958 1964 1970 1976 1982 1988 1994 2000 2006
BGS
USGS

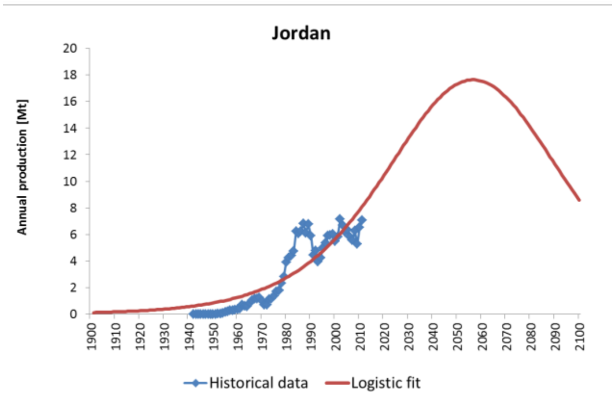
Appendix 2. Production modeling

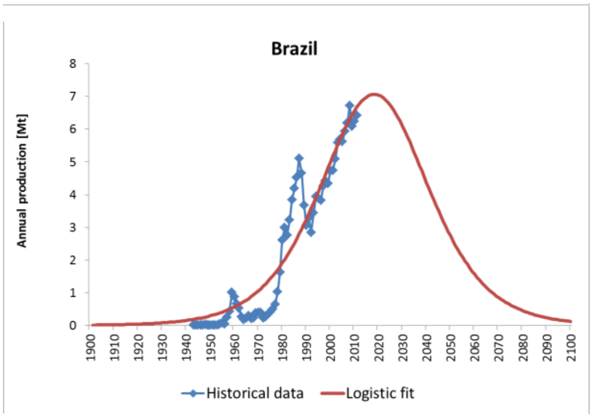
The modeled future production fitted to historic production data. Logistic models are used for all of the figures. The historic production data is the mean of the data from U.S. Geological Survey and the British Geological Survey.

