Model-Based Governance of Phosphate Market Imbalances

Mixing and matching model building blocks

Bas Keijser
Master Thesis
August 2016

Model-Based Governance of Phosphate Market Imbalances

Mixing and matching model building blocks

B.M.J. (Bas) Keijser
Student number: 4003136

Master thesis for MSc. in System Engineering, Policy Analysis and Management
Faculty of Technology, Policy and Management
Delft University of Technology

Date of submission: August 8th, 2016

Graduation committee:

Prof. dr. ir. A. Verbraeck	Policy Analysis, Faculty of TPM
Dr. E. Pruyt	Policy Analysis, Faculty of TPM
Dr. S.T.H. Storm	Economics of Technology & Innovation, Faculty of TPM
Dr. A.G.T.M. Bastein	TNO Resource Efficiency & Raw Materials

Cover photo: train loaded with phosphate rock in Metlaoui, Tunisia, via:
https://www.flickr.com/photos/22490717@N02/7860300620

Summary

Phosphorus is essential for all life on this planet as it is essential in biological cell formation. The material is highly needed in providing high productivity yields in modern agriculture. The phosphate market is characterised by three special characteristics: (i.) the strong connection of the phosphate market to food security, (ii.) the lack of a substitute of phosphate fertilizers in its agricultural application, (iii.) the extreme concentration of phosphate rock reserves in only a few countries. The uneven geological distribution of reserves causes complications for phosphate importers such as all European countries. Due to the lack of a substitute for phosphate fertilizers, food security is at risk in the event of supply interruptions. The phosphate rock market and the phosphate fertilizer market have an oligopolistic structure. This provides perspective for phosphate market distortions such as price overcharges that are felt in Europe as well as in development countries that do not have phosphate.

The phosphate market can endogenously move towards an imbalance between supply and demand induced by the dwindling of rock reserves or by investment cycles. Temporary severe scarcity can be induced by export restrictions instated by phosphate exporters that realise they are in a strategic position. Trade restrictions pose large problems for importers dependent on an oligopolistic market. Other causes of sudden market imbalances include political events and labour strikes. The previous determinants of market imbalances and their mutual interactions are investigated using a quantitative model. A phosphate market model was specifically designed from scratch to this cause.

The quantitative model was constructed from scratch using an open quantitative modelling process. A set of ten essential market aspects uniquely describing the phosphate market forms the system conceptualisation. On the basis of a requirements analysis model building blocks from different single modelling methods were selected, including: stock-flow mechanisms representing mines and processing facilities, decision-making mechanisms simulating investment and capacity utilisation behaviour of companies and market-clearing mechanisms to find rock and fertilizer prices over time. The quantitative model is implemented in an object-oriented fashion within a Python programming environment. The object orientation allowed for the flexible specification of a quantitative model consisting of building blocks that are not frequently combined into one commodity market model.

Two quantitative model instantiations have been used to simulate phosphate market development. An aggregated version of the model was used to investigate endogenous market determinants of global market imbalances towards 2100. This model includes: 5 to 7 companies active on the market, aggregated global phosphate demand of 45 million tonnes per year, and an aggregated phosphate rock buying party. These buyers and sellers interact in two Cournot-Nash style markets in which rock and fertilizer prices are determined every quarter of the simulation time.

A disaggregated version of the model was used to simulate the influence of export and production restrictions towards 2030. This market simulates three regional markets: (i.) Africa & South America, (ii.) Europe, and (iii.) the Middle East, Russia & India. This model includes: 6 to 8 companies active on the market, aggregated phosphate demand of 20 million tonnes per year divided over the three regional markets, and three aggregated rock buying parties. The Cournot-Nash market has been subdivided into three regional markets with different prices and transport costs for deliveries of rock and fertilizer to other markets. Export taxation and production restrictions have been implemented in this model. Importer policy measures that can be tested using the model include recycling and strategic buying of rock and fertilizer.

The global phosphate market model has been used to come to conclusions about the determinants of phosphate market imbalances towards 2100 under a broad range of uncertainties. The simulation results have shown that both situations of phosphate scarcity and phosphate abundance are plausible. Cumulative output of phosphate rock reserves to 2100 is projected to be between 9 and 35 billion tonnes: geological scarcity is not plausible. The most important determinant of phosphate market imbalances was found to be the extent to which investment in mines and fertilizer processing facilities suffices to match rising demand. Vertical integration of the value chain causes higher and more dynamic rock prices.

The three-region phosphate market model has been used to investigate the effect of selected export and production restrictions on phosphate importers in Europe. A 100 $/ton tax on rock exported from Africa & South America causes a median increase in the relative European phosphate rock price of 18 $/ton. A fixed 70 % limit on fertilizer production capacity in Russia, the Middle East and India causes a median European phosphate price increase of 110 $/ton. Similar effects have been found for phosphate export taxes and for rock production restrictions. The precise size of all these effects is dependent upon interactions with endogenous market developments already present when exogenous restrictions strike. This shows the importance of dynamic analysis of export and production restrictions on the phosphate market.

The three-region phosphate market model has also been used to investigate the effect of two coherent scenarios on the European phosphate market: (i.) a scenario of under-capacity and a subsequent tax on rock exported from Africa & South America, and (ii.) a scenario of tit-for-tat export taxation by both phosphate exporting regional markets. Confronted with the effects of these scenarios, the importer policy of phosphorus recycling was found to be a sustainable longer-term solution for alleviating European phosphate scarcity. Under the simulated, feasible recycling implementation, phosphate demand decreases by 26 % on average in 2030, phosphate scarcity is marginally lower in 2030, and median European rock price is 50 $/ton lower in 2030. Strategic buying is found to be only a temporary solution for alleviating market imbalances. The ratio of demand and supply is 0.5 points lower during implementation of the policy measure, but the price inflationary effect of export taxation is only strengthened: median rock price and median phosphate price are 35 $/ton respectively 70-90 $/ton higher in 2024 on the European market than when strategic buying is not implemented.

The quantitative model results presented show that phosphate market imbalances can be caused by both endogenous and exogenous factors. A lack of investment can quickly cause phosphate scarcity under conditions of rising phosphate demand. At the same time, phosphate importers should plan for the exogenous influence of export and production restrictions. The most sustainable policy measure available is recycling of phosphorus, although this measure has a planning synchronisation problem due to its long lead-time. Strategic buying of phosphate rock and phosphate fertilizers can only serve as a temporary crisis measure that has further price inflationary effects both within Europe as well as on other regional phosphate markets. In the end only a concerted package of phosphate market policy measures implemented at the European level can make sure that food security is preserved.

The open type of modelling and object-oriented implementation that was used has made it possible to generalise the applicability of the quantitative model to other commodity markets. New and different model building blocks can easily be mixed and matched within the current phosphate market model implementation to perform a different case study. The quantitative model can then be used to understand a different commodity market.

Contents

List of figures

List of tables

Part 1 – The (Research) Problem of Phosphate Scarcity

1 Introduction

Phosphorus is essential for all life on this planet. The majority of the demand for the element is due to its use as an artificially added macronutrient in the form of fertilizer (Cordell & White, 2014). It is needed to provide for high productivity yields in modern agriculture: a key part of the Green Revolution that took place in the 20th century. There is no substitute for phosphorus as a macronutrient, as it is essential for biological cell formation. Demand for food – and thus demand for fertilizer – grows steadily with the growth of the world population and thus food insecurity becomes an even larger problem through time (FAO et al., 2015). Yet, phosphate rock reserves are highly concentrated: only a few countries worldwide have considerable reserves of the commodity.

This section introduces the problem of phosphate scarcity. In section 1.1 the value chain of phosphate rock and phosphate fertilizer is presented. In the last few years a number of interesting trends on regional scarcity and supply risks have unfolded, these are discussed in section 1.2. Section 1.3 then introduces the oligopoly economics of the phosphate market and its effect on importers. In section 1.4 the importance of coping with phosphate market imbalances is stated.

1.1 The value chain of phosphate rock and fertilizers

The value chain starts with mineral phosphate rock, see Figure 1. Phosphate rock is only found in a small number of countries – only Morocco, China, Algeria, Syria and a few others have considerable reserves, in order of decreasing reserve size (USGS, 2016). Higher-grade reserves are emptying in the U.S. and in China, while Morocco seems to have enough phosphate rock for a number of decades to come. It will thus even increase its market share in the coming century (Cooper et al., 2011). Different phosphate fertilizers are produced through chemical processes. Combining phosphate rock with sulphuric acid produces phosphoric acid, the focal semi-processed product of the value chain. Some exporting countries keep the rock and the fertilizers for themselves. China for example, produced 45% of the phosphate rock in the world in 2015 (USGS, 2016). But it exports almost no rock (van der Weijden et al., 2013). It does export some phosphate fertilizers. After their agricultural use, phosphorus flows leach into water run-off from the land (Elser & Bennett, 2011). The mineral cannot easily be regained.

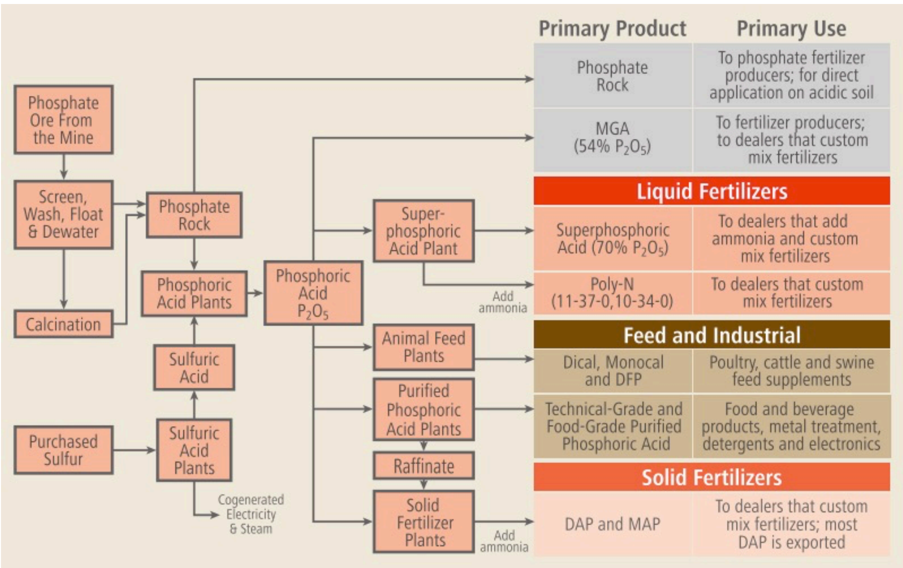

Figure 1 – Chemical value chain of phosphate rock and fertilizers (PotashCorp, 2014)

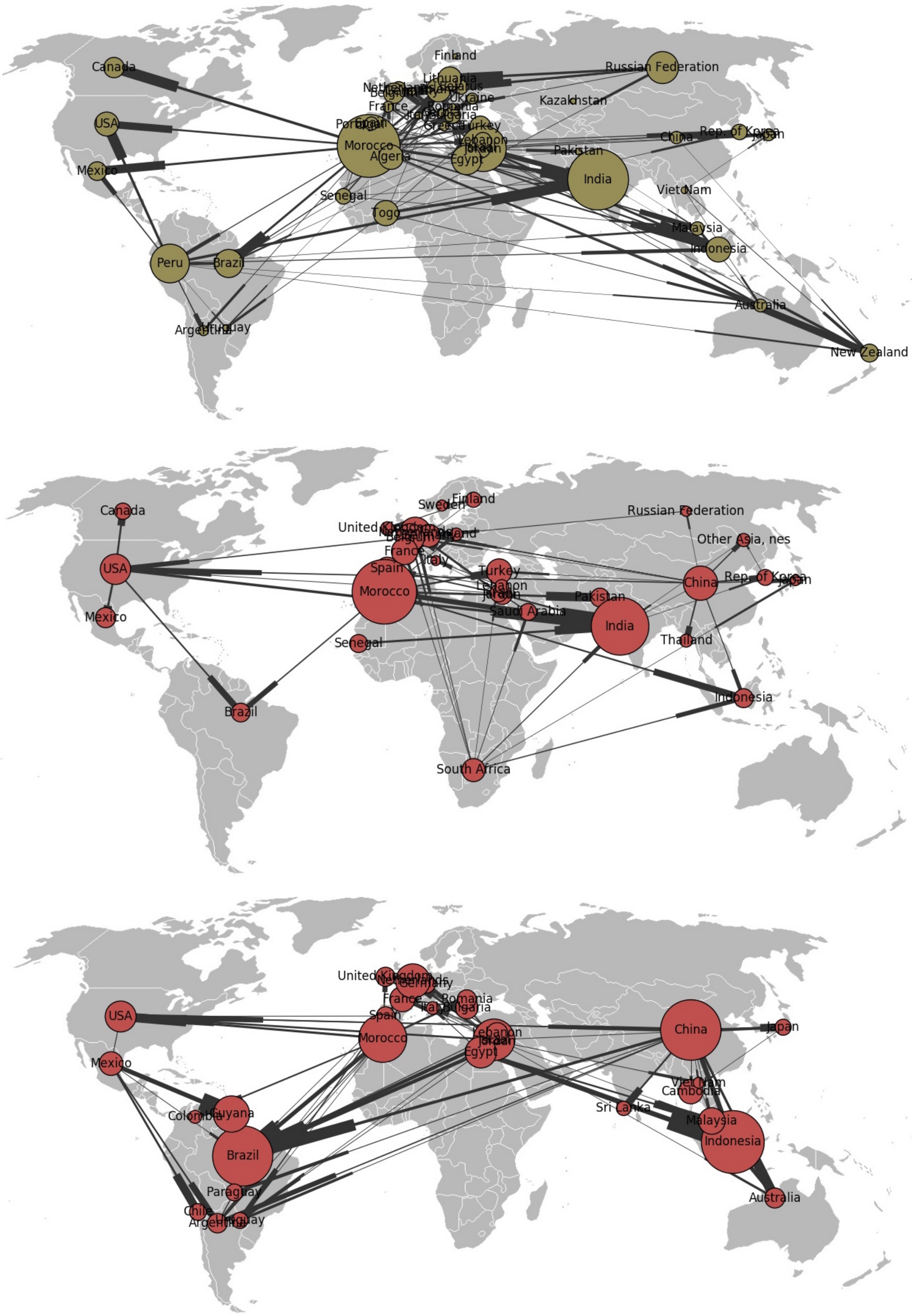

Figure 2 – Trade of phosphate rock (HS4-2510), phosphoric acid (HS4-2809), and phosphate fertilizers (HS4-3103) in 2014. Size of node represents relative size of sum of imports and exports. Width of edges represents relative size of trade flow. Most important countries and most important flows have been shown. Between 80 and 95% of total reported trade flows of respectively 25, 6 and 8 million tonnes have been shown. All data is from United Nations (2016)

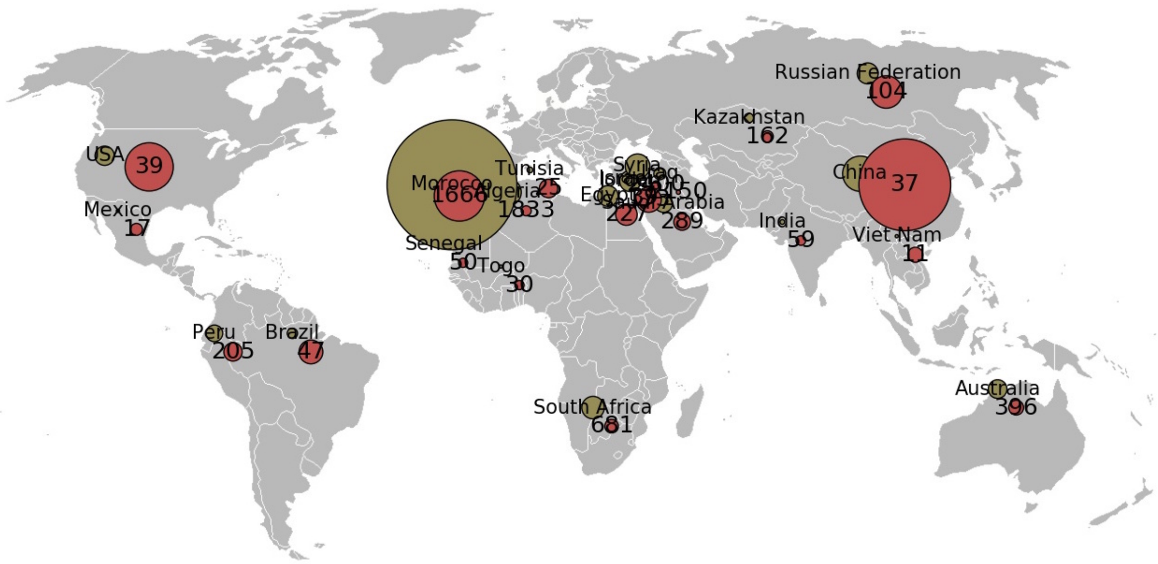

Figure 3 – Phosphate rock reserves and production in 2015. Sizes of nodes show relative size of both. Reserve production ratio on the country level is also shown. All data is from (USGS, 2016)

1.2 Trends in regional scarcity, supply risks and prices

A regional analysis of production and trade of phosphate rock and fertilizers shows the geo-economical concerns about phosphate import dependence. Observations from the analysis shown in Figure 2 and Figure 3 are collected in Table 1. The main conclusion, from the perspective of the European Union, is that the continent is fully dependent on phosphate imports. The continent does not have any phosphate rock production. European countries are thus big parties on both the rock and the fertilizer markets, as seen from the trade analysis on the previous page. There are also a number of developing countries that are very dependent on phosphate imports. India mainly imports phosphate rock and phosphoric acid. Sub-Saharan Africa is generally only active on the mixed fertilizer market. And finally, countries in Latin America, such as Brazil and Argentina have minimal reserves of rock, but strong imports of both acid and phosphate fertilizers. A last observation is that the United States and China are very large producers, but their reserves are dwindling rapidly: reserve production ratios of both countries below 40 years.

In recent years, the price of phosphate rock has shown a marked spike causing a similar peak in fertilizer prices, as exemplified by the price of DAP (see Figure 4). Between 2007 and 2009 the price of rock rose by about 600-800%, after which it retracted to a four times higher plateau than where it was before 2007, at about 160 $/ton (Mew, 2016). The most cited reason for this increase in price is the fact that there was a severe shortage of mining capacity (Al Rawashdeh & Maxwell, 2011). A competing explanation is peak phosphorus rumoured to take place already in the coming decades (Elser & White, 2010; Walan, 2013). Rising scarcity rents induces a longer-term trend of rising prices (von Horn & Sartorius, 2009). Others however note that peak phosphorus is not imminent at all (Heckenmüller et al., 2014; Van Vuuren et al., 2010), by pointing at geological reserves that will become available on the market at higher prices. Analysts do agree about the possibility of regional scarcity in the future (Cordell & White, 2014; Hees, 2013).

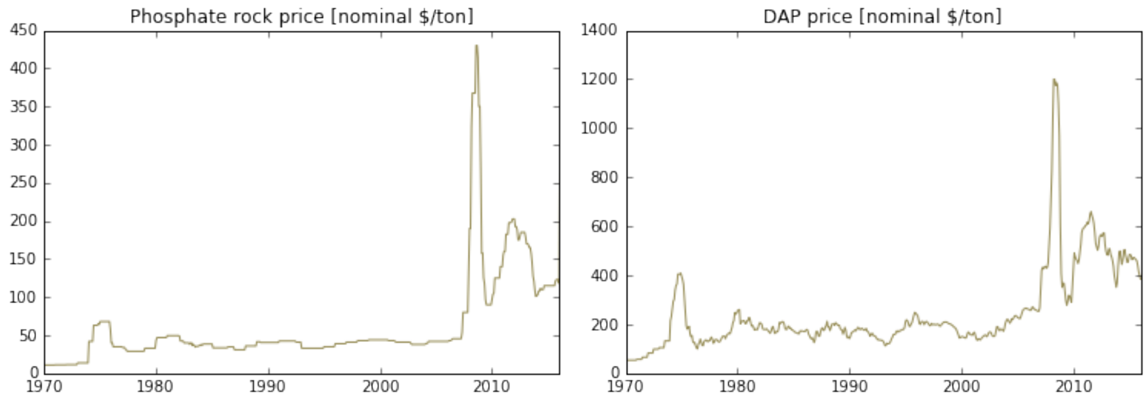

Figure 4 – Phosphate rock and DAP prices since 1970 [nominal $/ton] (World Bank, 2016)

Table 1 – Analysis of import dependence and sufficiency of production, based on data (FAO, 2013; International Fertilizer Association, 2016; United Nations, 2016; USGS, 2016) as well as analysis by others (Heckenmüller et al., 2014; Hernandez & Torero, 2010)

Region	*Rock imports / P_2O_5-cons.*	*P_2O_5-imports / P_2O_5-cons.*	*P_2O_5-prod. for self-cons.*	*Exploratory conclusions on current status of regional market*
European Union	68 %	90 %	90 %	✓ Fully dependent on import of phosphorus flows (no reserves) ✓ There are also production and exports
Northern America	15 %	12 %	107 %	✓ Self-sustaining production of P_2O_5 ✓ However the static R/P of main producer USA is only 40 years
Latin America	13 %	37 %	37%	✓ Mainly dependent on fertilizer inflows (Brazil is large consumer) ✓ There are some reserves (Peru), but this will not suffice
Western Asia	34 %	29 %	198%	✓ Considerable reserves (although not stable, e.g. Jordan and Syria) ✓ Very low import dependence
Eastern Asia	12 %	6 %	129%	✓ Very low import dependence, but strongly dwindling reserves ✓ Eastern Asia (mainly China) is relatively disconnected from the fertilizer market
Africa	Nil	57 %	215%	✓ Majority of global reserves is located in Morocco ✓ Strong regional imbalance with Sub-Saharan Africa, where demand is growing
Southern Asia	35 %	35 %	59%	✓ Almost no reserves, while India has a very large demand ✓ There is a lot of P_2O_5 production, though high import dependence

1.3 Oligopoly economics, restrictions and the effect on importers

The uneven geological distribution of phosphate rock reserves causes complications on the market. The world market for phosphate rock has a concentrated nature, as only a few countries have major exports: primarily countries in the Middle East such as Morocco, Jordan and – until the Arab Spring and the civil war – Syria. In markets such as China and the United States there is also a small number of suppliers. In the future, the excessive amount of reserves in the hands of Morocco will even exacerbate market concentration (Cooper et al., 2011; de Ridder et al., 2012). The market for fertilizers also has a oligopolistic market structure, it is found to be prone to cartelization (Taylor & Moss, 2013). The market shares of the top five fertilizer producing countries on all of the phosphate fertilizer markets are 50 to 70 % (Hernandez & Torero, 2013). This gives rise to price overcharges and other market distortions.

From the perspective of import-dependent regions such as the European Union, market distortions on the rock and fertilizer markets could spell problems: they cause large uncertainty in the supply of phosphate. Standard economic theory finds that in a market with a large number of buyers and a low number of sellers, prices tend to be high. The countries that currently export phosphate rock to the European Union include geopolitically unstable countries such as Morocco, Russia, Algeria, and others in the Middle East (de Ridder et al., 2012; Rosemarin, 2004). Many of these exporting countries also have mining companies in charge of phosphate mines that are in state ownership (for example, Office Chérifien des Phosphates in Morocco). This provides further perspective for market distortions through for instance trade restrictions.

From a world developmental perspective, it is also important to be able to import phosphate fertilizers. These fertilizers are needed to accommodate for agriculture becoming more and more productive: a positive, essential stimuli for development of in particular Sub-Saharan Africa, but also of Latin America and India (Cordell & White, 2014; Schröder et al., 2010). These countries export their feedstock to the developed world, constituting a further dependency to the European Union. On the basis of data by the European Commission it can be noted that at least 40-50% of agri-food imports to the European Union comes from more or less developing countries that do not have phosphate rock reserves of their own, see Table 2. In a phosphate market of increasing prices and strong price volatility, development goals of low-income countries and global food security are severely hampered.

Table 2 – Top 20 origin countries of agri-food imports to EU-28, percentages shown are fractions of imports in April 2014-March 2015 (European Commission, 2016a)

Top 20 origin countries of agri-food imports to EU-28			
1. Brazil (13%)	6. Switzerland	11. Thailand	16. Malaysia
2. USA (10%)	7. Indonesia	12. New Zealand	17. Canada
3. Argentina (5%)	8. Ukraine	13. South Africa	18. Australia
4. China (5%)	9. India	14. Chile	19. Colombia
5. Turkey (4%)	10. Ivory Coast	15. Vietnam	20. Peru (1.5%)

1.4 The uncertain future of an essential material needs to be investigated

Investigating the phosphate market is paramount for three reasons: the extreme concentration of reserves in only a few countries, the huge importance of fertilizers for food security and the lack of a substitute for phosphate in their main, agricultural use. Contemporary concerns over the geo-economic dimensions of phosphate supply risks include the influence on supplies of political events such as Arab Spring (de Ridder et al., 2012), the repressive regime of Morocco in the Western Sahara (Kingsbury, 2015; Western Sahara Resource Watch, 2014), and the imposition of hefty export restrictions by phosphate-producing countries (Fliess & Mard, 2012). In the future it will be necessary for importing regions such as the European Union to cope with a possibly unstable phosphate market. This instability is felt through price overcharges and trade restrictions.

Endogenous development of the market might cause emerging demand supply imbalances, when for instance reserves are dwindling such that mining of phosphate rock becomes more and more expensive, or investment cycles gyrate so strongly that longer-term price oscillations induce severe scarcity. Exogenous development of the market might cause sudden imbalances, when for instance export restrictions give rise to a temporary severe scarcity. Both of these types of developments – as well as their mutual interactions – can and should be investigated. If the risks of supply and demand imbalance would not be explored and acted upon, modern agriculture might be moribund and food security might thus contract greatly. The actual question is: how to keep phosphate scarcity manageable? And: how to make sure that the uncertain determinants of demand supply imbalance will remain manageable in the future?

2 Research problem

Investigating imbalances between commodity supply and demand and resulting scarcity has been of broad policy interest in the last decade – and it continues to be so. Commodities have become essential for economic growth and welfare of the modern society (Graedel et al., 2015). This section provides an overview of existing methods for the investigation of commodity market imbalances (section 2.1), and states the research problem as well as its scientific and societal relevance (section 2.2).

2.1 Existing methods for demand supply imbalance investigation

A number of commodities can be characterised as critical. A material is said to be critical when both the probability of a supply interruption and the economic importance are large (Achzet & Helbig, 2013; Graedel & Reck, 2015). Phosphate rock is one of many critical commodities in the views of such policy studies as have been commissioned by the U.S.-government, the European Union, the Dutch government and numerous others (Bastein & Rietveld, 2015; Bedder, 2015; European Commission, 2014; NRC, 2008). Other critical commodities include: rare-earth metals, cobalt, antimony and magnesium.

There are a number of existing methods to look at commodity supply risks. These methods investigate the risk of supply interruptions by investigating proxy variables such as geological, economic, social, regulatory and geopolitical factors (Graedel et al., 2012). These proxy variables cluster endogenous and exogenous effects that might cause supply interruptions, including: country concentration, country risk, depletion time, and by-product dependency (Achzet & Helbig, 2013). Material criticality is then represented by a simple indicator, in a criticality matrix or by executing quantitative supply and demand analysis (Erdmann & Graedel, 2011). The main strength of these material criticality methods is in the quantification of elusive supply risks: criticality situations for different materials are made comparable. The studies can be used to inform policy budget decisions and to size efforts directed at different materials accordingly.

Investigating material criticality using proxy variables for comparability reasons also has a number of shortcomings. These typically include arguments such as the incomplete representation of a complex market structure by simple indicators (Lloyd et al., 2012) and the lack of taking dynamics and uncertainty inherent to commodity markets into account (Glöser et al., 2015). Using proxy variables for instance fails to reflect the large differences between endogenous and exogenous reasons for market imbalances. Neither are all commodity markets the same. On the contrary, some commodity markets are quite competitive, the market for phosphate rock and phosphate fertilizer are highly oligopolistic. Because taking into account the more difficult determinants of supply risks is highly labour-intensive, it is frequently simply not done (Buijs et al., 2012).

Most current criticality methods cannot live up to the demand of understanding the dynamical effects of trade restrictions on the supply risks of phosphate. The uncertainty inherent to decision-making by suppliers and exporting countries on the market is not taken into account. Exceptions of studies that are far better at incorporating dynamics and uncertainty however do exist (Glöser & Hartwig, 2015; Kwakkel et al., 2013; Ragnarsdottir et al., 2011). Such studies implement quantitative commodity market models that can be used to provide a long-term view of market development. The effect of policy measures can also be tested using model simulations.

2.2 Quantitative model of the phosphate market, scientific and societal relevance

To investigate phosphate market imbalances over time a quantitative commodity market model specifically investigating supplier and exporting country behaviour was needed. Conclusions had to be both policy relevant and methodologically valid. By providing insight into the plausibility and severity of demand supply imbalances as well as their underlying mechanisms conclusions are relevant for policymakers. Both mechanisms endogenous to the market (such as economies of scale, the low number of suppliers and cost structures), as well as exogenous influences (such as export restrictive measures and production restrictive causes) were to be included in the quantitative model. In the optimal case, policy-makers are able to understand the precise workings of phosphate market imbalances through quantitative simulation results. In this way policy measures can be designed such that they actually alleviate market imbalances. The conclusions were to be phrased in such a way that they inform policymakers in their decision-making, in such a way that policy responses such as recycling of phosphorus flows can be managed (in similar words as European Commission, 2014, use).

Going further than using simple indicators also preserves methodological validity. The dynamic and uncertain nature of the phosphate market was to be included in the quantitative model. Effort needed to be put into building up a tailor-made quantitative model that specialises in investigating the effect of export and production restrictions on market imbalances under conditions of oligopoly economics. For this purpose, the model developed includes the limited geographical availability of reserves as well as the resulting price overcharges that have been empirically observed on the rock and fertilizer market. The scientific and societal relevance of the research problem is shown in Table 3.

Table 3 - Scientific and societal relevance of the research project

Scientific relevance

- ✓ Provide a quantitative model investigating the determinants of demand supply imbalances taking into account the dynamic, uncertain nature of commodity markets
- ✓ Provide a deep conceptual understanding of the causal relationship between export and production restrictions and market imbalances of phosphate rock, phosphate fertilizers

Societal relevance

- ✓ Provide a deep understanding, conclusions and recommendations on how to govern market imbalances of phosphate rock and phosphate fertilizer products
- ✓ Provide conclusions on the causal relationship between export and production restrictions on the one side and demand supply imbalances on the other side that are also applicable to other, similar commodities
- ✓ Provide insight into a key determinant of food security both within the European Union as well as in developing economies

3 Research goal and method

From the above problem statement it is apparent that understanding of phosphate market imbalances can be strengthened. The effects of export and production restrictions on demand supply imbalances can more specifically be better understood, the research goal is stated in section 3.1. An open modelling approach combining quantitative model building blocks from different methodologies was used to provide conclusions on phosphate market policy, the research method is elaborately discussed in section 3.2.

3.1 Research goal: effect of export and production restrictions on imbalances

The main research goal of this research has been to understand the effects of export and production restrictions on phosphate market imbalances. An open modelling approach to the problem was chosen. The method of modelling has been non-conformist relative to pre-existing single modelling methodologies that are used to model public policy problems. The next subsection details the chosen modelling method.

To provide for a structured research design, sub-questions were derived, see Table 4. The essential characteristics of the phosphate market that the quantitative model should capture are found (*question 1*). A part of these market aspects is grounded in oligopoly economics. There are both structural and behavioural aspects of oligopoly economics having effect on the market. Also, the occurrence of export and production restrictions is described and explained. When these aspects of the phosphate market had been gathered, a detailed, informed choice was made as to what model components should be combined into a working quantitative model. The quantitative model was then constructed from scratch (*question 2*).

The model is used for two distinct purposes. An aggregated version representing the global phosphate market is used to understand the longer-term endogenous development of the market. Determinants of endogenous market behaviour over time are determined. A multi-regional implementation of the model is used to understand the effect of export and production restrictions as exogenous factors on the market. Using the results of the model experiments, the determinants of phosphate market imbalances are stated (*question 3*). This is done in such a way that conclusions and recommendations for governance of the phosphate market from the perspective of importers are stated (*question 4*). In conclusion, the generalizability of the findings to other commodity markets is discussed (*question 5*).

Table 4 – Research questions

Question	*Background*
1. What essential aspects of the phosphate market should a quantitative model capture?	Section 4
2. How can the phosphate market be captured in a quantitative model designed from scratch to model the effect of export and production restrictions on market imbalances?	Section 5, 6, 8
3. What market aspects are the determinants of phosphate market imbalances? What is the role of export/production restrictions?	Section 7, 9
4. What policies should phosphate importers – such as the European Union – use to cope with phosphate market imbalances?	Section 9, 10
5. In what way can the findings generated with the quantitative model be generalised to other commodity markets?	Section 10

3.2 Research method: proof of concept of an open modelling approach

The key research method has been to develop a quantitative commodity market model from scratch. Although it is not common practice to report on a modelling process, developing quantitative models from scratch without resorting to single modelling methods was the main challenge of this research. It is worthwhile to state these challenges inherent to the modelling process in detail. The modelling steps are shown in Figure 5.

The first step of developing a quantitative commodity market model from scratch was to conceptualise the real world phosphate value chain. Theory-oriented analysis of the phosphate market was used to understand the real-world phosphate value chain. This was complemented by empirical analysis of the phosphate market. On the basis of the analyses a set of market aspects uniquely describing the phosphate market is presented (available in section 4.1 to 4.3). The analysis of oligopoly economics was an essential input to the first modelling study that was taken up next. The analysis of export and production restrictions was used to describe realistic exogenous scenarios in the second modelling study.

After the conceptualisation phase that forms the answer to question 1 (see Figure 5), in the next step a set of requirements was derived. To capture all essential phosphate market aspects the quantitative model fulfils these requirements. By structural, systematic investigation of these requirements quantitative model building blocks are identified to construct a quantitative model structure. This provides the liberty to analyse the phosphate scarcity problem without resorting to single worldviews.

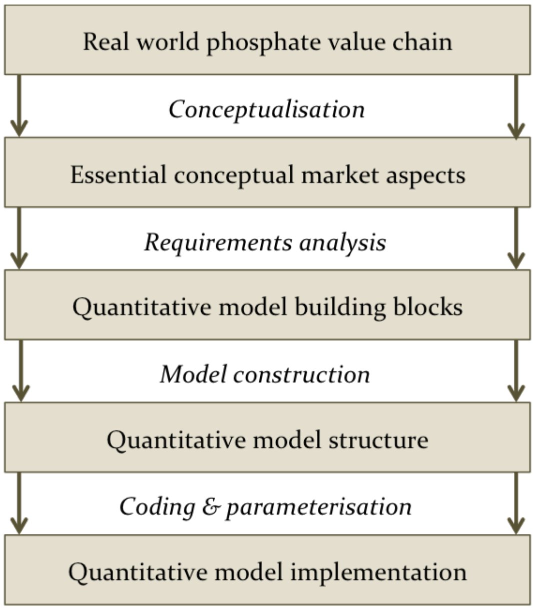

Figure 5 – Modelling steps

The commodity market model was specifically designed to simulate the effect of export and production restrictions on market imbalances. The model was developed from scratch by combining building blocks inspired by different modelling methods: agent-based models (Bonabeau, 2002), system dynamics models (Pruyt, 2010; Sterman, 2000) and economic game theory (Kolstad & Mathiesen, 1991; Shapiro, 1989). The model is build up of stock-flow, decision-making and market-clearing mechanisms. These mechanisms are not frequently integrated into one quantitative model (Lättilä et al., 2010). In the quantitative model company agents are attributed stock-flow structures that describe mine capacity and processing capacity over time. In the sense of Swinerd & McNaught (2012), the model is thus of an integrated hybrid design. More precisely, agents have a rich internal structure. Yet, the model also ties together agents making decisions over time into regional market structures – the market is thus viewed in an aggregated manner. To clear the market at every point in time, optimisation mechanisms are needed. Regional markets are then placed on a network structure with transport costs between the nodes. This way of working goes further than do earlier applications of mixing model building blocks from agent-based models, system dynamics models and economic game theory applications.

The quantitative modelling process is described in detail in section 5. Lastly, the quantitative model structure has been implemented in a Python computational environment through coding and parameterisation. To answer question 3 the quantitative phosphate model is used to systematically investigate market development over the medium and the long term. The endogenous determinants of phosphate market imbalance are the subject of the first modelling study. This model analysis has an 85-year time scale. It is provided in sections 6 and 7. Endogenous market development provides the framework within which exogenous determinants of market imbalances such as export restrictions are investigated. These are subject of the second modelling study with a 15-year time scale. This modelling study is provided in section 8 and 9.

The effect of export and production restrictions on the phosphate market under conditions of oligopoly economics can be described and quantified, as is done in section 9. The model results provide policy makers with a clear view of what policies can contribute to the reduction of phosphate market imbalances – answering question 4. The results show what they can do to strengthen fertilizer security and food security given plausible future market developments. Discussion of the policy implications and methodological implications are available in section 10. Methodological implications drawn relate to economic commodity market modelling and to quantitative modelling by combining model building blocks from different modelling methods. Conclusions are then drawn in section 11 – all research questions are explicitly answered there.

Part 2 – Stock-flow, Decision-making and Market-clearing Mechanisms

4 Conceptualisation

This section contains a systematic investigation of the essential phosphate market aspects that are needed to decide on the model building blocks used to construct a quantitative phosphate market model. The conceptualisation of the phosphate value chain through ten essential market aspects is available in sections 4.1 to 4.3. Further background to the occurrence of export restrictions in the market is provided in section 4.4. The importance of the case study of phosphate is reiterated in section 4.5.

4.1 The phosphate value chain

The phosphate value chain consists of three parts: (i.) phosphate rock production, (ii.) phosphate rock, phosphoric acid and fertilizer trade (interlaced with chemical process steps), and lastly (iii.) phosphate demand (see Figure 6). These parts are described one by one and the typical aspects that become apparent are stated in the rest of this section. Some market aspects generally describe commodity markets; others describe specific characteristics of the phosphate market. Some representative, empirical observations are made on the phosphate market after which an *essential phosphate market aspect* is specified. In describing the market aspects connections with relevant literature will be shown.

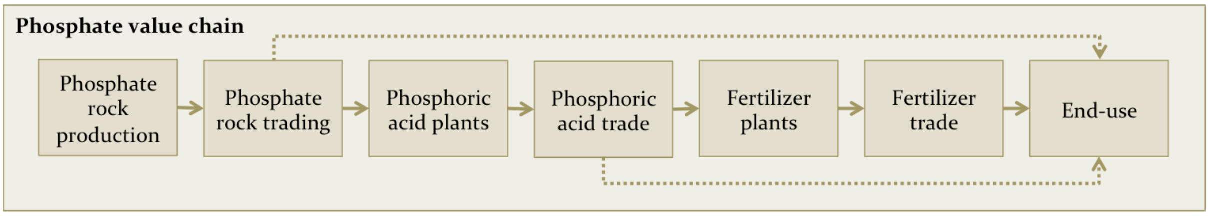

Figure 6 – Simplified view of the phosphate rock and fertilizer value chain, based upon the chemical value chain as cited earlier (PotashCorp, 2014)

Production of rock takes place in locations at which reserves are mined. Reserves of phosphate rock are found in only a limited number of countries (predominantly Morocco, see Table 5 as well as the description in section 1 and Cooper et al., 2011). There is a very uneven distribution of sources of phosphate rock. Clearly, phosphate rock reserves are exhaustible, this makes commodities anomalous compared to many other markets for general goods (World Trade Organization, 2010). Exhaustibility is the root cause for the problem of phosphate scarcity. Geographical presence of rock reserves, mine exploration, and production and capacity decisions are further causes.

Table 5 – Ten largest reserves of phosphate rock, according to (USGS, 2016)

Phosphate rock reserves	
1. Morocco (72%)	6. Russia (2%)
2. China (5%)	7. Jordan (2%)
3. Algeria (3%)	8. Egypt (2%)
4. Syria (3%)	9. USA (2%)
5. South Africa (2%)	10. Australia (1%)

Classification of available sources of phosphate rock is done using a technique that is based on the original McKelvey box for investigating mineral resources (McKelvey, 1972). Using a slightly adapted classification the available sources can be divided into reserves, resources and resource base (chapter 3 of Tilton, 2003). The resource base is the full amount present in the

Earth's crust and resources are those sources that cannot be mined economically. Reserves are sources that are both identified and economically extractable. It is clear that exploration – identification of reserves – is induced when the market price of phosphate rock increases. Reserves then increase and a new mine might be opened. The total amount of reserves available on the market currently is 69 billion tonnes of phosphate rock relative to a 2015 production of 223 million tonnes (USGS, 2016). Exploration might also be induced by new exploration technology becoming available making it easier or cheaper to explore the underground for new reserves (Tilton, 2003). Exploration takes considerable time and there are significant sunk costs that might not be regained (de Ridder et al., 2012).

Market aspect #1: Phosphate rock is an exhaustible commodity (*exhaustibility*) and its reserves are distributed highly unevenly across a small number of countries (*uneven distribution).* High prices trigger exploration for more reserves, becoming available with delay (*explorative delay*).

Production of phosphate rock mostly takes place from sedimentary reserves (USGS, 2016). Ore grades however strongly differ between different locations and thus different levels of beneficiation are needed. Also the cost of mining phosphate rock at different locations differs. Other causes of cost differences include: capacity utilisation of the mine, mine size, deposit quality, mine age and transportation cost (Al Rawashdeh & Maxwell, 2011; Gustin & Idoniboye, 2015; Mew, 2016). Transportation costs are a relatively important part of production costs because of the comparatively low value of phosphate rock (Al Rawashdeh & Maxwell, 2011). Phosphate rock increasingly needs to be cleansed of heavy metals, this might in the longer term increase costs due to the development of new processing steps to separate heavy metal contaminations with as much as 10 $/ton (von Horn & Sartorius, 2009). Cost differentiation between different producers is relatively large: production costs range between 13 and 93 $/ton (mining and pre-treatment, Mew, 2016).

When exploration has been undertaken, identified but not yet mined reserves have thus increased. Then financial analysis of the available reserves is undertaken. This analysis may give rise to the mining company deciding on increasing its capacity (Heckenmüller et al., 2014). Both the exploration decisions as well as the capacity decisions are made recurrently in time. This is done when: new reserves become available, the phosphate rock market price changes, or technological mining capabilities increase. New production capacity of phosphate rock comes available after a period of 5-10 years (de Ridder et al., 2012; USGS, 2016). Thus, rock price information can only be fully incorporated into mining companies' capacity decisions with a considerable delay.

Market aspect #2: Phosphate rock mines operate at strongly differing cost rates (*differentiated mining costs*), furthermore they decide upon mining capacity recurrently – looking at market price and technology available – with new capacity only becoming available through investments after a significant delay of about 5-10 years (*capacity decision and delay*).

Trade in phosphate rock is governed by bilateral negotiations and subsequent contracts between suppliers and buyers (von Horn & Sartorius, 2009). Currently, the only major exporters of phosphate rock include Morocco and some countries in the Middle East (Heckenmüller et al., 2014; International Fertilizer Association, 2016). Together they form more than three quarters of world exports of phosphate rock. Examples of bilateral contracts for the supply of phosphate rock include the supply of phosphate rock by OCP to Potash Corporation in the United States (Taylor & Moss, 2013). But also delivery by OCP to European buyers and Indian buyers (ICIS News, 2012).

The contents of the contracts including agreed-upon prices are notoriously hazy (see also the discussion in Tilton, 2003, chapter 4). Some general principles can be noted; prices are generally determined using *free on board* constructions. This means that the seller ships the phosphate rock to a port, where it is loaded onto a ship chartered by the buyer (see an example of an anonimised contract in United States Securities and Exchange Commission, 2005). The contracts are generally renewed every few years: the exemplary contract has a length of 3 years.

Market aspect #3: Trade in phosphate rock is governed by bilateral contracts between miners and fertilizer companies (*bilateral contracts*), through regular negotiations these contracts are renewed (*contract negotiations*).

A further dynamic in the middle part of the value chain is that mining and phosphate rock processing into phosphoric acid and fertilizer products are increasingly under the ownership and control of a single firm (de Ridder et al., 2012). The value chain is increasingly vertically integrated. This can also be seen from the fact that world trade in phosphate rock is comparatively small when compared to phosphate fertilizer trade: only 15% of phosphate rock produced is being traded (International Fertilizer Association, 2016). Vertical integration proves a profitable business: cost advantages of mining higher-grade phosphate rock can be combined with economies of scale to produce large margins on the fertilizer markets (de Ridder et al., 2012). Al Rawashdeh & Maxwell (2011) note that large mining companies could reap hundreds of millions of revenues extra by processing rock themselves. The number of companies and type of companies active in the phosphate value chain changes over time.

Market aspect #4: Phosphate rock mining companies increasingly also control phosphate rock processing to phosphoric acid and phosphate fertilizers (*vertical integration*).

In the middle part of the value chain a number of different phosphate fertilizers are produced. Before these fertilizers can be produced, phosphate ores are beneficiated to produce marketable grade phosphate rock (USGS, 2016), containing about 30% P_2O_5 (Heckenmüller et al., 2014). Due to grade differences, together with the occurrence of heavy metal contamination, phosphate rock is not a fully homogeneous product. As discussed in section 1, a fraction of phosphate rock is not used for fertilizer production, about 8-9% is used for food additives and 9-10% is used in other industrial applications (Heckenmüller et al., 2014). Furthermore the phosphate fertilizer chain typically starts by producing phosphoric acid (PotashCorp, 2014), this acid plays a central role in the value chain of phosphate fertilizers. Furthermore, numerous fluid and granular fertilizers are then produced: superphosphates and mono-ammonium phosphate (MAP) and di-ammonium phosphate (DAP) as well as complex fertilizers that also contain potash and nitrogen (Cordell & White, 2014). The fertilizers have different applications. See Table 6 for the chemical background.

Table 6 – An overview of phosphate fertilizer products (Rutland & Polo, 2005)

Type of fertilizer	*Chemical formulae*	*Type*
Phosphoric acid	H_3PO_4	Semi-processed product
Diammonium phosphate	$(NH_4)_2HPO_4$	Multi-nutrient
Monoammonium phosphate	$NH_4H_2PO_4$	Multi-nutrient
Single superphosphate	$Ca(H_2PO_4)_2 \bullet H_2O + 2CaSO_4$	Single-nutrient
Triple superphosphate	$3\ Ca(H_2PO_4)_2 \bullet H_2O$	Single-nutrient
NPK	*various*	Complex, blended

Market aspect #5: The value chain of phosphate rock and phosphate fertilizer consists of different fertilizer products (*numerous fertilizers)*; beneficiation is needed before trading in case of grade ore differences and contaminations (*beneficiation for trade*).

After phosphate rock has been traded production takes place in large-scale facilities. As was also seen in the preliminary analysis of section 1, production of phosphate fertilizers mainly takes place in the United States, China, India and Russia (FAO, 2013; Hernandez & Torero, 2010, 2013). The general structure of the market is reminiscent of the structure of the phosphate rock market, as exchange is governed by bilateral contracts too (ICIS News, 2012). Furthermore – use of phosphate fertilizers happens all over the world in many regional markets – buyers are many (Taylor & Moss, 2013). Trade towards end consumers is executed via wholesale and retail traders, there is both trade in bulk and in 10 or 50 kg packages (see for instance, for a detailed analysis of West African markets, Johnson, 2011).

Market aspect #6: Trade in phosphate-containing fertilizers is governed by bilateral contracts between fertilizer companies and fertilizer importers (*bilateral contracts*). Trade takes place in a whole range of phosphate fertilizers via importers and subsequently wholesale and retail traders (*numerous fertilizers, numerous traders, numerous regional markets*).

Demand for phosphate is almost fully determined by agricultural applications, 90% of phosphorus flows are used in agriculture (Heckenmüller et al., 2014). Phosphate is essential in the realization of high productivity returns in numerous agricultural applications, there does not exist a substitute for phosphate in this role (USGS, 2016). Phosphate is applied to soils that do not yet contain enough of it to feed plant growth. The added phosphate is then partially taken up by crops grown on the land, as well as buffered in the ground water, and finally leeched off the land. Every crop needs different amounts of phosphorus concentrations for optimum productivity, whereas after the optimum amount there is no added productivity any more from using more fertilizer (Syers et al., 2009). Countries with problematic, low indigenous phosphorus concentrations include Argentina, Bangladesh, Russia as well as countries in Western Africa (Cordell & White, 2014). There is an intricate connection between phosphate soil deficiency or surplus and resulting demand for phosphate. Over- and under-application of phosphate fertilizers for anthropogenic reasons pose grave problems too.

Fertilizer use is very important to food production. Demand is price inelastic (von Horn & Sartorius, 2009). Estimates of price inelasticity are however difficult to give, as note Gruhn et al. (1995). It is clear that there is a price plafond above which agricultural end-users will refrain from buying their normal amounts of fertilizer, this price plafond was reached in the 2009 price spike at about 1200 $/ton of DAP (Mew, 2016). In the longer term however, when soil phosphate buffers again empty after a seasonal decline in application, phosphate fertilizer demand snaps back. With a growing world population fertilizer demand is projected to grow strongly (FAO, 2015). This demand growth mainly takes place in countries such as Brazil, India and China. Without phosphate fertilizers food security is at risk: the root of all civilization is being affected.

Market aspect #7: End-use demand for phosphate rock and phosphate fertilizers is almost fully in the agricultural sector (*agricultural end-use*), demand is price-inelastic in the short term, price elastic in the medium term due to soil buffering capacity and inelastic in size in the long term due to the lack of a substitute for phosphorus in growing feedstock, food security is thus at risk (*demand inelasticity and food security connection*).

Recycling of phosphorus flows is strongly connected to demand development. In the last few years, scientists and policy makers have again warned for the environmentally external problems that leeching of phosphorus flows and subsequent eutrophication of rivers and seas (Elser & Bennett, 2011) – although these problems have already been acknowledged as early as the 1970's. This renewed call has given rise to increasing interest in being able to recycle phosphorus flows after their use – both for reasons of reducing phosphate rock dependence as well as reducing environmental externalities. This movement can be seen by attention garnered on for example the European level. Legislation as well as awareness platforms such as the European Sustainable Phosphorus Platform focus on stimulating action towards increasing recycling of phosphorus flows.

Recycling measures include recycling of human excrements and wastewater amongst many other (Cordell & White, 2013). Recycling then happens via differing methods: i.e. via compost, incineration, fermentation et cetera (Egle et al., 2015). The best-developed method of recycling phosphorus flows currently available regains struvite from wastewater (Kataki et al., 2016; Le Corre et al., 2009), this can be used as a marketable substitute for primary phosphate fertilizers (Talboys et al., 2016). An important concern to the applicability of recycling measures includes its relative competitiveness compared to using fertilizers from primary phosphate rock (Cordell & White, 2013). In the near future it is simply too expensive – without government intervention – to recycle large amounts of phosphorus.

Market aspect #8: Technological possibilities of recycling phosphorus flows are many and their application is recognized as an essential policy measure for sustainable phosphorus use (*potential of recycling*); their practical, cost-efficient application is however still lacking (*lack of practical application*).

4.2 Oligopolistic structure and oligopolistic behaviour

After completing the description of the above eight market aspects of the phosphate market, the focus can be drawn to the oligopolistic structure of both the phosphate rock and phosphate fertilizer markets. Firstly, due to the uneven distribution of geological reserves of phosphate rock over the globe (see market aspect #1), the market for phosphate rock has a highly oligopolistic structure. General economic reasons such as high barriers to entry and economies of scale – rooted in the large capital requirements of phosphate rock mining – typically exacerbate this effect. There are thus simply few sellers and many buyers for phosphate rock. Although, the structural observation of high concentration is counteracted by the dynamics of vertical integration implying a decrease in the number of buyers and smaller global trade in phosphate rock.