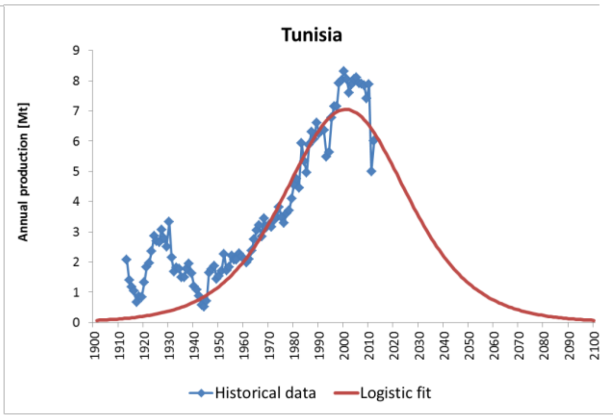


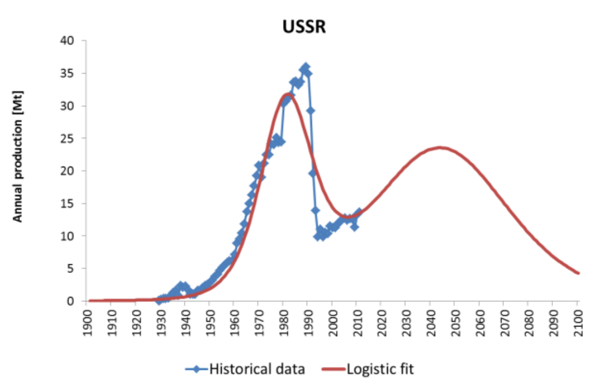
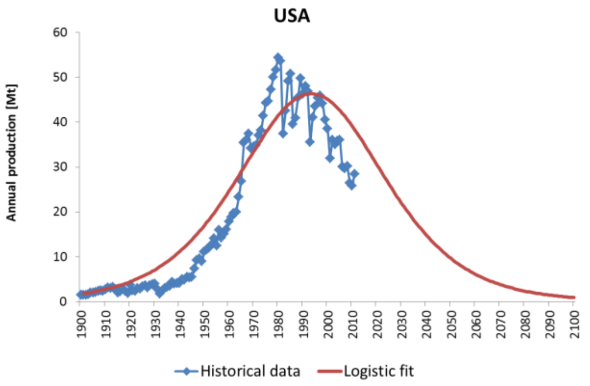
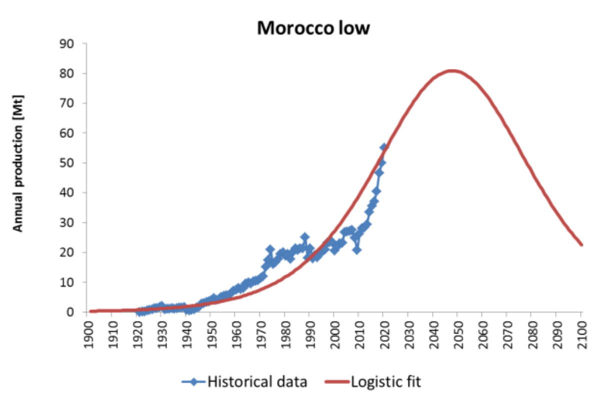
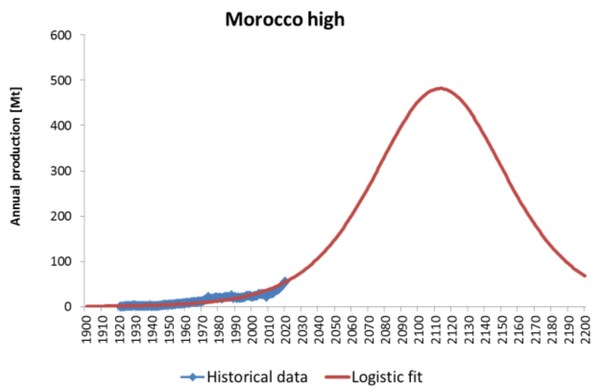
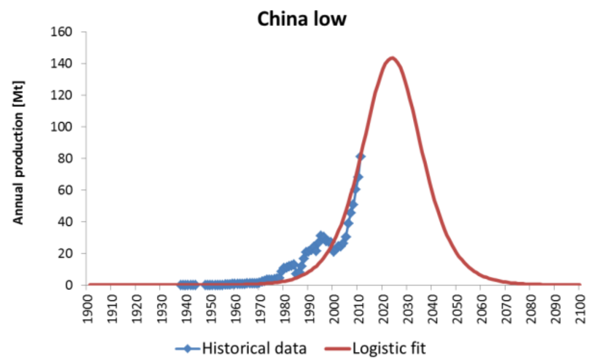
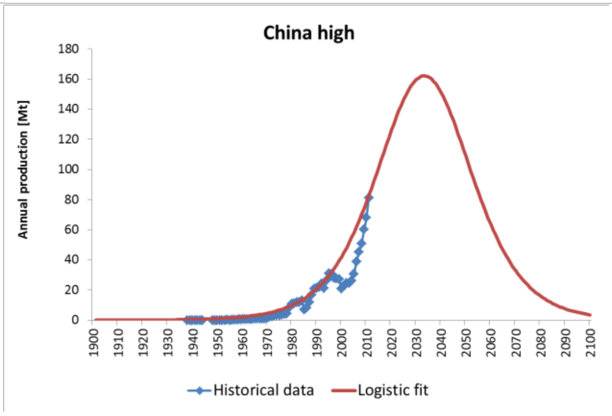
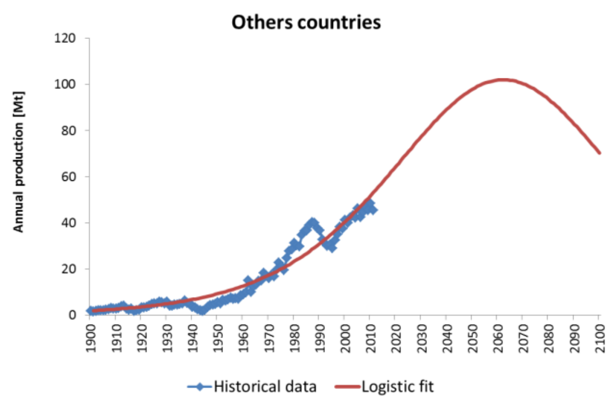











USSR
Annual production [Mt]
Historical data
Logistic fit

USA
Annual production [Mt]
Historical data
Logistic fit

Morocco low
Annual production [Mt]
Historical data
Logistic fit

Morocco high
Annual production [Mt]
Historical data
Logistic fit

China low
Annual production [Mt]
Historical data
Logistic fit

China high
Annual production [Mt]
Historical data
Logistic fit

Others countries
Annual production [Mt]
Historical data
Logistic fit