The market for phosphate fertilizers comparably also has an oligopolistic structure. The phosphate fertilizer market has a high and increasing concentration. Global market shares of the five largest producers on markets of all phosphate fertilizers are between 50% and 70% (Hernandez & Torero, 2013). Within some countries similar or even higher market shares fall onto a few companies only. Numerous other factors play a role in the prevalence of high concentrations on fertilizer markets, including: inelastic demand due to usage for feedstock production and high barriers to entry due to high capital requirements of building fertilizer plants (Taylor & Moss, 2013). There are some counteracting developments to the move of a more oligopolistic market structure. There are for instance movements in the market towards coordinated buying, for instance in China and India buyers group themselves into *powerful buyers* (Taylor & Moss, 2013).

It is generally observed in both the phosphate rock and the fertilizer market that there is (perspective for) oligopolistic behaviour (Cordell & White, 2014; de Ridder et al., 2012). This perspective has also been historically signalled, in the 1970s the presence of a phosphate cartel in the market was hypothesised (Johnson, 1977). Price overcharges have been investigated and it has been hypothesised that the rock and fertilizer price spike of 2008 was partially caused by the market players themselves. They at least gained a lot from it (Taylor & Moss, 2013). It has been shown that the high concentration of the fertilizer markets gives rise to actual higher prices of fertilizer (Hernandez & Torero, 2013). This behaviour has a large impact on the phosphate market.

Both mining companies as well as fertilizer companies are frequently in state ownership (OCP in Morocco, JPMC in Jordan, GPC in Tunisia). This shows that there is a strong government presence on the market, and that there might be companies that pursue completely different goals than simple profit maximization (McCorriston & MacLaren, 2007), this might distort trade further (Hoekman & Martin, 2012). There is also a move of oligopolisation: in China smaller market parties are pushed out of the market by the government, seemingly for reasons of environmental regulatory efficiency (de Ridder et al., 2012). In conclusion, the role of governments on the phosphate market is strong and possibly increasing, this will be seen too when describing the next market aspect.

Market aspect #9: Both the markets for phosphate rock and phosphate fertilizers have an oligopolistic structure (*oligopolistic structure*), oligopolistic behaviour is observed as well as an increasing influence of state ownership (*oligopolistic and state owner behaviour*).

4.3 Export restrictions

In recent years exporting countries have noticed their phosphate might very well be of humongous strategic importance. In response they have restricted trade in a number of possible ways. For instance, China has levied hefty export tariffs on phosphate rock and phosphate fertilizers (de Ridder et al., 2012). The underlying motifs of the Chinese government have been to strategically restrict export of fertilizer well as insulate the domestic market from price volatility on the global market (Persona, 2014). Furthermore, the Chinese policy has probably been given in by industrial policy goals of stimulating fertilizer production within its borders (Espa, 2015). In the absence of severely alleviated global market prices the Chinese government has recently retracted its trade restrictive measures, but in future times of volatile prices these measures – or similar export restrictions implemented by other countries – might very well snap back.

Government regulation is not the only reason for restrictions imposed on the phosphate market. Reasons for production restrictions include geopolitical events such as the current civil war in Syria, or local labour conditions. Good (2015) provides the example of Tunisia's resource wars on phosphate mining. There is also environmental regulation that is relevant for mining companies and fertilizer companies (de Ridder et al., 2012). The implications of such events are also felt both in the domestic market and the global market.

Market aspect #10: The phosphate market has been and is characterized by export restrictions and production restrictions due to government intervention and geopolitical events (*presence of export and production restrictions*); export restrictive measures might very well be used again by exporting countries' governments (*perspective of export restrictions in the future*); the effect of these export restrictions are both felt on the domestic market of the exporter as well as on the global market (*effect of export restrictions*).

4.4 Background on export restrictions

To better understand the incidence of export restrictions as well as their underlying reasons and effects, it is good to provide some background information. The increase of the usage of export restrictions for all kinds of goals on the phosphate market is part of a broader move towards protectionism and resource nationalism that has been seen on amongst others the commodities markets (Dannreuther & Ostrowski, 2013; Qasem et al., 2011). Commodity markets are seemingly in a special position both for reasons of their strategic importance and because of the large extent to which some economies depend on them (World Trade Organization, 2010). Furthermore, export restrictions are far more effective on markets with high levels of concentration, because diversification possibilities for importers are simply limited. The move towards more state presence on the commodities markets has resulted in the increasing use of trade instruments on metals and minerals markets (Datt et al., 2011; Espa, 2015; Fliess & Mard, 2012; OECD, 2016). Export taxation and quota as well as other measures such as exporter licensing schemes have been used on multiple minerals and metals markets.

Reasons for instituting export restrictions vary: to strengthen a country's terms-of-trade, to stabilize prices and income from exports, to reduce inflationary pressures, to favour certain sectors in a political economic way or to easily collect government income from taxes (Fung & Korinek, 2013; Piermartini, 2004; Thennakoon, 2015). Effects of these export restrictive measures are felt both on the domestic markets (as is the intention of the measure) as well as on the global market (Fung & Korinek, 2013; Gandolfo, 2014). In the case of an export tax, domestic consumers of the raw material profit, because the material becomes cheaper for them. Domestic suppliers, however, receive a lower price for their products. An export tax thus effectively subsidises the downstream industry (Latina et al., 2011). On the global market, there is a higher price and thus consumers lose out, whereas competing suppliers might gain. There are also broader employment and service delivery effects of export taxes (Fung & Korinek, 2013). The precise welfare effects depend on sizes of all the previous effects, for exporting countries it might be profitable to institute an export restriction. In conclusion, export restrictive measures can have significant effect on supply and demand imbalances.

4.5 Phosphate as an important case study

The phosphate market aspects presented above uniquely represent that market. Of course, many of the aspects identified also hold for other commodities. A lot of commodities such as copper, rare earths, bauxite, are exhaustible. A notable exception includes agricultural commodities grown seasonally. Capacity and investment decisions are important in all commodity value chains. Demand for some other commodities is also inelastic.

Yet, the combination of three market aspects distinguish the problem of phosphate scarcity: the extremely uneven distribution of reserves, the lack of a substitute to phosphate fertilizer and therewith the critical dependence of food security on fertilizers, and the highly specific way in which demand is dependent on phosphorus soil buffering capacity. Although, rare earths have a far more concentrated production (Bastein & Rietveld, 2015). Although, there are more materials for which there is no substitute in its main application such as lead, copper and many of the rare earths (Graedel et al., 2015). Without phosphate fertilizer modern agriculture would be far less productive and food security would definitely be damaged. It is thus fully worthwhile to focus on phosphate market development. To be able to model the phosphate market the presented, specific market aspects were to be taken into account as much as possible in the quantitative phosphate market model.

5 Requirements analysis

Requirements for a quantitative model of the phosphate market are now specified. These requirements are of both a general nature as well as of a case study-specific nature, they are discussed in section 5.1. The quantitative model has been specifically designed to study the long-term development of the phosphate market, to investigate the determinants of phosphate market imbalances and to more specifically derive the effect of export and production restrictions on phosphate market imbalances. In section 5.2 it is shown how these requirements are translated into building blocks for a quantitative phosphate market model.

5.1 Criteria for a quantitative model

To take the frequent criticisms of material criticality assessments into account both the dynamical nature and the uncertainty inherent to commodities markets are explicitly modelled. Strongly connected to the dynamical nature of the market is the time scale on which the model is simulated. A relevant time scale for the long-term analysis is 85 years. The explicit effects of trade restrictions are investigated on the time-scale of 15 years. Then, investment effects can be seen and the dynamics inherent to multiple restrictions in a row can be shown. To provide applicable policy recommendations the model has an empirical basis: the model is initialized using empirical data on production, trade and consumption as presented in section 1 and 4 of this document. The model also provides flexibility and ease-of-use to the analyst.

Further conditions for constructing a suitable quantitative model include a number of aspects that are at the intersection of the market being described and the type of conclusions that need to be found. Roughly speaking, the model describes the workings of the phosphate market; it represents mines and processing facilities as well as trade and demand for rock and fertilizer. It also describes the market's hypothesised oligopolistic structure and the resulting oligopolistic behaviour. On top of this, the model is able to describe export and production restrictions and its effect on both exporting and importing countries. Both generic essential market aspects as well as those applied to oligopoly economics and restrictions have been described extensively in the previous section. For the provision of policy recommendations the effect of such policy measures as recycling and strategic buying that can be instigated by the European Union are also modelled. The set of criteria is more completely described in Table 7.

Table 7 – Set of criteria for a quantitative phosphate market model

1	Capture the **dynamics and uncertainty** of the phosphate market;
2	Describe the phosphate market from an **empirical basis**;
3	Provide **ease-of-use** to the analyst;
4	Capture the **workings of the phosphate market** (aspect #1-#8);
5	Capture the **oligopolistic structure** of the market and the **oligopolistic behaviour** exhibited by market players (aspect #9);
6	Determine when oligopolistic market players use which instruments of **oligopolistic behaviour** that they have available (aspect #9);
7	Determine when exporting countries use **export restrictions** (aspect #10);
8	Determine when **production restrictions** strike (aspect #10);
9	Determine what is the **effect** of oligopolistic behaviour and export and production restrictions on imbalances between supply and demand;
10	Determine what is the **effect of policy measures** taken by importers in Europe.

5.2 Quantitative model components

The choice for components of the commodity market model has been made by structurally investigating the implications of criteria as specified in section 5.1 for the quantitative model to be developed. Translating every criterion into generic model components the building blocks out of which the quantitative model have been built were derived. The reasoning that is used is shown in Figure 7. Every criterion from the list presented in the previous section was translated into an underlying basic model aspect, which was translated into a result for the model on what it should be able to do.

Quantitative model building blocks have been found that indeed have the needed function. An example of this reasoning can be found by looking at the criterion of exhaustibility, uneven distribution and explorative delay – market aspect #1. The underlying basic model aspect is then that there need be some kind of reserves modelled which include a certain conception of size as well as be able to become bigger if exploration takes place. The model should thus be able to model reserve size as well as the decision to explore extra resources. In conclusion, it is found that the model should contain a dynamic reserve of phosphate rock – the first quantitative model building block.

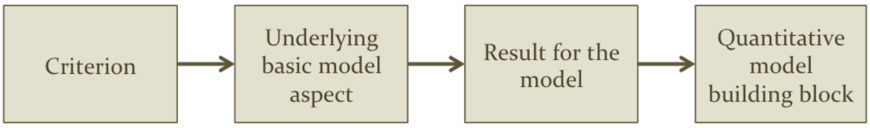

Figure 7 – Line of reasoning for quantitative model building blocks

By continuing such a systematic investigation it has been found that the quantitative model should contain model components as shown in Table 8. The components could not have been readily combined into one working quantitative model. Decision-making mechanisms, market clearing mechanisms and dynamic reserves all operate using different quantities, time scales and programming implementations. They are however all necessary to construct a quantitative model that can capture the hypothesised phosphate market characteristics.

Table 8 - List of quantitative phosphate market model building blocks

- ✓ A dynamic reserve and resource base of phosphate rock
- ✓ Decision-making mechanisms for mining companies on exploration and capacity
- ✓ The functional forms that provide the translation of production into phosphate rock, and P_2O_5-flows on the market (i.e. describe the technical value chain)
- ✓ Regional market-clearing mechanisms for both the phosphate rock and fertilizer markets (on which domestic and imported production compete) that take oligopolistic structure and possible resulting behaviour into account
- ✓ Decision-making mechanisms for market parties (possibly state-owned) to decide on when and to what extent they use their market power (including connections to the relevant market clearing mechanisms)
- ✓ Decision-making mechanisms for exporting countries governments to decide when they use what export restrictive measures (including connections to the relevant market clearing mechanisms)
- ✓ The market network structure to be able to describe transportation costs
- ✓ Functional forms to describe the demand of phosphate rock and fertilizer products on all regional markets
- ✓ Functional forms to describe the usage of recycling as well as its relative costs to employing phosphate rock for fertilizer products

Part 3 – Global Phosphate Market Model

6 Quantitative phosphate market model

An aggregated global phosphate market model is now presented. This version of the model is used to investigate endogenous market development of the phosphate rock and phosphate fertilizer market over the coming 85 years. In section 6.1 the construction of the quantitative model from the model building blocks found in the previous section is discussed. Section 6.2 states the overarching, computational implementation of the model as consisting of computer objects. In section 6.3 generic model control scripts are discussed and the sequence of model procedures used to simulate the phosphate market model is given.

6.1 Quantitative model construction

The list of quantitative modelling building blocks has been combined into a model structure, which is shown in Figure 8. This model structure represents a strongly conceptual view of the global phosphate value chain consisting of rock production in mines and fertilizer production in processing facilities. The value chain contains two marketplaces – one for rock and one for fertilizers. Demand for rock on the upstream market is formed mostly by the producers of fertilizers – there is also a small part of direct end-use. End-use demand for fertilizers completes the value chain at the downstream side.

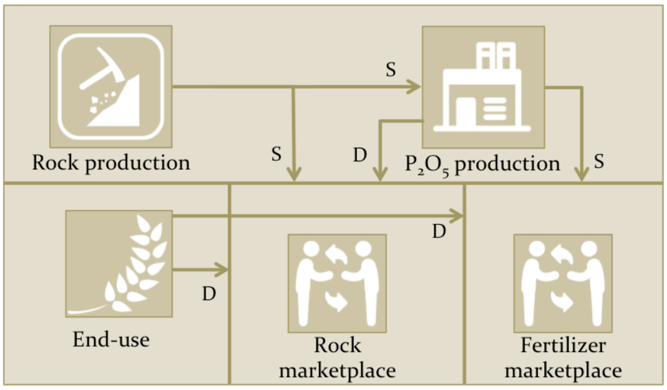

Figure 8 – Overview of the aggregated model structure, flows described include supply (S), demand (D)

For practical and computational reasons it has not been possible to fulfil the requirements of a phosphate market model to the utmost extent. Firstly, some different aggregations have been used. Fertilizer products have been aggregated into P_2O_5-containing products. Multiple smaller traders into one conceptual market player. For all proposed model building blocks there are a number of possible implementations coming from different original modelling methodologies. Every component has been implemented in such a way that the model is implementable with a reasonable investment of time and effort –fulfilling the condition of ease of use for the analyst. All this makes sure that the model is computationally tractable.

The model structure contains a dynamic reserve of phosphate rock, although its size is not explicitly calculated. Exploration is not decided upon, mining companies can simply mine at a certain extraction cost – which increases when cumulative output from the reserve increases. Mine capacity decisions are made effectuating with a delay. Rock flows are functionally translated into P_2O_5-flows. In terms of markets, the proposed model structure only has a single marketplace for both rock and fertilizer, thus transport costs between different markets cannot be reflected (yet). In the model implementation the market is solved such that market parties always use their market power. Thus market price always reflects the market power of suppliers – they do not separately decide upon this. Ownership of companies varies, some companies are of an integrated nature and others are specialised. Vertical integration dynamics over time cannot easily be simulated in the current implementation. The total market share of each type of company however does differ due to diverging investment decisions. Both rock and fertilizer demand is represented in demand curves. These curves are a conceptual substitute for seller-buyer negotiations. Herein, the dynamics of negotiations and inflexibility of contracts cannot be fully taken into account. The current implementation has been chosen for reasons of practicality.

6.2 Quantitative model implementation

The quantitative model structure shown above has been turned into a programming model. In such a programming model it is possible to represent all of these types of components as computer objects. Structural market change can be implemented over time as well as long-term projections can be generated (cf. with Labys, 1999 on programming models). The quantitative model is implemented in a Python programming environment. The reason for choosing a pure Python implementation is mainly in the flexibility it provides through strong object orientation (Goldwasser & Letscher, 2014). The different components of which the model consists are the following – they are described in appendix 1 – an overview of the model structure is shown in Figure 9:

- **Objects** representing reserves that are mined, companies mining phosphate rock and making decisions on capacity utilisation and investment in mining and processing capacity, and buyers that have certain aggregated characteristics on price and demand
- Objects representing **stock flow structures** representing two ageing chains – per company – for mining and processing capacity respectively, being constructed, in operation and being decommissioned due to end-of-lifetime and being unprofitable
- Interaction between objects in Cournot-Nash **market clearing mechanisms** representing non-cooperative oligopolistic market behaviour implemented using a quadratic optimisation solver for the rock and the fertilizer market
- A set of **generic control scripts** creating all objects and their relations, keeping time of the different parts of the model is implemented and lastly sequencing object interactions

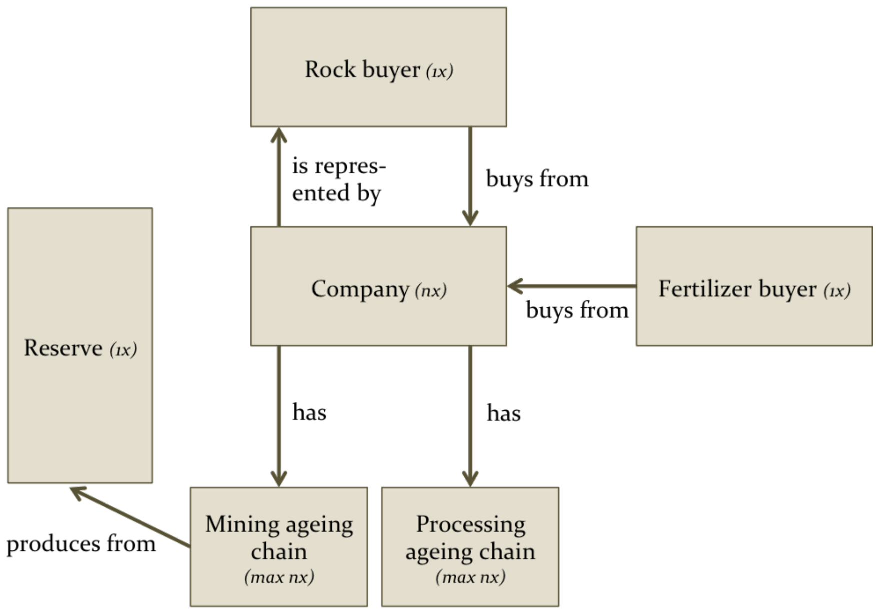

Figure 9 – Quantitative model object structure of the aggregated phosphate market model

6.3 Generic control scripts

To govern time synchronisation of the different model parts, a number of generic control scripts are needed. These scripts roughly have three functions: (i.) creating all objects, their attributes and methods, and the relations between objects, (ii.) time keeping, (iii.) providing sequencing of all object interactions. The creation of objects and relations between them is performed in an initialisation phase in which all company objects, reserve objects and buyer objects are instantiated under the right parameters. Using these parameters the model can be fitted to an empirical situation of the modeller's choice. See the next section for the chosen operationalization describing the global phosphate market model.

Some generic control scripts govern time keeping. As noted above, the stock flow structures run using a numerical integration script. Such procedures as market clearing take place in discrete time steps that can be thought of as rounds of buyer/seller-negotiations. The solution that has been chosen for this time synchronisation problem is to run the stock flow structure for a quarter, after which information on capacities is the input to the market of the quarter. Then, companies decide on their capacity utilization and capacity investment and divestment in the next quarter. This hierarchical combination of continuous and discrete time axes amounts to a practical solution to explore plausible market development. Lastly, the model provides sequencing to govern model simulation. Model simulation amounts to the running of multiple sequences of interactions between all objects that the model is constituted of. The sequencing of procedures is shown in Table 9. The complete model has been thoroughly verified and validated against real-world observations, the results of these processes are shown in Appendix 4.

Table 9 - Sequencing of model procedures in the quantitative phosphate market model

1	Run the stock-flow structures for a quarter
2	Calculate resulting production of rock and P_2O_5
3	Store the produced rock and P_2O_5
4	Add amounts of rock produced from the reserves to its cumulative output
5	Calculate each company's extraction and processing costs
6	Clear the market for P_2O_5 (i.e. find imperfectly competitive equilibrium)
7	Update capacity utilisation, investment and divestment in P_2O_5-producing facilities
8	Determine demand for rock that will be used next quarter
9	Clear the market for rock (i.e. find imperfectly competitive equilibrium)
10	Update capacity utilization, investment and divestment in mines
11	Update fertilizer demand for next quarter

7 Demand-supply imbalances over 85 years

An aggregated version of the model is used to investigate endogenous market development of the phosphate rock and phosphate fertilizer market over the coming 85 years. This chapter presents the experimental motive as well as the experimental design itself and the experiment results on endogenous development of the phosphate market over the next 85 years.

7.1 Experimental motive and empirical basis

The experiments are used to understand phosphate market dynamics over longer time periods and the determinants of market imbalances under conditions of large uncertainty. By developing a quantitative notion of the longer-term endogenous development of the phosphate market it is possible to sketch the framework within which export restrictions influence the market. A broad set of plausible market dynamics is shown over numerous uncertainties. This is necessary to provide for a robust overview of the problem of phosphate scarcity. Experimenting with this endogenous quantitative market model, it is possible to sketch a view of the influence of market parameters such as extraction cost over time, company investment behaviour and vertical integration in the phosphate value chain.

Worldwide, generic economic scarcity of rock and fertilizer can be investigated with the quantitative model setup. The model used does not implement different regions. There are no transport costs implemented for hauling between different regions. Thus export restrictions can also not be modelled. These are per definition only levied on trade crossing borders. It is thus not possible to investigate regional scarcity with this model implementation. Exogenous developments such as policy measures taken by European importers as well as export and production restrictions are also left for the second set of model experiments. In the chosen configuration the model is computationally tractable to be run for long periods of time over a large number of experiments. Plausible global phosphate market dynamics under broad uncertainties can be scrutinised.

7.2 Experimental setup

To declare an experimental setup a large number of parameters on different levels of the phosphate market – on global level as well as on company level – need to be set. More elaborate explanations including sources for all experiment parameters are available in Appendix 5. The first set of parameters is constituted of three parts. The parameters are presented in Table 10.

Firstly, there are six parameters describing reserve and therewith primarily extraction cost properties. These parameters are needed to construct the extraction cost curve as a function of cumulative output from the reserve. The values are estimated to approximately fit the real world situation in terms of known reserves (about 70 billion tonnes of phosphate rock, USGS, 2016) and their extraction costs (between 13 and 90 $/ton, Mew, 2016). The workings of the extraction cost curve function are further described in section 6.2 above. Two values of lost production as well as maximum and stable demand are used to construct the kinked demand curve that governs fertilizer buyer demand. These parameters are set such that price elasticity of demand for fertilizer is low in normal price ranges, but at the same time there still is a plafond to the utility that farmers reap from using fertilizer. In reality this plafond is different for every buyer of which the fertilizer buyer aggregate object is made up. The reason to not include different buyer agents is a limitation on the number of different types of model mechanisms that could be taken into account in this study.

The parameters of basic demand growth, amplitude and period long cycle are used to construct time trends for fertilizer demand. With the help of these parameters time trends for these variables are constructed. Demand growth is roughly based upon FAO (2015), it is also checked with long-term scenarios as used by Van Vuuren et al. (2010). Processing cost growth parameters are also used to sample different time trends for processing cost over time. Lastly, the two construction parameters and lifetime parameters form essential parameters in the stock-flow structures that describe mine capacity and processing capacity.

Table 10 – Global parameters for aggregated phosphate market model

Variable		
Initial rock cost	Value of lost production, low	Minimum processing cost growth
Initial rock price	Stable fertilizer demand	Maximum processing cost growth
Initial reserve	Maximum fertilizer demand	Construction time mine
Shape extraction cost curve	Basic demand growth	Lifetime mine
Extraction cost jump	Amplitude long cycle demand	Construction time processing facility
Extraction cost jump speed	Period long cycle demand	Lifetime processing facility
Value of lost production, high	Period shift demand	

Market structure parameters are also varied, as shown in Table 11. Parameters include the number of companies, the market type, integrated or separated, company size distribution, as well as initial processing and initial mining capacity. Together these parameters determine the market concentration in both the phosphate rock and the phosphate fertilizer market. When company size distribution is set to even, all companies have the same initial mine capacities as well as processing facilities – provided they are of a company type that has such facilities. In case of uneven size distribution specialised companies are twice as big as integrated companies (in both mining and processing). Furthermore, the size of initial processing and initial mining are varied such that both initial situations of under- and over-capacity are simulated. Sampling over these market structure parameters makes sure that conclusions on longer-term phosphate scarcity under different market structures can be drawn.

Table 11 – Global parameters used to determine rock and fertilizer market structure

Variable		
Number of companies	Company size distribution	Market type
Initial mining relative to processing	Initial processing relative to demand	

The last set of parameters in Table 12 describes individual company parameters. By sampling differences in all these parameters, further company diversification is simulated. Almost all of these parameters describe dimensionless variables. Companies are diversified in the extent to which they undertake certain activities – such as what is their preferred mine capacity and processing capacity utilization on the basis of which they decide on investments, called buffer capacity. Further parameters include the rock input buffer: how much rock companies buy on top of their expected own rock demand. The propensities to invest respectively divest in rock-and P_2O_5-facilities are speed factors between 0 and 2 where 0 is the slowest investment or divestment and 2 is the fastest. The minimal margin to input is a key factor in determining rock buyer utility, here a minimal margin on input of 1 means that resulting rock utility will be high. Lastly, two types of supply expectation mechanisms are used. Half of all companies form their expectations on the basis of the memory mechanism, the other half by an adaptive expectations mechanism.

Table 12 – Company parameters to govern cost structure as well as decision-making behaviour

Variable		
Processing cost	Propensity to invest rock	Minimal margin on input
P_2O_5 buffer capacity	Propensity to invest P_2O_5	Expectation type
Rock buffer capacity	Propensity to divest rock	Expectation parameter
Rock input buffer	Propensity to divest P_2O_5	

7.3 Experimental results I

In total 2000 experiments have been run. This amount of experiments gives good insight into the model's behaviour. It is at the same time computationally tractable to be run within a day on the computational setup used. Of course, further exploration of the parameter space is warranted to provide a complete search of the uncertainty space.

Market behaviour is explored by looking at a variety of representative dynamic scenarios generated. Firstly, the ratio of demand and supply of P_2O_5-flows is investigated. Using a hierarchical clustering method (see Appendix 7), ten representative dynamic scenarios are shown in Figure 10. Both situations of scarcity as well as abundance are plausible over the 85 years to 2100. Many runs show that global phosphate scarcity might occur between 2020 and 2060. Yet, in more than 30% of all runs no scarcity occurs at all between 2015 and 2100, with scarcity defined as ratio of demand and supply being over 2. These situations with a lack of scarcity are desirable futures for the phosphate market. To better understand the determinants of scarcity detailed analysis of the ten dynamic scenarios is performed.

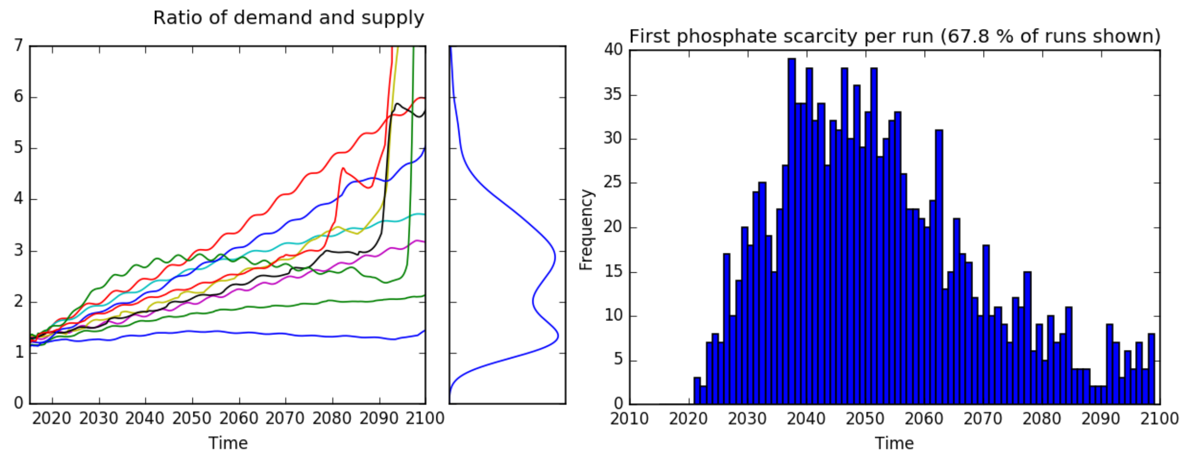

Figure 10 – Left: ten representative dynamic scenarios for ratio of demand and supply to 2100, high values indicate global phosphate scarcity. Kernel density estimate for end values is also shown. Right: histogram of point in time of first situation of global phosphate scarcity for all runs, defined as having a ratio of demand and supply larger than 2. Only 67.8% of runs are shown, in the other runs no global phosphate scarcity occurs during the whole model run

The ratio of demand and supply can be compared to other model values over time within the dynamic scenarios, see Figure 11. In the single run in which ratio of demand and supply is larger than 4 from about 2065 on, mine capacity and processing capacity available in the market does not increase over the whole 21st century. In the single run in which phosphate scarcity does not occur over the whole simulation run, there is apposite investment. Both amounts of capacity in the market are doubled by 2090. Under this dynamic scenario, both the rock price and the fertilizer price do not increase by much over time. In some other plausible futures, the rock price does show large cycles. The trajectories of fertilizer price over time show not that much dynamical behaviour. This is partially to be expected because demand for fertilizer has been modelled relatively simply in an almost exogenous fashion. In the model, the height of fertilizer price is only a limited indicator of scarcity. Further analysis of types of scarcity in the market is in Appendix 7.

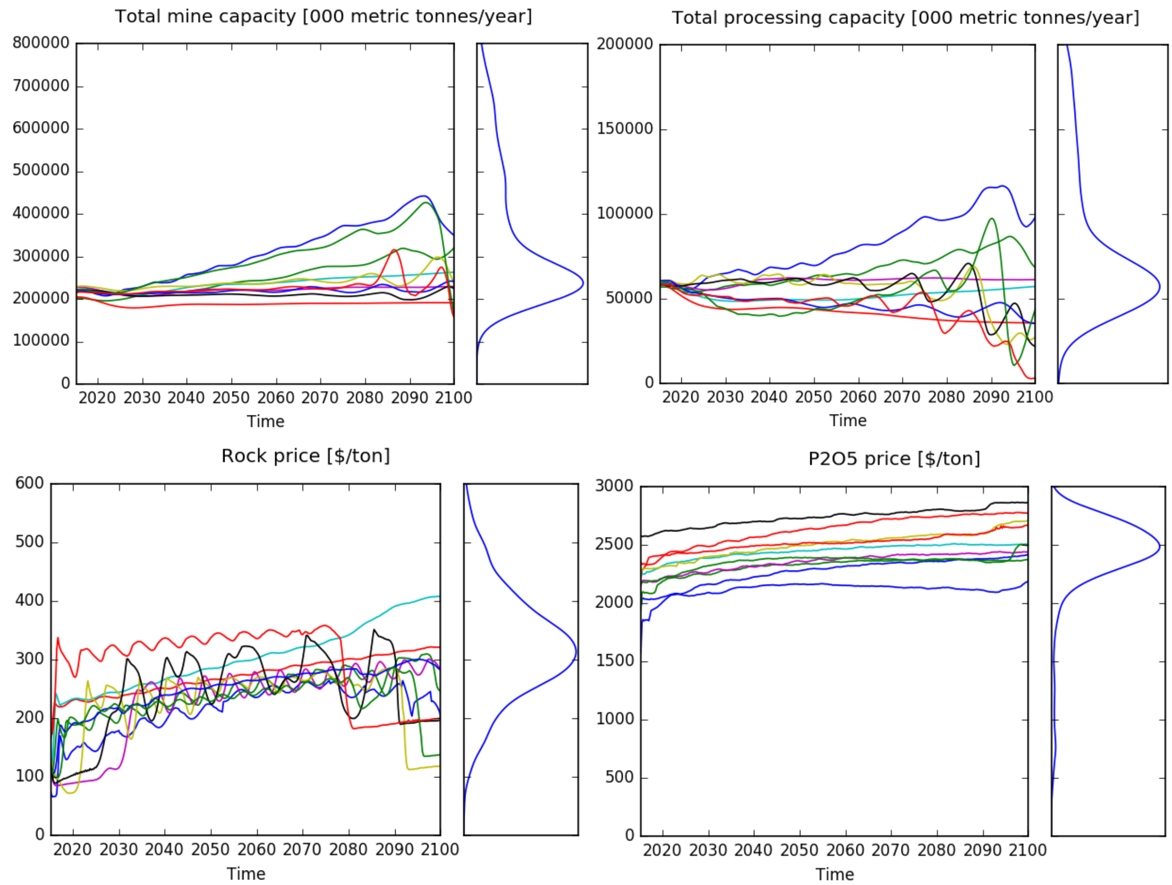

Figure 11 – Ten representative scenarios for total processing capacity ['000 tonnes/year], total mining capacity ['000 tonnes/year], phosphate price [$/ton], and rock price [$/ton] to 2100. Kernel density estimates of end-of-run values are also shown.

It is found that there is a rising price floor in the market: rock price is almost always larger than rock extraction cost at all points in time by between 100 and 200 $/ton, see Figure 12. Only in a few runs does the rock price decrease such that extraction cost acts a real price floor, see the kernel density estimates in the plot. Extremely low rock prices only occur when there is far too much rock on the market. On top of the price floor the phosphate rock price shows further dynamics that reflects rock market structure as well as the situation of over-capacity or under-capacity on the market. The effect of vertical integration is also analysed below.

Cumulative output of rock is projected to be between 9 and 35 billion tonnes of phosphate rock in 2100, see Figure 12. Provided that current estimates of rock reserves are reasonably good, this means that a considerable part of current reserves of about 70 billion tonnes might be used up in the 21st century, but no near end to rock mining is in sight. However if phosphate rock reserves turn out to be much smaller and cumulative output ends up in the top range of the estimate. Then, extreme geological phosphate scarcity occurs towards the end of the 21st century.

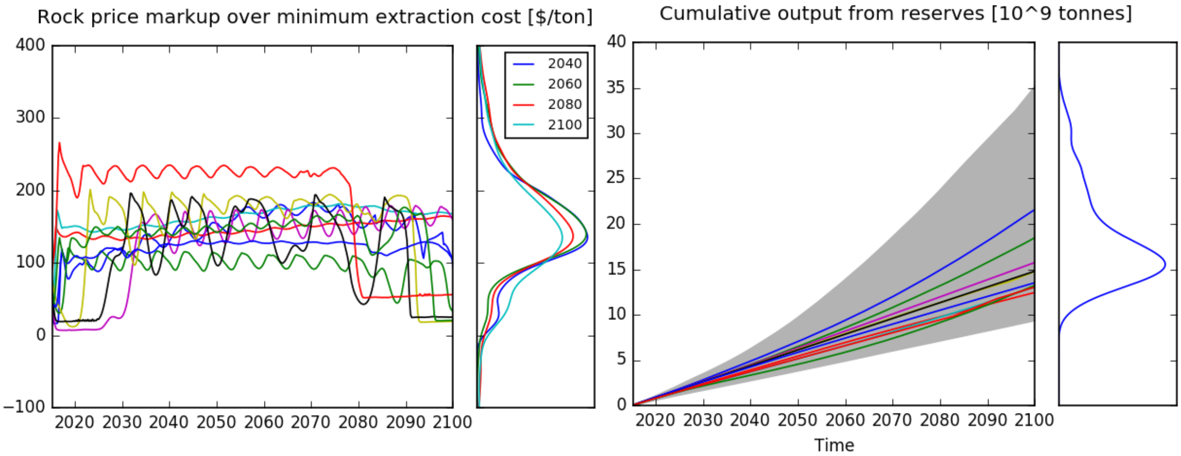

Figure 12 – Left: Ten representative scenarios for rock price mark-up over minimum extraction costs [$/ton]. Kernel density estimates over all runs are shown for 2040, 2060, 2080 and 2100. Right: ten representative scenarios for cumulative output from phosphate rock reserves [10^9 tonnes] to 2100. Kernel density estimate of end values is shown. Shaded area shows full bandwidth of 2000 runs

Heterodox company reactions to phosphate scarcity

Companies react differently in a situation of phosphate scarcity. Firstly, they only have limited market information. In the model they decide upon production by taking into account their own historical market supply and market growth. If they are short on buffer capacity they invest. The workings and the outcome of this decision-making process however differ per company. Companies need to be willing to react by investing in capacity to alleviate the scarcity. An example from the model runs is found by comparing experiments in which the propensities to invest and divest differ in one of three categories: high, low and uneven. Figure 13 shows such a comparison over time, a difference in the occurrence of scarcity is clearly observed. It is found that if companies are willing enough to act on phosphate scarcity over time, extreme phosphate scarcity can be fended off. The majority of experiments run with high propensities to invest and divest result a ratio of demand and supply below 2 in 2100.

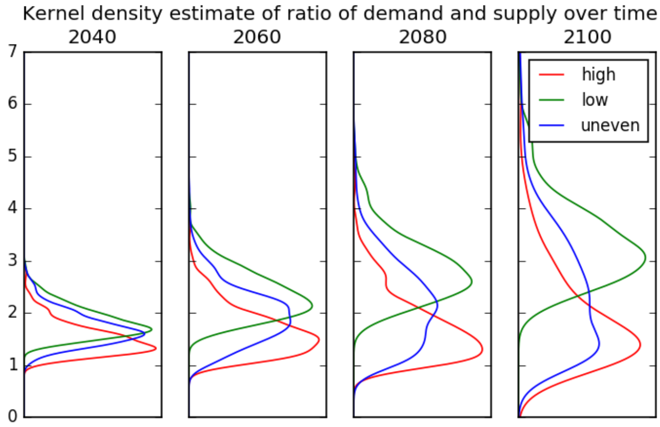

Figure 13 – Kernel density estimates of ratio of demand and supply for 2040, 2060, 2080 and 2100 for respectively high (red), low (green) and uneven (blue) propensities to invest. The distributions are based on 2000 experiments separated in three evenly sized parts

Differences in companies' reaction to phosphate scarcity can even better be shown in the model results by zooming in on one scenario with large propensities to invest and divest. The dynamic scenario earlier analysed in which no phosphate scarcity occurs is taken. Figure 14 shows total and company-level disaggregated data on mine capacity and processing capacity over time. It is found that only two companies active in respectively the rock market and the phosphate market more than double their supply capacity. Yet, all companies had the same decision-making parameters. In this way the interaction between heterogeneous company investment behaviour and overarching market dynamics is seen. In this representative run it is enough for only a few companies to decide on increasing their supply capacity to alleviate phosphate scarcity.

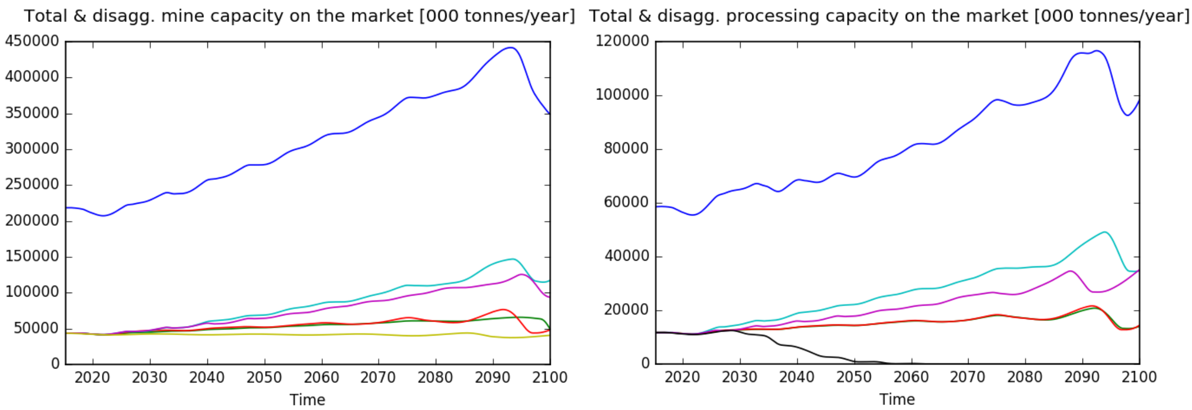

Figure 14 – One representative dynamic scenario for total and company-level disaggregated mine capacity and processing capacity ['000 tonnes/year] to 2100.

Effects of vertical integration

To provide insight into the effect of vertical integration, a comparison is made between runs with an integrated value chain and runs with a separated value chain. In the case of vertical integration the rock market has a liquidity of about 40-100 million tonnes per year over the whole run time, in the separated value chain liquidity stays of about 70-150 million tonnes per year. Figure 15 shows that rock prices are more dynamic under vertical integration. This is found by investigating time series maximum values and time series roughness (inspired by Islam & Pruyt, 2016). Median logarithm of roughness for runs with an integrated market is

4.42 against 4.34 for runs with a separated market. The median of maximum values for rock price is 364 for runs with an integrated market, against 334 for runs with a separated market. Furthermore, both distribution differences are significant at the 1 %-level according to both the Kolmogorov-Smirnov as well as the Anderson-Darling test. See also appendix 10 for more background on these test statistics.

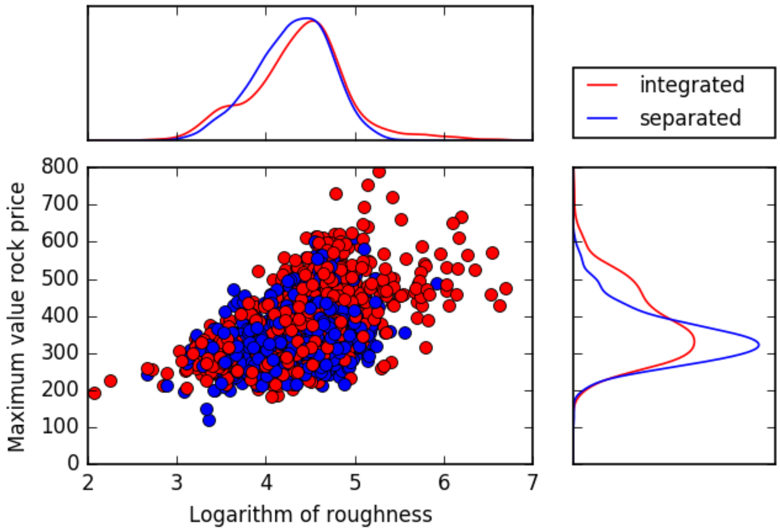

Figure 15 – Plot of logarithm of roughness of rock price versus maximum value of rock price [$/ton] for all 2000 runs. Kernel density estimates for both logarithm of roughness (above) and maximum value of rock price (right) are also shown. Red dots and red density estimates indicate runs with integrated market. Blue dots and density estimates indicate runs with separated market

7.4 Overview of experimental results I

The experimental results have shown that both dynamic scenarios of phosphate scarcity as well as dynamic scenarios of phosphate abundance are possible throughout the 21st century. The model results provide many quantitative representations of these dynamic scenarios. Rising prices are plausible: extraction costs provide a longer term rising price floor in the rock and fertilizer markets. In the model results – signifying the effect of the limited number of market players – rock price mark-up over cost is plausibly about 100 to 200 $/ton along the whole 21st century. Rock price also tends to be more volatile in the model, especially in runs with a vertically integrated phosphate market. In these runs rock price time series over time have a higher maximum value and a larger time series roughness. Cumulative output from global phosphate rock reserves is broadly projected to be between 9 and 35 billion tonnes compared to currently estimated reserves of about 70 billion tonnes. This shows that phosphate rock reserves are plausibly not emptying within the 21st century.

Steady investment in fertilizer processing capacity and rock mining capacity is paramount to fend off phosphate scarcity in the long term. Dynamic model scenarios in which mine capacity and processing capacity is about doubled over the 21st century show no signs of phosphate scarcity arising. In these scenarios companies slightly overreact to situations of phosphate scarcity. Company level analysis of capacity over time has shown the interaction between heterogeneous investment decision-making behaviour and resulting aggregate market dynamics. In an example it was seen that if only a few companies pick up on investment, scarcity is still alleviated. An overview of the experimental results is given in Table 13.

Table 13 – Overview of the results of model experiments of the global phosphate market model

Experimental result	Explanation
1. Plausibility of phosphate scarcity	• Both situations of phosphate scarcity as well as phosphate abundance are endogenously possible market developments • In more than 30% of model experiments no phosphate scarcity arises over the whole 21st century • Cumulative output of phosphate rock reserves to 2100 is projected to be between 9 and 35 billion tonnes • Geological scarcity of phosphate rock is not plausible towards the end of the 21st century provided that current estimates of rock reserves are about right
2. Importance of investment	• The most important determinant of phosphate scarcity is the extent towards which investment in mines and processing facilities suffices to match rising phosphate demand • If mine capacity and processing capacity are doubled over the 21st century scarcity can be fended off, this was reachable in the global market model if companies slightly overreact to phosphate scarcity • Even if only a few companies active in the value chain pick up on investments scarcity can be alleviated
3. Rock price dynamics	• Plausibly rising extraction costs provide a rising price floor in the rock market that is only broken in situations of extreme oversupply • Cost overcharge for phosphate rock price over the whole time scale is between +100 and +200 $/ton with outliers at no overcharge and at +400 $/ton
4. Vertical integration	• Phosphate rock market liquidity is 40-100 million tonnes per year in case of a vertically integrated market versus 70-150 million tonnes per year in case of a separated market • In case of a vertically integrated market rock prices over time show more dynamics: the differences between the distributions are statistically significant and the median of rock price time series maximum values is about 9 % higher and logarithm of roughness is about 2 % higher

Part 4 – Multi-Regional Phosphate Market Model

8 Multi-regional market model with restrictions and policies

This chapter discusses a model implementation that is adapted to the situation of multiple regional markets. The multi-regional version is different than the aggregated phosphate market model in a number of ways. The changes are presented in section 8.1. Sections 8.2 and 8.3 subsequently discuss the modelling implementation of restrictions and importer policies.

8.1 From single-regional to multi-regional implementation

The first step in implementing a multi-regional version of the model of the phosphate value chain was to embed the markets for phosphate rock and phosphate fertilizer in multiple regions. To build a multi-regional model, multiple collections of companies, a reserve and stock-flow structures representing mines and processing facilities have been attributed to overarching region objects. Every region thus has a different reserve object and each of these reserves have a different extraction cost structure. A further extension is in the fact that a spatial implementation of the market clearing mechanism has been implemented. This implementation has been based on Kolstad & Burris (1986) and Kolstad & Mathiesen (1991). Within the framework of this market clearing mechanism, companies have as many decision variables as there are regional markets. The Cournot-Nash equilibrium now is thus a set of supply decisions to the different markets. In the implementation of the spatial oligopoly versions of the phosphate rock and phosphate fertilizer markets, transport costs are calculated when companies want to haul their produce from one to another regional market. Every company is thus present on each of the regional markets, although their marginal costs for supplying to each of the markets differ by the transport cost differences.

Essential market structure differences between regional phosphate markets can also be reflected in this multi-regional implementation of the model. Single companies essentially dominate some regional phosphate markets, for they have both mines and processing facilities, as is the case in for instance Morocco, Jordan and Saudi Arabia. Markets such as the United States and China are however of a less concentrated nature (see also section 1 for a review). On the importer side, differences in regional scarcity are also shown. An export restriction might for instance make it not profitable anymore to export to a foreign market, causing imbalances in relatively distant markets. On the domestic market there is a reduction of scarcity. Lastly, market structure differences between regional markets are reflected to be able to investigate regional effects of export restrictions as well as production restrictions. These effects have been discussed in section 4.4 above.

The empirical basis of the model implementation that has been constructed is such as to be able to model three regions: (1.) Africa and South America, (2.) Europe, (3.) Middle East, Russia and India. It has been chosen to model these regional markets, because from the view of importers in Europe, the other two markets are the most important, as their imports come from these regions. The African market is characterised by the big producer Morocco as well as some smaller producers of phosphate rock such as Tunisia, South Africa, Egypt and Togo. Demand on the African continent is relatively small. Yet, demand in South America is quite large and growing. Europe is implemented as a regional market on which only processing companies are active that are in need of phosphate rock as an input. Demand in Europe is considerably larger, although demand growth is not as large as in Africa and South America. Lastly, the Middle East, Russia and India market is constituted of other exporters of phosphate rock and phosphate fertilizer to Europe: Jordan, Israel, Saudi Arabia and Russia. India has a large demand for phosphate fertilizer. See also Table 14. Total phosphate demand represented in the model is about 50% of current global phosphate demand.

Table 14 – Regional model structure overview

Model region	Rock production by	Model types of company	P_2O_5 demand [t./yr.]
1: Africa & South America	Morocco, Tunisia, South Africa, Egypt, Togo, Peru, Brazil, Mexico	Integrated, processing, mining companies	8.3 million
2: Europe	*None*	Processing companies	2.6 million
3: Middle East, Russia & India	Jordan, Israel, Saudi Arabia, Russia, & India	Integrated, processing, mining companies	9.5 million

Notable omissions of markets that are very much of interest when analysing the world phosphate market are China and the United States. Phosphate demand in these markets is a further 33% of global demand. Exclusion of these markets has mainly been given in by the conceptual and computational difficulties that are inherent to the novel way of hybrid modelling that is implemented. Importers from Europe also do not import much phosphorus flows from other regions than Northern Africa, Russia and the Middle East. Europe does compete for supplies from those regions with such countries as Brazil and India. Thus, these regions have been taken into account. It is acknowledged that a full and more valid analysis of the phosphate market – also from the perspective of Europe – would need to acknowledge the possibly changing role of the United States and China markets too.

To make sure that the model is computationally tractable a further simplification of the model structure had to be made: both the fertilizer demand curve and the rock demand curve has been implemented as a linear curve. In normal price ranges, price behaviour of this demand curve is relatively close to the price behaviour in the model with only endogenous development. However, in higher price ranges the demand curve diverges strongly from the situation of endogenous demand, because there is no real elastic demand-line piece in the current implementation of the demand curve. To prevent prices from fully decreasing below the level of zero companies have a break on putting capacity on the market when the rock or fertilizer price becomes lower than marginal costs. If this is the case they will shut off part of their capacity in the next quarter and therewith refrain from inducing lower prices. This situation only occurs in situation of extreme over-capacity within a regional market.

8.2 Implementation of export and production restrictions

Two types of restrictions are implemented within the multi-regional model of the phosphate market. Firstly, export taxes have been implemented. Governments levy export taxes when goods traverse a customs border (see section 4.3 and further for the empirical background material). These export taxes are implemented in the model as a temporary mark-up over transport costs between different regional markets. Implicitly, single governments do not levy taxes – as is the case in the real world – but all companies within a regional market are affected by export taxes being implemented. The effects of export tax implementation by single governments on both the regional market as well as other regional markets can thus be approximated. It has been chosen to not implement export quota. These are often equivalent to export taxes set at the equivalent level.

The second type of restriction that is implemented is a production restriction. Such production restrictions are effectuated on the phosphate market for a host of reasons. Empirically, production restrictions have been induced for reasons of labour strikes, war or other conflicts (see section 4.3 for the empirical background material). Such production restrictions then may have a severe exogenous limiting effect on mining and processing facility capacity to produce. These constraints are implemented in the quantitative model as hard, exogenously defined constraints on production capacity even before the market is cleared. In this way, a certain form of production quota can thus be implemented, a government is not deciding upon the limit, as in the case of export taxes, but it is fully exogenously set.

8.3 Strategic options for importers: recycling, strategic buying

Two types of strategic options for importers are implemented in the multi-regional model: recycling of phosphorus flows and strategic buying of phosphate rock and phosphate fertilizer. These policy measures can be used by importers to restrain the effects of export and production restrictions on their regional markets as well as endogenous development towards scarcity. These policy options are acknowledged as central policy options to govern the phosphate market from the view of importers, see for instance de Ridder et al. (2012) and Weterings & Bastein (2013).

Recycling is implemented as a comparably simple reduction in demand for phosphate fertilizers. On a 15-year time scale recycling of struvite from wastewater is seen as the best phosphate recycling option (Cordell & White, 2013; Kataki et al., 2016; Le Corre et al., 2009). The implementation of recycling as a strategic policy option is firstly analysed in a separate spread sheet application, see Appendix 3 for the background of this material. In this application an estimation of projected P_2O_5 flows that can be generated using struvite recycling is derived. The implementation of recycling in the quantitative market model is then slowly increasing in a typical S-curve fashion. All parameters of the transition towards using struvite recycling can be changed: the speed of the transition as well as its length and the total amount of phosphate that can be generated by struvite recycling.

Because struvite is not fully equivalent in use to primary phosphate fertilizers (Talboys et al., 2016), phosphate flows from recycling may not be competitive at every point in time. Policy makers can implement measures to make sure that this competitiveness difference is closed. Substitution of primary phosphate fertilizer for struvite should be investigated much deeper. This is however beyond the scope of this study. In this study it is reasoned that demand for fertilizer from the primary value chain decreases when struvite recovery increases. Model experiments will show the dynamic effects of the phase-in of recycling on the phosphate market.

Strategic buying of phosphate is implemented in both the phosphate rock market as well as in the phosphate fertilizer market. In the phosphate rock market companies can decide to simply buy more rock than they directly need. In essence, the rock input buffer that processing companies producing fertilizer hold, is made larger. Confronted with an export or production restriction, companies can hold out by eating into their rock input buffers. In strategically buying phosphate fertilizer extra (for instance 1.25x as much as is directly needed), fertilizer buyers fill up a strategic reserve that is available for buyers in the region. In every quarter there is a strategic reserve available, a certain amount of this reserve can then be used up extra (for instance 25% of the strategic reserve) to potentially alleviate scarcity on the market.

9 Restrictions versus strategic importer policies

In this section the results of the second set of model experiments are presented. The results sketch the mechanisms behind exogenous influences on the market on top of endogenous phosphate market development. The three-regional implementation of the phosphate market model is used to experiment with the effect of export and production restrictions on the phosphate market. For that purpose, section 9.1 presents a detailed experimental motive and an overview of the scenarios that are tested. Section 9.2 presents the experimental setup. The dynamic effects of individual export and production restrictions on the European market are shown (section 9.3). Lastly, the effect of importer policy measures directed at alleviating regional demand-supply imbalances in importing markets will be investigated (section 9.4). The last section, 9.5, then summarises the results.

9.1 Experimental motive, empirical basis and scenario descriptions

The experiments run using the phosphate market model with three regional markets focus on the effect of export and production restrictions on regional phosphate scarcity. The time scale of the experiments is chosen to be 15 years, the period between 2015 and 2030. On this time scale the effects of restrictions can be investigated. In this setting the experiments are computationally tractable at the same time; the optimisation included in the market clearing mechanism is relatively slow when a multi-regional market is implemented. The analysis is performed under conditions of oligopoly economics as well as increasing extraction costs and demand growth, a situation comparable to the global market analysis in previous sections. The motive of the experiments is to show in a more practical situation than do most theoretical exercises what are effects on the phosphate market.

Comparing to the state of the art in this field, there are some economic models that investigate the effects of export restrictions on commodities markets. Notable studies include: Bouët & Debucquet (2010) looking at food markets; the OECD-developed Cournot-Nash model by Fung & Korinek (2013) describing industrial raw material markets more specifically; and an application to the international gas market is in Growitsch et al. (2014) also using a Cournot-Nash equilibrium model. A more complete operationalization of long-term dynamic, structural modelling – especially for the case of the phosphate market – however seems to be lacking. The experimental results provide for both a better understanding of the effect of export and production restrictions in the case study of the phosphate market as well as a better investigation of the criticality of phosphate from the perspective of importers. The model experiments complement theoretical investigations on resource trade as well as complement policy relevant material criticality studies.

The experimental results firstly show the effects of export and production restrictions when they are implemented in isolation, although superimposed upon endogenous market developments, see also Figure 16. In this way the dynamic effects of both types of restrictions on the phosphate market can be shown. Export restrictions tested are: a 100 $/ton export tax on phosphate rock implemented by governments in region 1 (South America and Africa) and a 300 $/ton export tax on phosphate fertilizers implemented by governments in region 3 (Russia, Middle East and India). Production restrictions tested are: a 70% restriction on mine capacity in region 3 and a 70% restriction on phosphate processing capacity. Such a restriction might come to be by an exogenous event such as a labour strike, as has happened in Tunisia, or the sudden outbreak of war, as has happened in Syria. All restrictions are active between 2020 and 2024. In the case of export restrictions both effects on the domestic as well as all other markets will be shown. In the case of production restrictions both direct effects on rock and fertilizer production as well as broader influences on the market will be shown.

The experimental results also provide insight into the effects of two coherent scenarios of export and production restrictions on the European phosphate market. The first scenario is roughly based on the developments that took place on the phosphate rock and phosphate fertilizer markets in the period of 2007-2009. According to literature (de Ridder et al., 2012; Mew, 2016), under-capacity in the market caused prices to rise – investment in new capacity is needed and costs large amounts of cash – in response to which some exporting countries implemented export taxes to prevent sudden scarcity (primarily China did this). This strategic move then again exacerbated rising prices. The scenario is implemented by setting an artificial, increasingly stringent limit on capacity in region 1 starting in 2018 until Q3 of 2020. This is then followed between 2020 and 2024 by an export tax on rock of 120 $/ton implemented in region 1.

A plausible scenario of tit-for-tat export restrictions implemented by multiple exporting countries is also investigated. After one country (first mover) implements an export tax, another region (follower) can do the same without the difficulty of becoming relatively more expensive than other producers. At that moment in time the follower-producer already has a cost advantage on the global market relative to the first mover-producer. Then the first mover increases its export tax and the follower also does so again. In this case a strategic interaction between two exporters emerges that might be profitable for both of them. In the scenario region 1 (first mover) starts by implementing a 75 $/ton export tax on rock from 2020 onwards, at the start of 2021 region 3 (follower) reacts by implementing a tax at the same level. After which – in 2023 – region 1 increases its tax to 100 $/ton, and region 3 follows in 2024 by doing the same. From 2026 onwards the export taxes are both retracted.

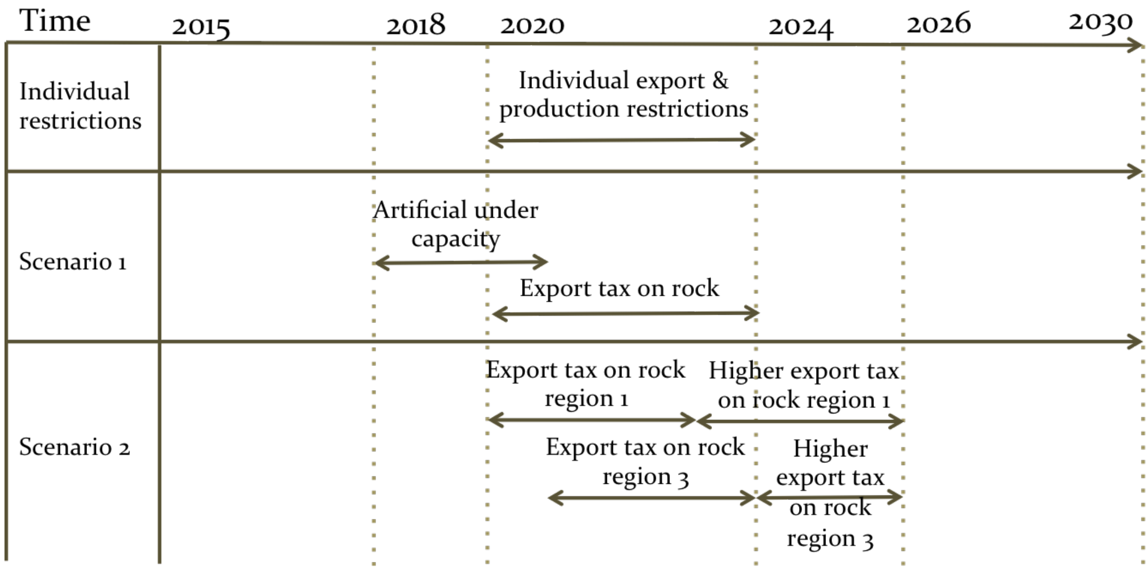

Figure 16 – Visualisation of the time dimension of all individual export and production restrictions and of the two coherent scenarios

9.2 Experimental setup

To perform the analyses of the effect of export and production restrictions two large sets of experiments have been run, see Table 15. The first consisted of 1000 experiments, the second of 1200 experiments. In this case every category of model runs consist of 200 runs, so that they are comparable. The first set of 1000 experiments has been subdivided into five parts. In each one fifth of experiments the effect of a different export or production restrictive measure has been tested. The second set of 1200 experiments has been subdivided into six parts, amounting to all possible combinations of policies (doing nothing, recycling, strategic buying) and coherent scenarios (under-capacity and rock export tax, tit-for-tat export taxation).

Table 15 – Overview of the experimental setup

Experiment set	**Goal**	**Exporter scenarios**	**Importer policies**
1. Single trade restrictive measures (5 *x 200 = 1000 runs*)	Investigating the effect of single export and production restrictions (*compared to a situation of no restrictions)*	• *Doing nothing* • Export tax on rock • Export tax on fertilizer • Production cap on rock • Production cap on fertilizer	*None*
2. Coherent scenarios versus importer policies (2 x 3 x 200 = *1200 runs*)	Investigating the effect of scenarios of export/ production restrictions (*comparing situations with and without importer policy implementation)*	• Scenario of under-capacity and extreme rock export tax • Scenario of tit-for-tat rock export tax implementation	• *Doing nothing* • Recycling • Strategic buying of rock and fertilizer

Regional model parameters are set on the global level, on the regional level, as well as on the level of companies. On the global level such parameters as the lifetime and construction time of mines and processing facilities are set. High-level market characteristics such as market type, relative company size and initial fit of supply and demand of both fertilizer and rock are set. The values of these variables are similar as in the situation of the aggregated market.

On the regional level, parameters governing extraction cost over time, demand and processing cost characteristics are set. These parameters typically differ quite strongly when comparing over different regions, the differences are discussed in detail in Appendix 6. Difference in regional market parameters represents the essential differences between the regional markets of Africa and South America, Europe and lastly the Middle East, Russia and India. An important example among these differences being that Africa has far more rock production than there is fertilizer production, while Europe only has fertilizer production. The Middle East, Russia and India have comparably more fertilizer production than they have rock production. Lastly, on the level of companies, the same variables are set as in the case of the previously implemented aggregated model. Companies also have a variable location. In total there are between 6 and 8 companies present in the market, of which 2 or 3 companies in region 1 and 3, and 2 companies in region 2.

9.3 Experimental results IIa: Effect of export and production restrictions

The first set of experimental results is discussed now. In this set of results the effects of singular export and production restrictive measures are investigated. Categories of effects on phosphate importers include effects on price dynamics, on imports and on regional scarcity. In appendix 9 these effects are scrutinised from the point of view of phosphate exporters.

Price dynamic effects are investigated by calculating price differentials over time. These differentials are calculated by subtracting the average of prices on other markets from the European price. Trade dynamics and scarcity dynamics are scrutinised by investigating relative import changes and relative ratio of demand and supply changes. All these metrics are calculated right before implementation of the trade restriction, in Q4 2019, and a year later, in Q1 2021. This is done to isolate the effect of the export or production restriction as much as possible. Violin plots of the distributions of the effects of individual measures are shown in Figure 17, background numbers are in the appendices is in Table 25, more detailed analysis of the underlying dynamic time series is also in appendix 9. The distribution comparisons are also statistically tested: see appendix 10 for the background. All effects sketched in this section are statistically significant, except when the distribution is marked with an asterisk.

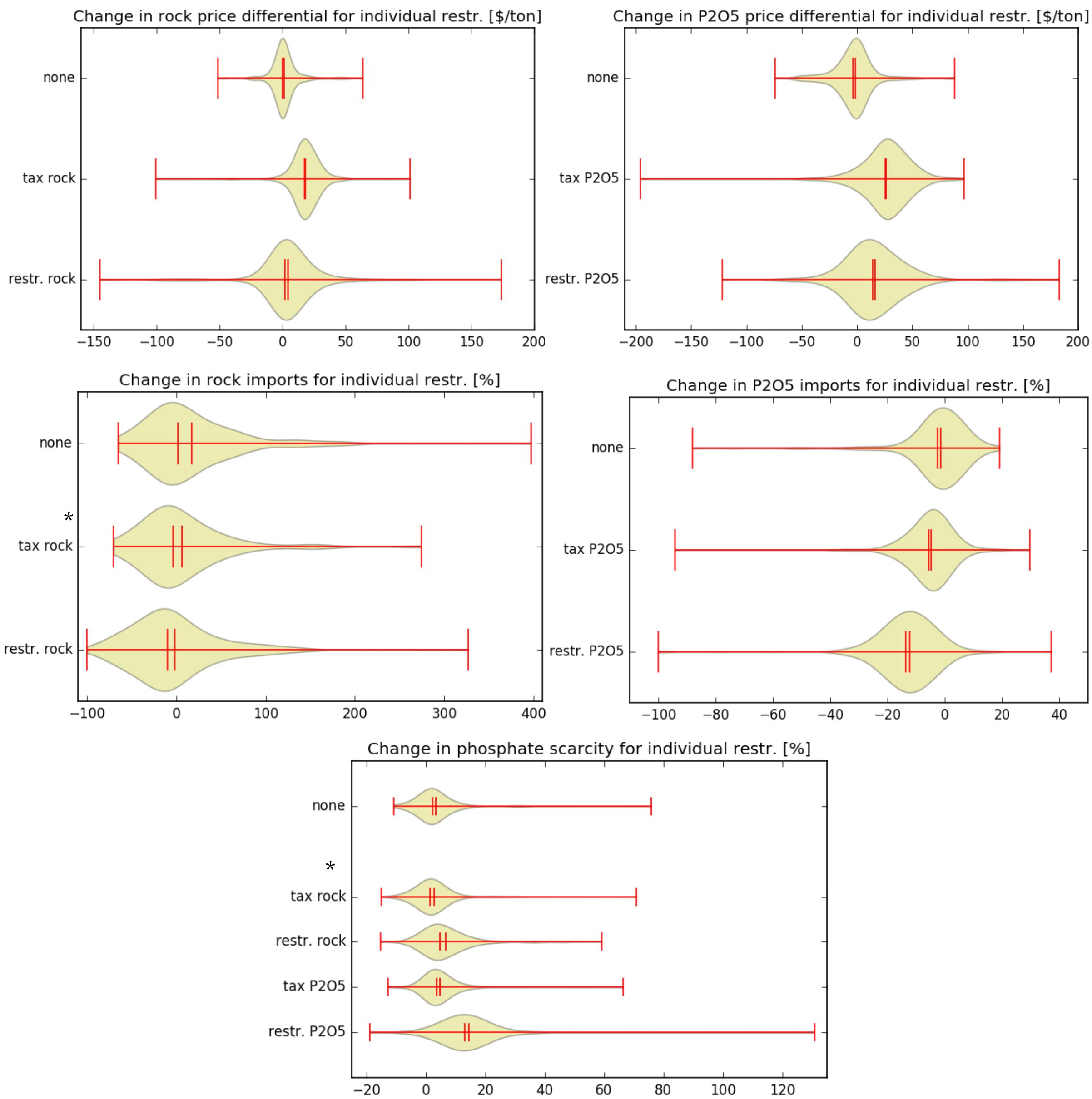

Figure 17 – Violin plots for the effects of individual restrictions on the European phosphate market. Change between Q4 2019 and Q1 2021 is shown on key indicators: rock/phosphate price [$/ton], rock/phosphate imports [%], and phosphate scarcity [%]. Kernel density estimates shown are all based upon the results of 200 simulation runs. Red lines show position of median, mean and extrema. Asterisks show which distributions are not statistically significantly different at the 1 %-level from runs with no restriction

The key negative effect of a 100 $/ton export tax on rock implemented by region 1 from the point of view of Europe is a rock price differential increase. The price increase between Q4 of 2019 and Q1 of 2021 is about 18-20 $/ton on the European market. Depending on endogenous market dynamics the price increase within a model run ranges between 10 and 30 $/ton. The export tax also has a negative effect on European rock imports, although this effect is not statistically significant. The rock export tax does not have a statistically significant effect on phosphate scarcity on the European market in the simulated runs.

The primary negative effect of a 300 $/ton export tax on phosphate fertilizer implemented in region 3 is a fertilizer price differential increasing effect on the European market. In comparison to runs without restrictions the phosphate price differential increase is about 25 $/ton more. Some runs show a phosphate price increase in Europe of up to 50 $/ton. There is furthermore a strong phosphate import decreasing effect. The median of import decreases is almost 5 %, with some runs also showing a phosphate import decrease up to 14 %. Scarcity in Europe also increases with up to 11 % although this is only a few percentage points more than in the case of no measures.

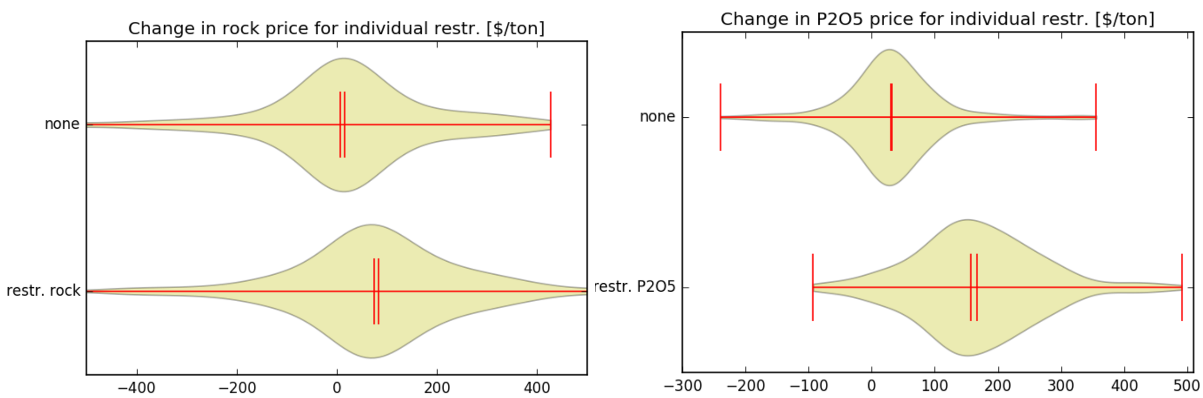

Figure 18 – Violin plots for the effect of production restriction on European phosphate market price. Change between Q4 2019 and Q1 2021 is shown in: rock price [$/ton] and in phosphate price [$/ton]. Kernel density estimates shown are based on 200 runs. Red lines show position of mean, median and extrema

Model runs in which a limit on phosphate rock production of 70% effectuates in region 3, are primarily characterised by an increase in rock price in Europe. Median European rock price increase between Q4 2019 and Q1 2021 is over 60 $/ton, see Figure 18, see Table 26 for the precise price statistics. Phosphate rock import changes are also more than 10 %-points lower when compared to the situation without restrictions. Lastly, regional phosphate scarcity increases more under a rock production restriction, albeit by only a few percentage-points.

The primary negative effect of a production cap of 70% on fertilizer production in region 3 is a strong increase in phosphate scarcity. Median scarcity increase on the European market is 13 %, with a 90-% quantile at a 23 % increase. Furthermore, over the whole set of experiments there is a negative effect on phosphate fertilizer imports in Europe: the import decrease is between 3 % and 25 %. Lastly, phosphate fertilizer becomes a lot more expensive on the European market: fertilizer price increase ranges between 50 $/ton and 290 $/ton, see Table 26 in the appendices.

9.4 Experimental results IIb: Planning for export restrictions

The second set of experimental results is now discussed. In these experiments the effects of importers using the policy measures of recycling and strategic buying of both rock and fertilizer will be shown. In total 1200 experiments have been run, in the first analyses comparison is made again with the 200 experiments of the previous set in which no policies nor scenarios are implemented. Scenarios investigated include the coherent stories of under-capacity followed by an export tax and tit-for-tat implementation of export taxes on rock by both rock-exporting regions. Policies include recycling and strategic buying. Detailed analysis of the results of these experiments is in Table 29 to Table 31 in the appendices. The focus here is on the most important effects of the scenarios and on what can be done using recycling and strategic buying from the perspective of Europe.

Scenario effects

The primary negative effect of the first scenario – severe market capacity shortage and a subsequent export tax – is increasing phosphate scarcity on the European market. Difference between the distributions of ratio of demand and supply in 2024 and 2030 are statistically significantly different at the 1 %-level. Median ratio of demand and supply on the European market in 2024 is 8 % higher in runs in which the scenario is implemented compared to no scenario implemented. In 90 % of the runs, the ratio is above 1.82 signalling situations of scarcity. In 2030 median ratio of demand and supply is 6 % higher than when no scenario is implemented in the model experiments. In 50 % of runs phosphate scarcity in 2030 is even above 2.3, sustained damage has then been done to the phosphate market. The distribution of rock prices over runs is also statistically significantly different in 2024 and 2030 at the 1 %-level. Median rock prices and phosphate prices in Europe in 2024 are 51% and 9% higher respectively under the scenario. In 2030 these prices are still 46% respectively 6% higher compared to the basic model runs. The effects discussed are visualised by kernel density estimates over time for ratio of demand and supply and rock price in Figure 19.

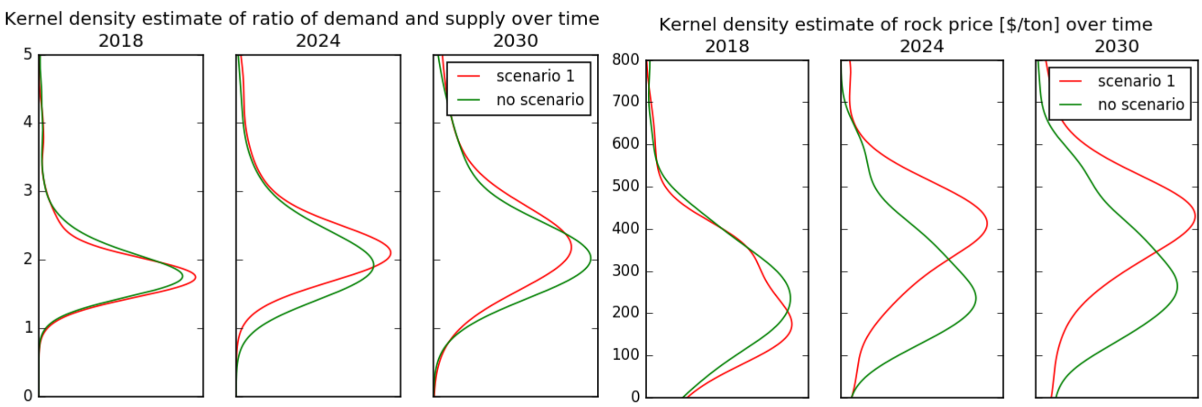

Figure 19 – Kernel density estimates of ratio of demand and supply and rock price [$/ton] for 2018, 2024, and 2030 for scenario 1 (red) and basic model runs (green). The distributions are based on two sets of 200 experiments

The effect of the scenario of tit-for-tat export taxation is of a different nature. The model experiments show no increase in phosphate scarcity on the European market, see Table 29 in the appendices. The median European phosphate rock price in 2024 does increase by almost 10% compared to the basic model runs. The primary negative effect on the European market is however that phosphate rock becomes relatively more expensive. This effect is seen in the price differential of the European market over the average price of the other two markets, see Figure 20. In 2022, median rock price differential in Europe is 11 $/ton larger than in model runs without the scenario implemented. In 2025, this difference in median price differential increases to 14 $/ton. The 90%-quantile of the rock price differential is more than 30 $/ton higher in model runs with the scenario implemented. Both in 2022 and in 2025 the differences between the distributions of rock price differential are statistically significant at the 1 %-level.

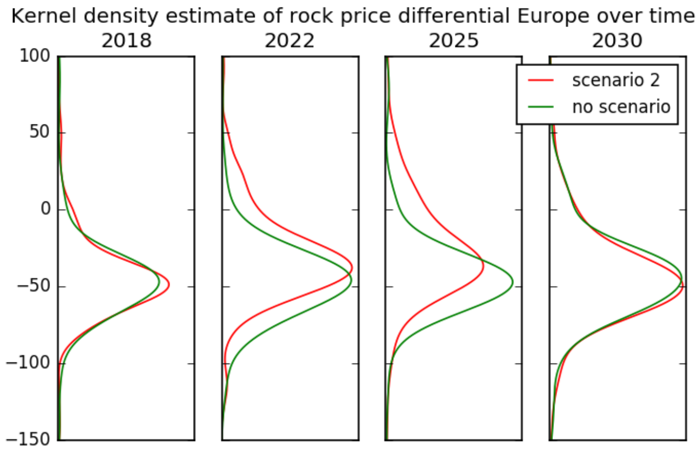

Figure 20 – Kernel density estimates of rock price differential in Europe [$/ton] for 2018, 2022, 2025 and 2030 for scenario 2 (red) and basic model runs (green). The distributions are based on two sets of 200 experiments

Using recycling to plan for scenarios

The first policy that can be used by phosphate importers in Europe to accommodate for the effects of export and productions is phosphate recycling. It has been estimated that about 1.2 million tonnes of P_2O_5-equivalent struvite can be recycled per year, see appendix 3 for this estimate. Between 2020 and 2030 this amount of phosphate equivalent struvite is recycled in response to the implementation of export and production restrictions by other rock and fertilizer exporting regions. The effect of this policy is analysed relative to the two coherent scenarios as analysed above. The analysis below contains 800 model runs – in 400 of these recycling has been implemented, in 400 other runs no policy has been implemented on the European market. Recycling is found to be a reasonably effective response to scarcity on the phosphate market, although it only works after an implementation phase. This result is found by analysing the ratio of demand and supply on the European market.

The effect of recycling – when importers are confronted with export restriction scenarios – on the European phosphate market is shown in Figure 21. Recycling causes actual phosphate demand on the European market in 2030 to be 26% lower on average compared to when recycling is not implemented. It is also found that – looking at the more detailed analysis in Table 29 in the appendices – recycling is limitedly effective in alleviating phosphate scarcity on the European market. The median ratio of demand and supply in 2030 under recycling is 2.14, while under no policy this value is 2.19. This difference of distributions over the simulations runs is not significant at the 1 %-level. Combined with the observation that market liquidity is smaller it still amounts to a reduction of dependence on phosphate. A further worthwhile effect of recycling is that the median rock price under recycling in 2030 is 50 $/ton lower than when that policy is not implemented. The difference between the distributions of rock price in case of the scenario of recycling compared with no policy implemented is indeed significant at the 1 %-level. Although some of the representative scenarios with recycling clearly show a decrease in phosphate price, the distribution over model runs of that price in 2030 does not change much when compared to the situation of no policy. Some further analysis of the side effects of recycling on other regional markets is in appendix 9 and in Table 32 and Table 33 in that appendix.

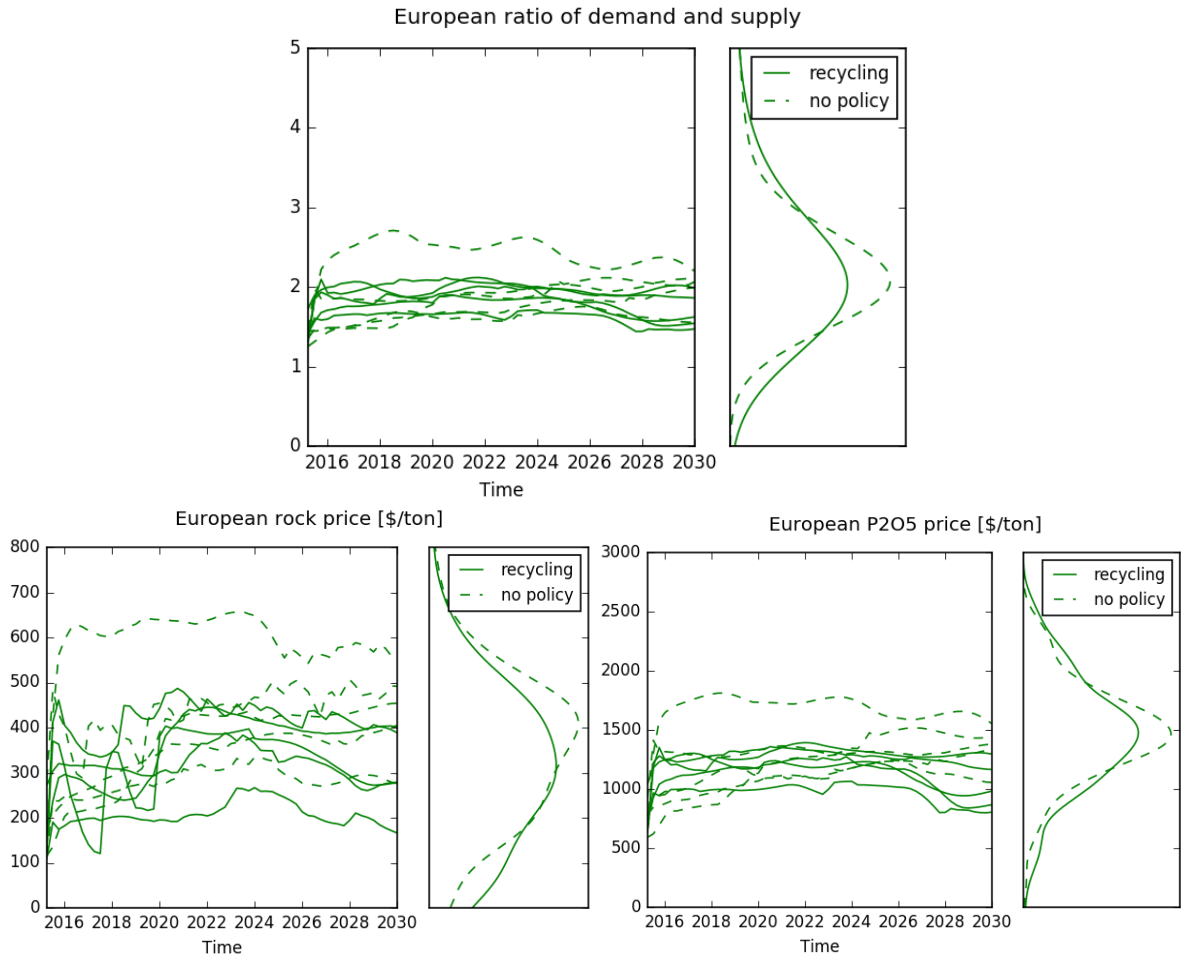

Figure 21 – Five representative scenarios in which recycling is implemented (line) and five representative scenarios in which no policy is implemented (dashed) for ratio of demand and supply, rock price [$/ton] and phosphate price [$/ton] on the European market to 2030. These scenarios are only representative of their own cluster; they cannot be compared across scenarios. Kernel density estimates are shown for the end values of recycling (line) and no policy (dashed) separately

Using strategic buying to plan for scenarios

The second importer policy that can be used is strategic buying of phosphate rock and phosphate fertilizer. Under this policy all companies that need rock as an input buy 25 % extra during the implementation of strategic buying. Also, a central reserve is filled with a strategic amount of phosphate fertilizers of which maximally 25 % can be used by end-consumers every quarter. The strategic buying policy is implemented between 2020 and 2025 on the European market. The analysis below contains 800 model runs – in 400 of these runs strategic buying has been implemented and in 400 others no policy has been implemented.

The effect of the strategic buying policy on the European phosphate market is shown in Figure 22. By simply claiming more phosphate rock and phosphate fertilizer, strategic buying causes phosphate scarcity to decrease sharply with about 0.5 points during policy implementation. The median rock price in 2024 in case of strategic buying is about 35 $/ton higher when compared to model runs without any policy implemented. The median phosphate price in 2024 in the case of strategic buying is about 70-90 $/ton higher when compared to model runs without any policy implemented. These differences are statistically significant at the 1 %-level. See also Table 29 to Table 31 in the appendices again. In 2030, strategic buying has a marginally negative effect on the European phosphate market. In 2030 median phosphate scarcity are all marginally higher compared to model runs without policies implemented, although these effects are not statistically significant at the 1 %-level. The effect of strategic buying is analysed from the point of view of phosphate exporters in appendix 9 and in Table 32 and Table 33 in that appendix.

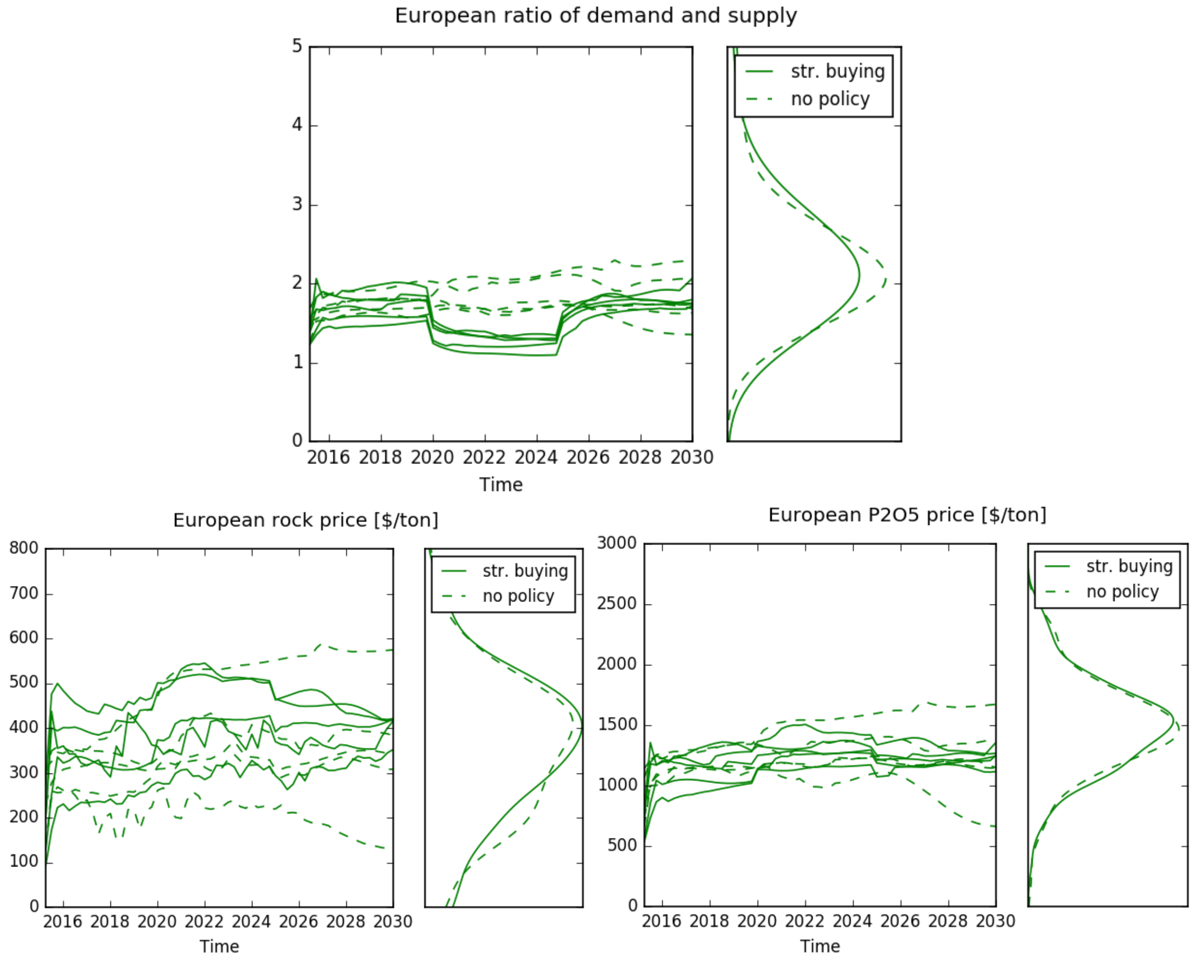

Figure 22 – Five representative scenarios in which strategic buying is implemented (line) and five representative scenarios in which no policy is implemented (dashed) for ratio of demand and supply, rock price [$/ton] and phosphate price [$/ton] on the European market to 2030. These scenarios are only representative of their own cluster; they cannot be compared across scenarios. Kernel density estimates are shown for the end values of strategic buying (line) and no policy (dashed) separately

9.5 Overview of experimental results II

The effects of export and production restrictions that have been hypothesized in literature are generally found in the model experiments as exemplified in this section. The results typically show the dynamic counterparts of the causal effects that are foreseen by using static models of export and production restrictions as others in literature and in policy papers implement them. The size of these causal effects, for instance the change in the price of rock or fertilizer after implementation of an export tax or the size of the change in trade flows, is however not always the same. Rock price differential in Europe for instance mostly increases by 10 to 30 $/ton within a year in reaction to a 100 $/ton export tax implemented by region 1. Phosphate price differential mostly increases by between 2 and 51 $/ton in reaction to a 300 $/ton export tax implemented by region 3. Similar broad ranges of results have been found for production restrictions effectuating in rock production and fertilizer production, see mainly Figure 17. The precise size of the effects of export and production restrictions depends on interactions with endogenous market structure and behaviour. These interaction effects more specifically seem to produce the most interesting – and least foreseeable – market behaviour.

In general it has been found that export and production restrictions have a negative effect on importers. Export restrictions generate price differential increases in Europe. Welfare is redistributed between exporting and importing countries. Production restrictions can be seen to have a negative effect for all market players, both in importing as well as in exporting countries. Under some circumstances production constraints cause strongly lowering rock and fertilizer production. Causing a reduction of rock and fertilizer imports in Europe, with up to 60% respectively 24% in case of a 70% capacity constraint for rock and fertilizer production. In a sense, investment uncertainty present may be the most distortionary feature of export and production restriction effect on the market. The efficient working of the phosphate market is blurred during the effectuation of the production restriction. Investment signals are being distorted and essential information on demand eludes producers, causing them to divest from the phosphate market. Thus, when a restriction takes too long, the market will be in severe under-capacity, also after retraction of the export restrictive measures in question. This has been seen in some simulation results.

The policy measures that importers such as the European Union have available constitute a start of being able to reduce the possibly growing – or even suddenly growing – imbalances between supply and demand. Recycling is the best longer-term solution for limiting market imbalances. Its effects in 2030 when Europe is confronted with the scenarios tested include: an average decrease of 26% in phosphate demand, a median phosphate scarcity decrease of 2 % and a median rock price decrease of 50 $/ton. There is a fundamental time synchronisation problem in using recycling to plan for sudden exogenous market imbalances: the success of the policy measure hinges on the successful phase-in of an innovative technology. Recycling as a policy measure is thus not yet effective in 2024, but only becomes effective by 2030.

Strategic buying of rock and fertilizer can directly help in breaking the strategic position of exporters that restrict trade to Europe. Phosphate scarcity decreases by about 0.5 points under strategic buying. There is however a price that must be paid for this reduction in phosphate scarcity – the damaging inflationary working on European phosphate rock and fertilizer prices of export restrictive measures is only strengthened. Median rock price in 2024 is about 35 $/ton higher and median phosphate price is about 70-90 $/ton higher than when no strategic buying is implemented and these differences are statistically significant. Furthermore, when the strategic reserve is taken out of operation, phosphate scarcity might well retract. As found in the results, strategic buying has a marginally negative effect on the phosphate market in 2030. Recycling and strategic buying seem highly complementary and they may well be implemented at the same time. Table 16 shows an overview of the results of this set of model experiments.

Table 16 – Overview of the results of model experiments of the multi-region model

Experimental result	Explanation
1. Effects of export and production restrictions	• The results mostly show the dynamic counterparts of the expected results from literature on price dynamics, trade dynamics, production and regional scarcity • Interaction between endogenous and exogenous market development causes the effects of export and production restrictions to be variable • A dangerous plausible effect of restrictions is a lack of investment in new mine and production capacity
2. The effect of export and production restrictions	• Export restrictions have a negative effect on importers such as the European Union, pronounced effects include: o Median rock price differential in Europe increases by 18 $/ton under a 100 $/ton tax by region 1 o Median P_2O_5 price differential in Europe increases by 27 $/ton under a 300 $/ton tax by region 3 • Production restrictions have a negative effect on importers such as the European Union, pronounced effects include: o Median rock price in Europe increases by 50 $/ton under a 70% mine production restriction in region 3 o Median phosphate price in Europe increases by 110 $/ton under a 70% fertilizer production restriction in region 3
3. Using recycling to plan for restrictions	• Recycling is a sustainable longer-term solution for alleviating phosphate scarcity in Europe and therewith in other regions o Phosphate demand decreases by 26% in 2030 o Phosphate scarcity is 2% lower in 2030 when recycling is implemented o Median European rock price is 50 $/ton lower in 2030 • There is a planning synchronisation problem in using recycling to plan for restrictions – recycling is only effective in alleviating market imbalances in 2030
4. Using strategic buying to plan for restrictions	• Strategic buying is a temporary solution for alleviating regional phosphate scarcity for Europe o Phosphate scarcity is 0.5 points lower in 2024, during export and production restrictions o Phosphate scarcity is marginally higher in 2030 • Strategic buying strengthens the price inflationary effect of export taxes in Europe during implementation of restrictions o Median rock price in 2024 is about 35 $/ton higher o Median phosphate price in 2024 is 70-90 $/ton higher

Part 5 – Discussion and Conclusion

10 Discussion

10.1 On understanding phosphate market imbalances in Europe

The principal policy aim of this thesis has been to inform understanding of phosphate market imbalances from the perspective of Europe as a fully dependent importer of phosphorus flows. The effects of export and production restrictions have been investigated in detail. The experiments run with the first, aggregated global phosphate market model have shown the determinants of phosphate scarcity on the longer term to 2100. The experiments run with a three-regional representation of the combined Africa, South America, Europe, Middle East, Russia and India phosphate market have shown the effects of export and production restrictions on European importers. Implications of the model results are now discussed, as well as limitations of the current study and a comparison to existing results from literature. On the basis of this discussion, conclusions are drawn in the next section.

Long-term phosphate market balance

The model results have shown that both situations of global phosphate scarcity and situations of global phosphate abundance are plausible, in 30% of runs no situation of phosphate scarcity arises over the whole 21st century, see section 7.3. Extraction cost acts as a dynamic price floor on the phosphate rock market. The cost overcharge on the rock market is mostly about 100-200 $/ton. This implies that rock and fertilizer prices would in the long term rise slowly but steadily – which is also found in literature (Mew, 2016). This does not necessarily imply rising phosphate scarcity, because of the large utility that consumers derive from using fertilizer. In the model it was assumed upfront that extraction costs are slowly rising over time – which in fact is part of the classical debate of technological progress versus mining costs within resource economics (Tilton, 2003). The diverging views on technological progress should have more broadly been taken into account in the modelling study. A minor problem with the model developed is that sometimes price dives below marginal cost – although this situation only occurs in times of extreme over-capacity of rock, in this case it is maybe even logical that prices tend to become extremely low.

From the model experiments run with the aggregated global phosphate market model it also follows that the sufficiency of investments is the key determinant of phosphate scarcity on the longer term. If companies are modelled to invest and divest 1.5x the difference between current capacity and desired capacity – scarcity can frequently be fended off (see the results in section 7.3). Under conditions of increasing demand, investment in first processing and then rock mining capacity is essential to fend off scarcity. The model is limited in representing the availability of investment opportunities. These opportunities hinge on availability of capital flows as well as the physical possibility to build a new plant or new mine that is in turn dependent on geological specificities of reserves. Furthermore, the model only represents the rock and fertilizer market as consisting of constant numbers of companies. Thus the influence of market structural changes – such as new players that enter the market by investing in rock mines or fertilizer-processing facilities – cannot be reflected. In defence of the model assumptions: barriers to entry on the phosphate market are typically very high.

If investments in the phosphate value chain turn out to lag demand over time, phosphate scarcity occurs – as is also found by others (for instance by Cordell, 2010). Of course, there are a number of structural assumptions that are fundamental to the model that would make this result lose its validity. Firstly, it is assumed that no substitute for primary phosphate fertilizers becomes available in the coming decades – not counting the possibility to recycle phosphorus flows as a real substitute. Because of the biological necessity of the presence of phosphorus in growing plants, this seems to be a valid assumption at least for the coming decades. Furthermore, it is assumed that no large, relatively easy-to-mine reserve of phosphate rock is found, in this case the situation of scarcity might also be alleviated.

Decision-making processes governing demand expectations and resulting capacity utilisation and investment decisions have been reflected in a relatively detailed way in the model. This focus on supply chain decision-making has enabled investigation of heterodox behaviour of mining, processing and integrated companies active in the phosphate market. The way of working has been comparable to that of complexity economics (Arthur, 2013). The representation of these decision-making processes is still far too limited when compared to reality.

Heterogeneity of behaviour between companies is actually even larger in reality. One possibly important determinant of behaviour that has not been taken into account is ownership structure. State-owned companies react completely differently to investment impulses than do private-owned companies, as is also seen on the phosphate market (de Ridder et al., 2012; Kowalski et al., 2013). State-owned companies are expected to have more capital available due to their ties to national governments. Companies also behave far more strategically in the market than currently reflected in the model. An example of this is the fact that the model only represents non-cooperative oligopolistic behaviour, whereas the phosphate market is also prone to cartelisation (Al Rawashdeh & Maxwell, 2011; Taylor & Moss, 2013): a form of cooperative oligopolistic behaviour. Such cooperative forms of market distortions might cause different market dynamics.

The need for fitting investment in the phosphate value chain shows that full information is necessary on what is underlying demand for phosphate rock and phosphate fertilizer on the side of end-users. Although this does not follow directly from the model results, the market might not always have that information due to demand structural characteristics. The capacity of farmers to buffer phosphorus in their soil for a few seasons has a negative effect on demand information reaching suppliers (Mew, 2016). This detailed notion of demand formation decisions would call for a far more detailed modelling of that side of the value chain. End-users and their fertilizer management decisions might be taken into the model as intelligent agents too. A time dimension should be included on which the phosphorus soil buffering decision is reflected. There is also a clear connection to the problem of fertilizer mismanagement. It is difficult to accept the occurrence of mismanagement if there is a real phosphate scarcity problem.

The effect of export and production restrictions

Experiments with the quantitative market model have shown that export restrictions generally have negative effects on Europe as an importer. For instance, in the case of a 100 $/ton export tax on rock exported from region 1, phosphate rock becomes between 10 and 30 $/ton more expensive relative to the other regional markets. Other effects of export and production restrictions include reduction of imports to Europe and severe phosphate scarcity. The size of induced rock and fertilizer price increases and the size of the retraction of trade depend on market structure and endogenous market behaviour. See the exemplary effect of the export tax on rock that ranges 10 and 30 $/ton. From analysis of the experimental results it cannot be made fully clear what the precise causes are in the differences of these effects – this would warrant further analysis and model extensions. In reality a complicating factor might be a certain resistance to change that is inherent in trade flows. Due to the presence of transaction costs inherent to contracting, redirection of trade flows – as predicted by theoretical analysis of export restrictions (Gandolfo, 2014; Latina et al., 2011; Piermartini, 2004) – might turn out to be smaller than thought.

From the model results it follows that production restrictions have a multilaterally negative effect on both exporters and importers, these caps on production simply represent efficiency losses in financial terms. For example in the case of a 70 % fertilizer production restriction in region 3, median phosphate scarcity increases by 13 % in Europe as well as in the implementing region, Russia, Middle East and India. In the case of effectuation of production restrictions again a lack of investment is the key problem that might have effect on the phosphate market. It is the question if these effects would also be observed in the real world. It might also be so that in response to a labour strike or temporary war situation mines and processing facilities are only temporarily mothballed and they can quite easily be taken back into operation, in which case rock or fertilizer output rebounds. The real world interaction between demand expectation formation and sudden exogenous capacity limitations remains difficult to represent in a quantitative model. It might be so that companies already know when a capacity limitation will end. In this case the company might simply wait until the cap on production is gone without divesting at all.

From the experimental results in section 9.3 it is found that limitation of investment is an extreme problem that might be caused by export restrictions taking effect on the market. Soft factors of investment uncertainty play a larger role than could be modelled. From the experimental results it is quite difficult to observe production and investment relocation effects (as hypothesised in Fung & Korinek, 2013) – only lower production and lack of investment trends are easily spotted. This might be a question of degree – the relocation effects are so small that they cannot be discerned from existing endogenous market trends – but it might also be that these effects can simply not be observed from the economically simple model that has been build.

Some further limitations of the current model of export restrictive measures include the choice of letting regions instate export taxes. In reality national governments mostly do this. There is also far more detail in export restrictions being implemented in the real world. Sometimes export quota, licensing schemes or more ingenious forms of export restrictions are implemented (Espa, 2015; Fliess & Mard, 2012). In effect, it is however likely that much of these other export limitations have the same trade-distorting effect as export taxation. Other forms of export restrictions can be included in more elaborate versions of the quantitative phosphate market model. This would call for an introduction of more fine-grained markets on the country level as well as for the introduction of agents representing national governments.

A very important decision-making feedback loop is missing on the strategic policy goal of implementing export restrictions. Export restrictions are often used with a strategic policy goal in mind they are implemented at specific points in time: when for instance prices are already increasing as China did in 2009 (Persona, 2014). Subsequently they are updated in response to the fulfilment of these strategic policy goals. By using scenarios with coherent narratives weaved in has been possible to represent some of these strategic effects. Using political economic explanations from literature (Anderson et al., 2013; De Gorter & Swinnen, 2002; Rausser & Swinnen, 2011; Thennakoon, 2015), it would also be possible to model this decision-making feedback mechanism directly. In this case government agent structures might instate export restrictions when for instance domestic phosphate rock prices start increasing to protect their domestic markets. Another goal of export restrictions is stimulation of the junior industry of fertilizer processing: the goal of Chinese trade restrictive policies.

Importers planning for export and production restrictions

Given that recycling can be broadly implemented on a medium time scale this importer policy can help in partially alleviating phosphate market imbalances. From the model results it is found that actual phosphate demand in Europe is lowered by 26 % in 2030 under recycling and median phosphate scarcity marginally decreases by about 2 %. The median European rock price is also 50 $/ton lower under recycling in 2030. To make sure that recycling of phosphorus is implemented, struvite and other phosphorus recycling flows should be made to compete on a market with primary value-chain fertilizers. Competitiveness of phosphorus recycling products is currently not reached (Molinos-Senante et al., 2011), but directed government policy can accomplish this. Clear policy maker decisions – with possibly very high costs via subsidies on buying struvite as well as on the part of for instance wastewater treatment plants to implement new treatment technologies – can be made to direct phosphorus recycling towards implementation. A further important policy goal that would be served by increased phosphorus recycling is that groundwater quality increases through limitations on eutrophication (Elser & Bennett, 2011).

Although recycling is an important longer-term phosphate scarcity-limiting policy, there is a clear time synchronization problem in using it as a policy measure to plan for market imbalances due to sudden export and production restrictions. In the model results the effects of recycling are not yet visible in 2024, recycling only has its full effect by 2030. Recycling must optimally be started up well before the exogenously induced measures have their effect on the market. Observing the start of the creation of legislation on phosphate recycling on an European level, this might still be possible (European Commission, 2016b). Recycling is the most reliable option of reducing European phosphate scarcity by directly becoming more independent from phosphorus flow imports.

Strategic buying can be used as more of a crisis measure when Europe is confronted with a sudden export or production restriction. According to the model results both the phosphate rock and the phosphate fertilizer prices would actually go up on the European market by 35 $/ton and 75-90 $/ton respectively – even strengthening the damaging price inflationary effects of export taxation. But strategic buying can help in actively limiting regional scarcity effects on the European market during the effectuation of a supply restriction by about 0.5 points. This is also found by de Ridder et al. (2012). In the optimal case rock and fertilizer reserves should already be filled up before the export or production restriction takes hold. Then the cost of buying produce that is strategically stored is kept as low as possible. Of course, storing rock or fertilizer is expensive, thus implementing a strategic reserve might cost a lot. But in general, extreme export and production restrictions are only temporary measures, thus costs of implementation are also held limited.

Comparing recycling and strategic buying as importer planning options, there are a number of clear differences. From detailed analysis of the model results it is clear that recycling is a policy option having multilaterally positive effects on all regional markets – both on phosphate importing markets as well as on phosphate exporting markets. In the case of strategic buying, a reduction in European phosphate scarcity is reached at the expense of increasing phosphate scarcity in Africa, South America, Russia, the Middle East and India. Furthermore, rock and phosphate prices on these other markets increase strongly. Europe simply claims a larger part of supply on the market. In this way strategic buying thus is a beggar-thy-neighbour policy just as are export restrictions. It might be ethically prohibitive to use strategic buying at the expense of food security in for instance Sub-Saharan Africa, Latin America, India or the Middle East.

10.2 On dynamic commodity market modelling of export and production restrictions

The developed quantitative model of the phosphate market can be placed within a long tradition of commodity market models, as discussed in for instance Labys (1999). Only sometimes has this kind of commodity market models been used for modelling the effects of export and production restrictions (as for instance done in Fung & Korinek, 2013; Growitsch et al., 2014; Paulus, 2011). Firstly, the quantitative market model implemented has reflected the anomalies of commodity markets discussed in World Trade Organization (2010): exhaustibility as well as the uneven distribution of resources has been explicitly represented in the model. The resulting imperfect market conditions have been translated into an imperfect phosphate rock and fertilizer market. The large presence of state-backed parties on the market that is common for many commodities – and especially also for phosphate – has not been reflected explicitly.

The structural model implemented has created the possibility of investigating the effects of the low number of companies active in the market. At the same time it has been possible to investigate the implications of company decision-making behaviour on the individual level. The model has shown the connection between individual companies coming to a decision about investment in mines and the resulting mine capacity available in the market. There is a direct and explicit connection between the decisions of companies and market dynamics. Thus, the model fits the real-world market in this respect. A further disaggregation on the demand side of the phosphate fertilizer market might be opportune in further research. Then decisions of fertilizer end-users can be better represented. Reducing long-term scarcity and strengthening food security can benefit a lot from also understanding the demand side of the fertilizer market into detail.

The market works with contracts between on the one side rock mining and fertilizer processing companies and on the other side wholesale buyers and fertilizer end-use buyer groups. These contracts were represented by a market equilibrium finding technique. This is one of the most important aggregations used in the model. It is possibly where the description of the phosphate market has diverged the most from the real world. Market distortions that have their effect on a contracting market might be very different from the market distortions reflected in the model. In the process of contracting, strategic behaviour by the negotiating parties can introduce extreme market distortions. Sometimes, buyers also exhibit strategic behaviour as was seen in negotiations of coordinated Indian buyers (Taylor & Moss, 2013). Contracted prices can easily be held a secret, in which case information in the market is limited, further distorting market efficiency. A completely other model implementation could represent the phosphate market using a matching algorithm, see for instance Roth (2002). The nature of contracting can then be represented more directly, although it is not clear upfront how market prices would then be calculated.

The model has represented the market as a Cournot-Nash equilibrium market. This has been done in many applications by others (Fung & Korinek, 2013; Growitsch et al., 2014; Kolstad & Burris, 1986). This implementation diverges from a perfect market formulation (Bouët & Laborde Debucquet, 2010), but the model still reflects the market as being in equilibrium in every quarter. No rational expectations model has been used, as is frequently done in analysing agricultural markets (Gouel & Jean, 2015). Thus, companies sometimes make inter temporally dumb decisions. They keep on using up the rock they have in storage, until they really need new rock. It might be better to spread the buying of rock input over a few quarters. This makes the rock market in the three-region market model sometimes severely unstable.

Other types of non-cooperative oligopolistic behaviour might have been chosen. Bertrand behaviour, companies deciding on price, does not seem logical, for in that case price would be equal to marginal cost (Shapiro, 1989). This situation does not apply to the phosphate market. Stackelberg behaviour on the part of a leader such as Morocco is another interesting model implementation (Wan & Boyce, 2013; Yang, 2013). Linear demand curves have been used in the three-region phosphate market, this has been necessary to make the optimisation implementation stable enough to run it without any errors. This might change the degree to which some conclusions hold.

Key in representing regional markets is the implementation of transport costs for hauling rock and fertilizer between markets. There is a long tradition of using perfect market models – that are actually equivalent to flow optimisations (Enke, 1951; Roehner, 1996; Samuelson, 1952) – in representing a perfect spatially separated market. The large distances already present within markets hamper the way in which transport costs for hauling between markets have been implemented. Costs for transporting to a company's own market have indeed been used to partially alleviate this problem. Transport from Morocco to Eastern Africa simply differs in cost from transport from Morocco to Brazil, whereas these distances are equal in the model implementation. The conclusions can be strengthened by investigating the implications of changing assumptions on transport costs or even by increasing the number of markets. The possibility of doing this in the current modelling setup was however limited due to computational time limitations. This would be an avenue of research that can profit from the integration of more intelligent geo-spatial modelling techniques.

The dichotomy between endogenous and exogenous market influences that lead to developing two different phosphate market models for different goals is also reflected in the developed understanding of the effect of export and production restrictions. The exogenous effect of the implementation of an export tax differs due to already present endogenous market development. The distinction between these two types of influences is of broad discussion in economic literature (Carter et al., 2011; Gouel, 2012; Mitra & Boussard, 2008). Endogenous reasons for market imbalance have classically been derived from naive expectation investigations such as in the classical hog cycle literature (starting in Kaldor, 1934; Tinbergen, 1930), whereas exogenous influences towards market imbalances include weather influences (as in the model of Deaton & Laroque, 1992). The implemented quantitative model has combined these types of influences by modelling demand expectation and resulting investment and exogenous influences in the form of export and production restrictions.

The interaction between endogenous and exogenous influences on phosphate market balance produces the most interesting and least foreseeable phosphate market behaviour. This has been seen in: (i.) dynamic analysis of the effects of restrictions over time, (ii.) regional analysis of the effects of restrictions, and (iii.) by comparing between different model simulations. The model results show the dynamic effects of these restrictions. In standard economic literature these effects are statically derived from economic theory (Gandolfo, 2014; Piermartini, 2004). Our analysis has therein strengthened understanding of trade restrictions by applying economic knowledge in an operationalized case study on the phosphate market.

It has been shown that it is needed to look at dynamic effects of trade restrictions. These can deviate quite a lot from the effects predicted from static, perfect-market models. In these models the price deviation between regions induced by an export tax is equal to the size of the export tax – as is the case in implementing transport cost models (Roehner, 1996; Samuelson, 1952). The model results showed that sometimes the price differential between markets is much larger than the tax – in most cases however the price differential is smaller than the tax.

10.3 On merits and disadvantages of mixing model blocks for commodity models

The phosphate market model constructed as part of this modelling research has clearly shown that quantitative modelling of commodity markets through mixing and matching model building blocks can strengthen commodity market understanding. The quantitative model has been of an integrated hybrid design – company agents were represented having a rich internal structure of stock-flow structures (one of the types named by Swinerd & McNaught, 2012). Agents were aggregated into sets of active market players on two types of dynamic markets – the phosphate rock and phosphate fertilizer market. The markets were cleared every quarter to determine rock and fertilizer prices.

This quantitative model design has provided for an open mind-set in modelling of commodity markets. More open even than by just building an agent-based model and a system dynamics model of a commodity market next to each other. The quantitative model of the given illustration described the phosphate market in a natural way. Instead of prescribing conceptual units that describe only parts of commodity markets such as feedback loops or agents, the model described multiple objects having a direct conceptual counterpart in the real-world market. This open-minded type of modelling complements single-methodology studies of commodity markets. As has been demonstrated in the case study of phosphate, mixing and matching model building blocks can gather meaningful insights on commodity markets.

The programming environment in which the quantitative model has been implemented – pure Python with a number of further packages – has provided a large degree of liberty in mixing and matching model building blocks. There are a number of reasons for this. Firstly, the programming environment is numerically fast. Lastly, there is no stringent limit on the applications and packages that can be implemented in an open-source language. The programming environment is also relatively easy to use for modellers experienced in thinking in object-based terms. The object-oriented structure of the model also allows for rapid creation of multiple versions of the same quantitative model describing different parts of the same commodity market. Modular design of quantitative models minimises the investment of labour needed to create models describing different commodity markets.

Three key difficulties remain in the implementation of quantitative models through mixing and matching of building blocks. Firstly, there is no easy step-by-step process for modelling by combining model components from different paradigms. The lack of formalisation of this step-by-step process can cause a delay in the typical length of a modelling project. Translation from the standard modelling cycle, consisting of conceptual analysis, formal analysis, verification, validation, conclusions, should be logically continued when mixing and matching different model building blocks. This sometimes calls for improvisation in assimilating models. There are no clear-cut choices to model commodity market aspects in a quantitative model assimilated from scratch. Building block choices must be justified by elaborate reasoning. The work presented has shown an outline for the translation of the standard modelling cycle to design models from scratch by combining building blocks.

Quantitative model building blocks can only be coded in formalised ways: the computer needs to be told exactly what it needs to do. The quantitative model implementation has shown a number of possible interpretations of model building blocks as programming objects. This way of working allows for model formalisation. The correspondence between conceptual model and formalised programming model must also be proven by extensive verification and validation. Existing validation methods can be combined to provide the same level of trust in the model results. There are also time synchronization problems between different model parts. Every modelling method has a different way of coping with time. Some methodologies implement continuous conceptions of time, other methodologies use discrete conceptions. A last difficulty in model formalisation is the lack of visualisation of model structure and model behaviour. Off-the-shelf modelling applications have visualisation features of both structure and behaviour available. When building a quantitative model in a generic programming environment visualisation features are not always available. This makes it important to conscientiously think about how to present the model and its results.

Lastly, the breadth of modelling methodologies that can be applied within such a flexible environment can well transcend the boundaries of the skill set of the analyst. The analyst ideally has experience building different types of quantitative models. Programming skills are also needed to be able to assimilate the quantitative model from scratch. Ideally, the analyst has a large number of model building blocks available to choose from. If a modeller with limited experience within only a single methodology would build a quantitative model according to the same modelling process, a model comprised of only similar building blocks might be the result. The proposed way of working is highly dependent upon earlier experience with building quantitative market models.

10.4 On generalisation of the quantitative model

The implemented commodity market model can represent most commodity market anomalies. Weighing the advantages and disadvantages of mixing model building blocks it is found worthwhile to generalise from the currently build model. The model building blocks can directly be used in the new model, because the model has been built in an object-oriented way. Multiplication of the number of objects for instance representing companies in a new model can be easily performed. Retracing the conceptualisation and model construction process step-by-step for a different material then makes it easier to build a second hybrid-type model of a commodity market model. A structured comparison of the situation for that other raw material with the situation of phosphate can inform a swift implementation of the second quantitative model.

A logical target would be to build a comparable model of the potash market. Although different countries are the big players there, there is a comparable situation on the market in terms of concentrated reserves, oligopolistic market players and a connection to the fertilizer market (be it the K_2O market instead of the P_2O_5 market). The currently developed model can be the start of a whole range of commodity market models consisting of different types of objects that in the best case would also be used interchangeably. The disadvantages of the open method of modelling can then be structurally strengthened. The large amount of time that the current modelling project has taken can be minimised. In that case, insight from a number of modelling methodologies into commodity markets can be combined in a single quantitative model. As much as possible can then be learned from quantitative models to alleviate the intricate problems of commodity markets.

11 Conclusion

In this section the conclusions of this work are presented. All research questions are answered. Therein, an overview is provided of both the quantitative modelling applied as well as of the policy question of phosphate scarcity. The research questions are repeated in Table 17.

Table 17 – Research questions

Question	*Background*
1. What essential aspects of the phosphate market should a quantitative model capture?	Section 4
2. How can the phosphate market be captured in a quantitative model designed from scratch to model the effect of export and production restrictions on market imbalances?	Section 5, 6, 8
3. What market aspects are the determinants of phosphate market imbalances? What is the role of export/production restrictions?	Section 7, 9
4. What policies should phosphate importers – such as the European Union – use to cope with phosphate market imbalances?	Section 9, 10
5. In what way can the findings generated with the quantitative model be generalised to other commodity markets?	Section 10

11.1 Answers to the research questions

Question 1 – Essential phosphate market aspects

The phosphate value chain has been scrutinised in detail. The conceptualisation has provided ten essential aspects that together uniquely describe the phosphate market, these are extensively discussed in section 4. The quantitative model implementation has been developed on the basis of this set of market aspects. The most important phosphate market aspects taken into account in the quantitative model are: (i.) phosphate rock reserves are extremely unevenly distributed over a small number of countries, (ii.) phosphate fertilizer are not substitutable in its main agricultural application and thus food security is at risk, (iii.) phosphate end-use demand is of a very specific nature due to phosphorus soil buffering capacity. The purpose of this research has been to investigate the determinants of phosphate market imbalances with a focus on the effect of export and production restrictions on importers. Thus, the quantitative model developed also described the precise content of export and production restrictions as well as the direct effects on market behaviour.

Question 2 – Quantitative model

The main contribution of this research has been to develop a quantitative commodity market model designed from scratch to model the determinants of market imbalance with a focus on the effect of export and production restrictions. The model development process has been explicitly and elaborately discussed in section 5. A requirements analysis for the model was performed. Criteria that the hybrid model fulfils are firstly of a general nature: the model takes into account dynamics and uncertainty inherent to commodities markets, the model can be used for long-term policy analysis, the model can be used to provide policy recommendations, and the model provides ease-of-use to the analyst through its implementation in a flexible software environment. Further criteria are of a case-specific nature: the quantitative model describes the set of phosphate market aspects up to a large extent, and the model describes the effect of importer policy measures such as phosphorus recycling and strategic buying.

A structured process of selecting model building blocks was followed. Building blocks used in different types of models were included: system dynamics-inspired stock-flow structures, agent-based inspired decision-making mechanisms and economic game theory-inspired market equilibrium techniques. Selection was based on fulfilment of the stated criteria for a quantitative model, see section 5.2. Section 6 provides the background to the chosen model implementation. The model has been implemented in an open-source environment in the Python programming language. By mixing and matching model building blocks a feasible way of building quantitative commodity market models without resorting to single modelling methods was shown to deliver for the case study of the phosphate market. The described model was instantiated for two policy purposes. The basic model structure as presented in section 6 was used to represent the global phosphate market in an aggregated way. Section 8 provides the model changes to describe a multi-regional phosphate market.

Question 3 – Determinants of phosphate market imbalances

The determinants of phosphate market imbalances were investigated in two model experiments. In section 7, model experiments were investigated on global endogenous phosphate market development to 2100. In section 9, model experiments were run in which export and production restrictions are implemented together with importer policies to 2030.

From the first set of model experiments – using a global phosphate market model implementation – it was found that both situations of global phosphate market balance and situations of global phosphate market imbalance are endogenously plausible market developments. Cumulative output of phosphate rock to 2100 is projected to be between 9 and 35 billion tonnes. This means that geological scarcity is not plausible between now and 2100. It was found that investment in mine capacity and fertilizer processing capacity are the most important determinants of phosphate scarcity over the long term. Both rock prices and fertilizer prices are projected to rise steadily over the 21st century. The endogenous market development of plausibly rising phosphate scarcity provides the framework within which export and production restrictions act on the phosphate market.

From the second set of experiments, the effect of export and production restrictions was quantified. This analysis used a three-region phosphate market model implementation describing 50% of global phosphate demand in: (i.) Africa & South America, (ii.) Europe, and (iii.) Middle East, Russia & India. Four export and production restrictions were investigated: (i.) a 100 $/ton export tax on phosphate rock from Africa and South America, (ii.) a 300 $/ton export tax on phosphate fertilizer from Middle East, Russia and India, (iii.) a 70 % production restriction on rock production in the same region and (iv.) a 70 % production restriction on fertilizer production in the same region. The effects of these restrictions on the European phosphate market are shown in Table 18, detailed background analysis is found in section 9.3.

All export and production restrictions have negative effects on the European phosphate market through price, trade and scarcity effects. The most negative, plausible effect of export and production restrictions that has been found in the model experiments is a lack of investment in mine capacity and processing capacity. This can cause structural damage to the European phosphate market. The model results provide insight into the size of all effects of export and production restrictions. From the results presented in section 9 it is clearly seen that the precise effect of export and production restrictions is dependent on existing endogenous market development. Dynamic analysis of these restrictions from the perspective of both exporters and importers is available in appendix 9.

Table 18 – Effects of export and production restrictions on European market

Restriction implemented	*Price effect in model experiments*	*Scarcity effect in model experiments*
Export tax of 100 $/ton by Africa and South America	Median rock price differential in Europe increases by 18 $/ton extra	Median phosphate scarcity does not change compared to situation of no tax
Export tax of 300 $/ton by Middle East, Russia and India	Median fertilizer price differential in Europe increases by 28 $/ton extra	Median phosphate scarcity increases by 1.5 %-points extra
Rock production restriction of 70% in Middle East, Russia and India	Median rock price in Europe increases by 50 $/ton extra	Median phosphate scarcity increases by almost 3 %-points extra
Fertilizer production restriction of 70% in Middle East, Russia and India	Median fertilizer price in Europe increases by 110 $/ton extra	Median phosphate scarcity increases by almost 10 %-points extra

Question 4 – Importer phosphate market policies

The second part of the model experiments run with the three-regional phosphate market model, investigated the effect of two coherent scenarios of export and production restrictions. The first scenario simulates a scenario of artificially created under-capacity in the rock market from 2018 on, after which an export tax of 120 $/ton on rock exports was instated starting in 2020. Both restrictions work on the regional market of Africa and South America. The second scenario investigated is tit-for-tat export taxation between the two phosphate rock exporting regions: Africa/South America and Middle East/Russia/India. Phosphate rock exports from the two regions are increasingly taxed starting from 2020, first with a 75 $/ton tax and then with a 100 $/ton tax. These scenarios are more elaborately described in section 9.1.

From the model results it has been found that the scenarios have strongly negative effects on the European phosphate market. The effect of the first scenario in 2024 is: an 8 % increase in median ratio of demand and supply, a 51 % increase in median rock price, and a 9 % increase in median phosphate price. In 2030 all these effects are still present, albeit in a slightly weaker form: a 6 % increase in median ratio of demand and supply, a 46 % increase in median rock price, and a 6 % increase in median phosphate price. The effect of the second scenario is of a wholly different nature. This scenario mainly has temporary effects on the European phosphate market. Median rock price on the European market is almost 10 % higher in 2024. Rock is mainly relatively more expensive on the European market: in 2022 by 11 $/ton extra on top of endogenous market development and in 2025 by 14 $/ton extra.

From the model results it was found that recycling is a partially effective policy measure for importers confronted with export and production restrictions. Recycling induces an average phosphate demand decrease of 26 % in 2030. At the same time phosphate scarcity decreases by about 2 %. Together this amounts to a significant reduction in dependence on phosphate imports. Also median rock price under recycling is 50 $/ton lower in 2030. Strategic buying has been shown to reduce scarcity in Europe by about 0.5 points. The policy only strengthens the price inflationary effects of export taxation: median rock price is 35 $/ton higher and median phosphate price 70-90 $/ton higher in 2024. In 2030, strategic buying has a negative effect on the phosphate market: median phosphate scarcity is marginally higher and both median rock price and phosphate price are 20 $/ton higher. Recycling has a positive effect on rock prices on other markets than the European in 2030, while strategic buying has a negative effect on regional scarcity on other markets: it is a strong beggar-thy-neighbour policy.

Recycling will be an essential importer policy measure. Policy makers are in a key position to conscientiously choose to stimulate recycling. In planning for sudden export and production restrictions there is however a time synchronization problem: the phase-in of such technological innovation might take considerable time. In the model results, recycling is only maximally effective by 2030, while strategic buying is effective almost directly. Together with efficient phosphate use, recycling is the best way to sustainably reduce phosphorus flow import dependence. Strategic reserves and strategic positioning of European governments relative to trade on the market must complement this on the short-term, although these policies have beggar-thy-neighbour effects in terms of price rises on other regional markets. In this way they mirror the effects of export restrictive measures. These beggar-thy-neighbour effects might not be justifiable relative to developing countries that are extremely dependent on the productivity of their agriculture.

Question 5 – Generalisation to other commodity markets

The conclusions on the effect of export and production restrictions that have been investigated here can also be generalised to other commodity markets. The qualitative content of the conclusions can be generalised, for instance: an export tax on a primary material induces a price increase on the importers market. The added value of this study is however in the quantification of effects, dynamic analysis and investigating the influence of broad uncertainties on the conclusions. The effects of importer policies can be balanced against trade restrictions. To make full use of these possibilities, the quantitative model of the phosphate market shall need to be generalised.

In section 10.4 generalisation of the quantitative phosphate market model was discussed. The highly flexible, object-oriented model implementation makes it easy to change the model to reflect other commodities markets. All model parameters can be set for the quantitative model to reflect a different market. Due to considerable similarities between the phosphate market and the potash market, see for instance Taylor & Moss (2013), it would be highly interesting to apply the hybrid type of modelling employed to the potash market.

11.2 Policy reflection

Judging from the model experiments and experience with the problem of phosphate scarcity, it is very plausible that only concerted efforts of policy measures can alleviate phosphate scarcity in the coming decades. Measures including recycling, strategic buying of extra rock and fertilizer and efficiency can only in combination be effective in limiting the effects of export and production restrictions. From the model results it is seen that export taxes have plausibly large effects on phosphate importers: rock and fertilizer prices in Europe increase, imports of rock retract and phosphate scarcity increases strongly. Thus, the occurrence of export and production restrictions must be minimised. Political efforts via the World Trade Organisation should be focussed on also building up legislation on export measures (Bartos, 2012; Espa, 2015). On the longer-term export and production restrictions are of course not the only challenges to phosphate market balance, an end to relatively cheap supplies of phosphate might well come: although, as model experiments with the global phosphate market model has shown, not necessarily within the 21st century.

In the end it is highly likely that trade restrictive measures will have their effect in the short term. Through their investment damaging effects they can have far-ranging effects on longer-term phosphate scarcity too. Strategic buying of phosphate rock and phosphate fertilizer might thus only buy time towards a transition of more sustainable phosphorus management. On extremely long time scales – into the 22nd century – it might be needed to minimise phosphate demand insofar as is possible. In the short-term, the medium-term and the long-term, recycling phosphorus flows and complementary efficient phosphorus use are the best shot at becoming more independent from phosphorus imports.

Strategic buying of phosphate rock and phosphate fertilizer only embodies a displacement of the problem of phosphate scarcity to exporting countries. These exporting countries might well be far more dependent on highly productive agriculture due to strongly growing populations than Europe is. The dependence on fertilizers in developing countries was clearly seen during the 2009 food crisis: sparking food riots in multiple countries. Fertilizer scarcity and after some time food scarcity might very well cause conflict within and between countries. Reducing imbalances in the phosphate market is an important ingredient of limiting the risks of damage to food security both in Europe as well as worldwide.

In conclusion, a concerted European phosphate market governance package should contain:

- A clear map of available phosphate mine and phosphate fertilizer processing capacity now and in the future, to be able to deduce investment needs and investment gaps
- A clear map of real underlying demand for phosphate fertilizers projected into the future in order to strengthen the information diffusion process on size of demand and therewith investment in mine and processing capacity
- Broad political effort aimed at reducing export restrictive measures through international trade political efforts by the European Union, as well as aimed at reducing production restrictive effects on the market through directed stabilization of those countries in which large amounts of phosphate rock are produced
- Recycling and efficient use of phosphorus should be stimulated, for these are currently the only long-term sustainable solutions to become less dependent on the import of phosphorus flows
- Strategic buying of phosphate rock and phosphate fertilizer can be implemented as a temporary crisis measure, although these measures have a clear negative effect in terms of regional scarcity on other regional markets such Latin America, Africa and India

Such a concerted European phosphate market governance package can contribute to the reduction of phosphate scarcity towards 2030 as well as in the rest of the 21st century. Food security risks induced by phosphate market imbalances are then limited.

Appendices

References

Achzet, B., & Helbig, C. (2013). How to evaluate raw material supply risks — an overview. *Resources Policy*, *38*(4), 435–447.

Al Rawashdeh, R., & Maxwell, P. (2011). The evolution and prospects of the phosphate industry. *Mineral Economics*, *2011*(24), 15–27.

Andersen, M. S., Dahl, J., & Vandenberghe, L. (2015). CVXOPT Documentation v.1.1.8. Retrieved March 24, 2016, from http://cvxopt.org/documentation/

Anderson, K., Rausser, G., & Swinnen, J. (2013). Political Economy of Public Policies: Insights from Distortions to Agricultural and Food Markets. *Journal of Economic Literature*, *51*(2), 423–477.

Arthur, W. B. (2013). Complexity Economics: A Different Framework for Economic Thought. In W. B. Arthur (Ed.), *Complexity Economics*. Oxford, Great Britain: Oxford University Press.

Bartos, J. (2012). Multilateralising regionalism: Disciplines on export restrictions in regional trade agreements. *OECD Trade Policy Working Paper, No. 139*.

Bastein, T., & Rietveld, E. (2015). *Materials in the Dutch Economy – A vulnerability analysis*. Delft, The Netherlands: TNO.

Bedder, J. (2015). Classifying critical materials: a review of European approaches. *Applied Earth Science*, *124*(4), 207–212.

Bonabeau, E. (2002). Agent-based modeling: methods and techniques for simulating human systems. *Proceedings of the National Academy of Sciences*, *99*(suppl. 3), 7280–7287.

Bouët, A., & Laborde Debucquet, D. (2010). Economics of Export Taxation in a Context of Food Crisis: A Theoretical and CGE Approach Contribution. *IFPRI Discussion Paper, No. 00994*.

Brander, J., & Krugman, P. (1983). A "reciprocal dumping" model of international trade. *Journal of International Economics*, *15*(3-4), 313–321.

Buijs, B., Sievers, H., & Tercero Espinoza, L. A. (2012). Limits to the critical raw materials approach. *Proceedings of the ICE - Waste and Resource Management*, *165*(4), 201–208.

Bumb, B. L., Johnson, M. E., & Fuentes, P. A. (2011). Policy Options for Improving Regional Fertilizer Markets in West Africa. *IFPRI Discussion Paper, No. 01084*.

Cairns, R. D. (1998). The Microeconomics of Mineral Extraction Under Capacity Constraints. *Nonrenewable Resources*, *7*(3), 233–244.

Carter, C. A., Rausser, G. C., & Smith, A. (2011). Commodity Booms and Busts. *Annual Review of Resource Economics*, *3*(1), 87–118.

Cooper, J., Lombardi, R., Boardman, D., & Carliell-Marquet, C. (2011). The future distribution and production of global phosphate rock reserves. *Resources, Conservation and Recycling*, *57*(2011), 78–86.

Cordell, D. (2010). *The Story of Phosphorus: Sustainability implications of global phosphorus scarcity for food security*. *Linköping Studies in Arts and Science*. Linköping University.

Cordell, D., & White, S. (2013). Sustainable phosphorus measures: strategies and technologies for achieving phosphorus security. *Agronomy*, *3*(1), 86–116.

Cordell, D., & White, S. (2014). Life's Bottleneck: Sustaining the World's Phosphorus for a Food Secure Future. *Annual Review of Environment and Resources*, *39*(1), 161–188.

Dannreuther, R., & Ostrowski, W. (2013). *Global Resources: Conflict and Cooperation*. London, UK: Palgrave Macmillan.

Dasgupta, P., & Heal, G. (1974). The Optimal Depletion of Exhaustible Resources. *Review of Economic Studies*, *41*(Symposium on the Economics of Exhaustible Resources), 3–28.

Datt, M., Hoekman, B., & Malouche, M. (2011). Taking Stock of Trade Protectionism Since 2008. *Economic Premise*, *72*.

De Gorter, H., & Swinnen, J. (2002). Political Economy of Agricultural Policy. In B. Gardner & G. Rausser (Eds.), *Handbook of Agricultural Economics* (Vol. 2, pp. 1893–1943).

de Ridder, M., de Jong, S., Polchar, J., & Lingemann, S. (2012). *Risks and Opportunities in the Global Phosphate Rock Market*. The Hague: The Hague Centre for Strategic Studies.

Deaton, A., & Laroque, G. (1992). On the behaviour of commodity prices. *Review of Economic Studies*, *59*(1), 1–23.

Egle, L., Rechberger, H., & Zessner, M. (2015). Overview and description of technologies for

recovering phosphorus from municipal wastewater. *Resources, Conservation and Recycling*, *105*(2015), 325–346.
Elser, J., & Bennett, E. (2011). Phosphorus cycle: A broken biogeochemical cycle. *Nature*, *478*(7367), 29–31.
Elser, J., Elser, T. J., Carpenter, S. R., & Brock, W. A. (2014). Regime shift in fertilizer commodities indicates more turbulence ahead for food security. *PLoS ONE*, *9*(5), 1–7.
Elser, J., & White, S. (2010). Peak Phosphorus. Retrieved August 4, 2016, from http://foreignpolicy.com/2010/04/20/peak-phosphorus
Enke, S. (1951). Equilibrium among Spatially Separated Markets: Solution by Electric Analogue. *Econometrica*, *19*(1), 40–47.
Erdmann, L., & Graedel, T. E. (2011). Criticality of non-fuel minerals: a review of major approaches and analyses. *Environmental Science and Technology*, *45*(18), 7620–30.
Espa, I. (2015). *Export Restrictions on Critical Minerals and Metals: Testing the Adequacy of WTO Disciplines*. Cambridge, UK: Cambridge University Press.
European Commission. (2014). *Report on critical raw materials for the EU, Report of the Ad hoc Working Group on defining critical raw materials*. Brussels, Belgium.
European Commission. (2016a). *Monitoring EU Agri-Food Trade : Development until March 2016*. Brussels, Belgium.
European Commission. (2016b). Proposal for a regulation of the European Parliament and of the Council laying down rules on the making available on the market of CE marked fertilising products. Brussels, Belgium.
European Environment Agency. (2013). Urban Wastewater Treatment. Retrieved June 29, 2016, from http://www.eea.europa.eu/data-and-maps/indicators/urban-waste-water-treatment/urban-waste-water-treatment-assessment-3
Eurostat. (2016). Population and Population Change Statistics. Retrieved June 29, 2016, from http://ec.europa.eu/eurostat/statistics-explained/index.php/Population_and_population_change_statistics
FAO. (2013). Data on Inputs: Fertilizers. Retrieved March 24, 2016, from http://faostat3.fao.org/download/R/RF/E
FAO. (2015). *World fertilizer trends and outlook to 2018. Food and Agriculture Organization of United Nations*.
FAO, IFAD, & WFP. (2015). *The State of Food Insecurity in the World*. Rome, Italy: FAO.
Fliess, B., & Mard, T. (2012). Taking Stock of Measures Restricting the Export of Raw Materials. *OECD Trade Policy Papers, No. 140*.
Ford, D. (1999). A behavioral approach to feedback loop dominance analysis. *System Dynamics Review*, *15*(1), 3–36.
Fung, K., & Korinek, J. (2013). Economics of Export Restrictions as Applied to Industrial Raw Materials. *OECD Trade Policy Papers, No. 155*.
Gandolfo, G. (2014). *International Trade Theory and Policy* (2nd ed.). Berlin Heidelberg: Springer.
Glöser, S., & Hartwig, J. (2015). The classical Cobweb Theorem and real commodity market behavior: Modeling delayed adjustment of supply in industrial metals' markets. In *Proceedings of the 33rd International Conference of the System Dynamics Society*. Cambridge, MA.
Glöser, S., Tercero Espinoza, L., Gandenberger, C., & Faulstich, M. (2015). Raw material criticality in the context of classical risk assessment. *Resources Policy*, *44*(2015), 35–46.
Goldwasser, M. H., & Letscher, D. (2014). *Object-Oriented Programming in Python*. Saint Louis, MO. Retrieved from http://cs.slu.edu/~goldwasser/oopp/
Good, A. (2015). Welcome to Tunisia's Resource Wars. Retrieved August 4, 2016, from http://nationalinterest.org/print/feature/welcome-tunisias-resource-wars-13058
Gouel, C. (2012). Agricultural price instability: A survey of competing explanations and remedies. *Journal of Economic Surveys*, *26*(1), 129–156.
Gouel, C., & Jean, S. (2015). Optimal Food Price Stabilization in a Small Open Developing Country. *World Bank Economic Review*, *29*(1), 72–101.
Govindarajulu, Z. (1976). A brief survey of nonparametric statistics. *Communications in Statistics -*

Theory and Methods, *5*(5), 429–453.
Graedel, T. E., Barr, R., Chandler, C., Chase, T., Choi, J., Christoffersen, L., … Zhu, C. (2012). Methodology of metal criticality determination. *Environmental Science and Technology*, *46*(2), 1063–1070.
Graedel, T. E., Harper, E. M., Nassar, N. T., & Reck, B. K. (2015). On the materials basis of modern society. *Proceedings of the National Academy of Sciences of the United States of America*, *112*(20), 6295–300.
Graedel, T. E., & Reck, B. K. (2015). Six Years of Criticality Assessments: What Have We Learned So Far? *Journal of Industrial Ecology*, *Early view*, 1–8.
Growitsch, C., Hecking, H., & Panke, T. (2014). Supply Disruptions and Regional Price Effects in a Spatial Oligopoly-An Application to the Global Gas Market. *Review of International Economics*, *22*(5), 944–975.
Gruhn, P., Goletti, F., & Roy, R. N. (1995). Proceedings of the IFPRI/FAO Workshop on Plant Nutrient Management, Food Security and Sustainable Agriculture: The Future Through 2020.
Gustin, K., & Idoniboye, I. (2015). Webinar: Phosphate market dynamics & industry outlook. Retrieved February 17, 2016, from https://www.integer-research.com/market-analysis/phosphate-cost-and-profit-margin-service/free-downloads/
Heckenmüller, M., Narita, D., & Klepper, G. (2014). Global Availability of Phosphorus and Its Implications for Global Food Supply: An Economic Overview. *Kiel Institute for the World Economy Working Papers*, *No. 1897*.
Hees, E. (2013). *Voedsel, grondstoffen en geopolitiek [Food, resources and geopolitics]*. Platform Agriculture, Innovation & Society.
Herman, J. D. (2014). stockflow: System Dynamics in Python. Retrieved March 24, 2016, from https://github.com/jdherman/stockflow
Hernandez, M. A., & Torero, M. (2010). Fertilizer market situation: market structure, consumption and trade patterns, and pricing behavior. *International Food Policy Reserach Institute*, 1–76.
Hernandez, M. A., & Torero, M. (2013). Market concentration and pricing behavior in the fertilizer industry: A global approach. *Agricultural Economics*, *44*(6), 723–734.
Hoekman, B., & Martin, W. (2012). Reducing Distortions in International Commodity Markets. In S. J. Evenett & F. Jenny (Eds.), *Trade, Competition and the Pricing of Commodities*. London: Centre for Economic Policy Research.
Hotelling, H. (1931). The Economics of Exhaustible Resources. *The Journal of Political Economy*, *39*(2), 137–175.
ICIS News. (2012). Morocco's OCP agrees Q1 phosphate rock price cut with Europe market moves. Retrieved February 18, 2016, from http://www.icis.com/resources/news/2012/02/17/9533181/morocco-s-ocp-agrees-q1-phosphoric-acid-price-cut-with-india/
International Fertilizer Association. (2016). IFA Data: Production and International Trade. Retrieved from http://www.fertilizer.org//En/Statistics/PIT_Excel_Files.aspx
Islam, T., & Pruyt, E. (2016). Scenario generation using adaptive sampling: The case of resource scarcity. *Environmental Modelling and Software*, *79*(2016), 285–299.
Johnson, P. H. (1977). Phosphates: The next cartel? *Fletcher Forum of World Affairs*, *1*(2), 154–163.
Kaldor, N. (1934). A classificatory note on the determinateness of equilibrium. *The Review of Economic Studies*, *1*(2), 122–136.
Kataki, S., West, H., Clarke, M., & Baruah, D. C. (2016). Phosphorus recovery as struvite: Recent concerns for use of seed, alternative Mg source, nitrogen conservation and fertilizer potential. *Resources, Conservation and Recycling*, *107*(2016), 142–156.
Kingsbury, D. (2015). The role of resources in the resolution of the Western Sahara issue. *Global Change, Peace & Security*, *27*(3), 253–262.
Kolstad, C. D., & Burris, A. E. (1986). Imperfectly Competitive Equilibria in International Commodity Markets. *American Journal of Agricultural Economics*, *68*(1), 27–36.
Kolstad, C. D., & Mathiesen, L. (1991). Computing Cournot-Nash Equilibria. *Operations Research*, *39*(5), 739–748.
Kowalski, P., Büge, M., Sztajerowska, M., & Egeland, M. (2013). State-Owned Enterprises: Trade

Effects and Policy Implications. *OECD Trade Policy Papers, No. 147*.
Kwakkel, J. H., Auping, W. L., & Pruyt, E. (2013). Dynamic scenario discovery under deep uncertainty: The future of copper. *Technological Forecasting and Social Change*, *80*(4), 789–800.
Labys, W. (1999). Modeling Mineral and Energy Markets. Boston, MA and Dordrecht, The Netherlands: Kluwer.
Latina, J., Piermartini, R., & Ruta, M. (2011). Natural resources and non-cooperative trade policy. *International Journal of Economic Policy*, *2011*(8), 177–196.
Lättilä, L., Hilletofth, P., & Lin, B. (2010). Hybrid simulation models - When, why, how? *Expert Systems with Applications*, *37*(12), 7969–7975.
Le Corre, K. S., Valsami-Jones, E., Hobbs, P., & Parsons, S. A. (2009). Phosphorus Recovery from Wastewater by Struvite Crystallization: A Review. *Critical Reviews in Environmental Science and Technology*, *39*(6), 433–477.
Lee, A. (2014). pyDOE: The experimental design package for Python. Retrieved from https://pythonhosted.org/pyDOE/
Liao, T. W. (2005). Clustering of time series data - A survey. *Pattern Recognition*, *38*(11), 1857–1874.
Lloyd, S., Lee, J., Clifton, A., Elghali, L., & France, C. (2012). Recommendations for assessing materials criticality. *Proceedings of the ICE - Waste and Resource Management*, *165*(2007), 191–200.
McCorriston, S., & MacLaren, D. (2007). Do state trading exporters distort trade? *European Economic Review*, *51*(1), 225–246.
McKelvey, V. E. (1972). Mineral Resource Estimates and Public Policy. *American Scientist*, *60*(1), 32–40.
Mew, M. C. (2016). Phosphate rock costs, prices and resources interaction. *The Science of the Total Environment*, *542*(2016), 1008–1012.
Mitra, S., & Boussard, J. (2008). Storage and the Volatility of Agricultural Prices : A Model of Endogenous Fluctuations. *Fordham Department of Economics Discussion Paper Series, No. 2008-1*.
Molinos-Senante, M., Hernández-Sancho, F., Sala-Garrido, R., & Garrido-Baserba, M. (2011). Economic feasibility study for phosphorus recovery processes. *Ambio*, *40*(4), 408–416.
Muth, J. F. (1961). Rational Expectations and the Theory of Price Movements. *Econometrica*, *29*(3), 315–335.
Nerlove, M. (1958). Adaptive Expectations and Cobweb Phenomena. *The Quarterly Journal of Economics*, *72*(2), 227–240.
NRC. (2008). *Minerals, Critical Minerals, and the U.S. Economy*. Washington DC: National Research Council of the National Academies.
Numpy Reference. (n.d.). Numpy Reference Guide v.1.11. Retrieved June 30, 2016, from http://docs.scipy.org/doc/numpy/reference/
OECD. (2016). Inventory on export restrictions on Industrial Raw Materials. Retrieved July 13, 2016, from http://qdd.oecd.org/subject.aspx?Subject=ExportRestrictions_IndustrialRawMaterials
Pandas. (2016). Python Data Analysis Library. Retrieved July 1, 2016, from http://pandas.pydata.org/pandas-docs/stable/
Paulus, M. (2011). *The Economics of International Coal Markets*. Universität zu Köln.
Persona, A. (2014). A half-policy announcement - The implications of China's new export tariffs on phosphates. Retrieved August 4, 2016, from http://www.crugroup.com/about-cru/cruinsight/The_implications_of_a_Chinas_new_export_tariffs_on_phosphates
Piermartini, R. (2004). *The Role of Export Taxes in the Field of Primary Commodities*. *WTO Discussion Paper*. Geneva, Switzerland.
PotashCorp. (2014). Phosphate - Overview. Retrieved March 24, 2016, from http://www.potashcorp.com/overview/nutrients/phosphate/overview/simplified-flow-diagram
Pruyt, E. (2010). Scarcity of Minerals and Metals: A Generic Exploratory System Dynamics Model. In *Proceedings of the 28th International Conference of the System Dynamics Society*. Seoul, Korea.

Qasem, I., van Dongen, T., & De Ridder, M. (2011). *The Global Financial Crisis and the End of the Free Market*. *Issue Brief* (Vol. 3).

Ragnarsdottir, K., Sverdrup, H., & Koca, D. (2011). Assessing long term sustainability of global supply of natural resources and materials. In *Sustainable Development: Energy, Engineering and Technologies - Manufacturing and Environment* (pp. 1–24).

Rausser, G. C., & Swinnen, J. (2011). Governance structures, political economy, and public policy. *American Journal of Agricultural Economics*, *93*(2), 310–316.

Roehner, B. M. (1996). The Role of Transportation Costs in the Economics of Commodity Markets. *American Journal of Agricultural Economics*, *78*(2), 339–353.

Rosemarin, A. (2004). The Precarious Geopolitics of Phosphorus. *Down To Earth: Science and Environment Fortnightly*, *June 30th*, 27–31.

Roth, A. E. (2002). The Economist as Engineer: Game Theory, Experimentation, and Computation as Tools for Design Economics. *Econometrica*, *70*(4), 1341–1378.

Rutland, D., & Polo, J. (2005). *Fertilizer Dealer Handbook: Products, Storage, and Handling*. Muscle Shoals, Alabama: International Center for Soil Fertility and Agricultural Development.

Salant, S. W. (1982). Imperfect Competition in the International Energy Market: A Computerized Nash-Cournot Model. *Operations Research*, *30*(2), 252–280.

Samuelson, P. A. (1952). Spatial price equilibrium and linear programming. *The American Economic Review*, *42*(3), 283–303.

Schlesinger, S. (1979). Terminology for model credibility. *Simulation*, *32*(3), 103–104.

Scholz, F. W., & Stephens, M. A. (1987). K-Sample Anderson-Darling Tests. *Journal of the American Statistical Association*, *82*(399), 918–924.

Schröder, J. J., Cordell, D., Smit, A. L., & Rosemarin, A. (2010). Sustainable use of phosphorus. *Wageningen: Plant Research International*, *Report 357*, 140.

SciPy Reference. (2016). SciPy Reference Guide v.0.17.0. Retrieved March 24, 2016, from http://docs.scipy.org/doc/scipy/reference/

Shapiro, C. (1989). Theories of Oligopoly Behavior. In *Handbook of Industrial Organization* (pp. 329–414).

Sterman, J. (2000). *Business Dynamics: Systems Thinking and Modeling for a Complex World*. McGraw Hill.

Swinerd, C., & McNaught, K. R. (2012). Design classes for hybrid simulations involving agent-based and system dynamics models. *Simulation Modelling Practice and Theory*, *25*(2012), 118–133.

Syers, J. K., Johnston, A. E., & Curtin, D. (2009). Efficiency of Soil and Fertilizer Phosphorus Use: Reconciling Changing Concepts of Soil Phosphorus Behaviour with Agronomic Information. *FAO Fertilizer and Plant Nutrition Bulletin*, *Number 18*.

Sympy Development Team. (2016). Sympy 1.0 documentation. Retrieved July 1, 2016, from http://docs.sympy.org/latest/index.html

Takayama, T., & Judge, G. G. (1964). Spatial Equilibrium and Quadratic Programming. *Journal of Farm Economics*, *46*(1), 67–93.

Talboys, P. J., Heppell, J., Roose, T., Healey, J. R., Jones, D. L., & Withers, P. J. A. (2016). Struvite: a slow-release fertiliser for sustainable phosphorus management? *Plant and Soil*, *401*(1-2), 109–123.

Taylor, R. C., & Moss, D. L. (2013). *The Fertilizer Oligopoly: The Case for Global Antitrust Enforcement* (No. 13-05). Washington DC: The American Antitrust Institute.

Thennakoon, J. (2015). Political Economy of Altering Trade Restrictions in Response to Commodity Price Spikes. *Review of Development Economics*, *19*(2), 434–447.

Tilton, J. E. (2003). *On Borrowed Time? Assessing the Threat of Mineral Depletion*. Washington DC: Resources for the Future.

Tinbergen, J. (1930). Bestimmung und Deutung von Angebotskurven Ein Beispiel. *Zeitschrift Für Nationalökonomie*, *1*(5), 669–679.

United Nations. (2016). UN Comtrade Database. Retrieved from http://comtrade.un.org

United States Securities and Exchange Commission. (2005). Agreement between Office Cherifien des Phosphates and Mississippi Phosphates Corp. Retrieved from www.sec.gov/Archives/edgar/data/1444754/000119312508209721/dex101.htm

USGS. (2016). *Phosphate Rock. Mineral Commodity Summaries 2016*. Reston, VA: United States Geological Survey.

van der Weijden, W. J., Hees, E., Bastein, T., & de Haes, H. A. U. (2013). *The geopolitics of raw materials for agriculture and food production*. Platform Agriculture, Innovation & Society.

Van Vuuren, D. P., Bouwman, A. F., & Beusen, A. H. W. (2010). Phosphorus demand for the 1970-2100 period: A scenario analysis of resource depletion. *Global Environmental Change*, *20*(3), 428–439.

von Horn, J., & Sartorius, C. (2009). Impact of supply and demand on the price development of phosphate (fertilizer). *Fraunhofer Institute Systems and Innovation Research*, 45–54.

Walan, P. (2013). *Modeling of Peak Phosphorus: A Study of Bottlenecks and Implications*. Uppsala University.

Wan, R., & Boyce, J. R. (2013). Non-renewable resource Stackelberg games. *Resource and Energy Economics*, *37*(2014), 102–121.

Waugh, F. (1964). Cobweb models. *Journal of Farm Economics*, *46*(4), 732–750.

Western Sahara Resource Watch. (2014). *P for Plunder*. Retrieved from http://afrika.dk/sites/afrika.dk/files/p_for_plunder_2014_web.pdf

Weterings, R., Bastein, T., Tukker, A., Rademaker, M., & de Ridder, M. (2013). *Resources for our Future: Key Issues and Best Practices in Resource Efficiency*. The Hague Centre for Strategic Studies and TNO.

World Bank. (2016). Commodity Price Data. Retrieved from http://data.worldbank.org/data-catalog/commodity-price-data

World Trade Organization. (2010). World Trade Report 2010: Trade in natural resources. Geneva, Switzerland: World Trade Org.

Yang, Z. (2013). Is the Leading Role Desirable?: A Simulation Analysis of the Stackelberg Behavior in World Petroleum Market. *Computational Economics*, *42*(1), 133–150.

Yücel, G. (2012). A novel way to measure (dis) similarity between model behaviors based on dynamic pattern features. In *Proceedings of the 30th International Conference of the System Dynamics Society*. Sankt Gallen, Switzerland.

Yücel, G., & Kwakkel, J. H. (2011). Clusterer. Retrieved July 18, 2016, from simulation.tbm.tudelft.nl/ema-workbench/ema_documentation/analysis/clusterer.html

1. Model implementation: objects and software implementation

This appendix contains a description of the quantitative model components: (i.) reserve, company and buyer objects, (ii.) stock-flow structures for mining facilities and processing facilities, (iii.) a Cournot-Nash market equilibrium mechanism for clearing markets. At the end of the appendix the software implementation is also discussed.

Reserve, company and buyer objects

As stated above there are three types of objects that are incorporated in the model: reserves, companies and buyers. The implementation of each of these objects will now be described by specifying its attributes, initialisation and its methods or functions. The first object that has been implemented is of the class **reserve**, objects of this class describe the reserves of phosphate rock in a certain region. Reserves are modelled in the dynamic tradition of McKelvey (1972), i.e. their size is directly related to the market price for phosphate rock. Furthermore, the cost of extracting phosphate rock from the reserves increases with cumulative output according to a pre-parameterised strictly increasing function (Tilton, 2003). The parameterisation of this cost function is such that extraction costs are equal to currently empirically estimated extraction costs (see the cost differentiation curve in Gustin & Idoniboye, 2015), and such that current reserve size corresponds to the current price for phosphate rock in the market (World Bank, 2016). In some runs, an extraction cost jump is implemented in the cost curve to be able to reflect the assumption of bimodality of the curve (after Tilton, 2003). The most important attributes – and the corresponding methods to iteratively update these attributes – are thus connected to cumulative output and resulting extraction costs over time. Reserve size is not explicitly calculated over time.

The second object that has been implemented is of the class **company**. There are three different types of companies: mining companies, fertilizer processing companies, and integrated companies (that employ both activities). Because companies are relatively intelligent decision makers, their set of attributes and methods is also the most elaborate. Firstly, they operate ageing chains; more on the workings of these stock-flow structures is shown below. Companies also have a number of methods that make it able to produce rock from their mining facilities and pass it on to processing facilities – be it through a market in the case of mining companies, or directly in the case of integrated companies. Furthermore, rock inputs into the processing facilities are translated into finished phosphate fertilizer products (specified in their P_2O_5-contents, the working ingredient), which can then be put into the fertilizer market. Next to this, they have a cost structure both for extraction and processing (far more detail in terms of microeconomics is given in Cairns, 1998). Companies mining from the same reserve during a single period in time have equal extraction cost. Cost differentiation over different companies having mining facilities is implemented in the global market model by adding a cost extraction mark-up to extraction cost of the reserve.

The last important set of functions incorporated in the company-objects describes two essential decision-making mechanisms that govern the overarching behaviour of companies in the market: the capacity utilisation mechanism and the capacity investment mechanism. The workings of these mechanisms have been based upon Cairns (1998) presenting stylised facts on capacity constraints as well as irreversibility of investments. It must be noted that companies in the quantitative model implementation do not have a sense of optimal production in the classic sense of Dasgupta & Heal (1974) and Hotelling (1931). Both decision mechanisms are specified for mines as well as for processing facilities.

Companies decide on the basis of the historic demand for their products in the market – according to two different decision mechanisms, adaptive expectations (Nerlove, 1958) or memory expectations (cf. a mechanism named in Muth, 1961) – how much of their mining and processing facility they will put to work in the coming quarter. Adaptive expectations are formed by taking into account half of the change in supply in updating the previous expected supply. Companies form memory expectations by taking the average of the previous four supplies to market. In the case of phosphate supply expectations, companies furthermore take into account overall growth of the market to strengthen their heuristics. Resulting decisions on capacity utilisations are then taken into account in production of the next quarter. Specification of this decision-making mechanism is related to literature on cobwebs (Kaldor, 1934; Waugh, 1964).

The second mechanism causes companies to invest and divest in their mining and processing capacities according to fixed propensities to invest and divest. To decide upon investments they use the same expectation mechanisms as described above for capacity decisions. In a typical situation a company would like to have a buffer capacity of about 20%, and thus its desired processing capacity will be 125% of what is the current demand for its product. If its current capacity is such that its buffer is only 10% it will start investing in new processing capacity at a certain speed (relative to its propensity to invest), such that in a few quarters the buffer capacity will be larger. The results of this decision mechanism are thus amounts of planned mining capacity and processing capacity and amounts of lost unprofitable mining capacity and processing capacity. These changes are then taken into account in the stock-flow structure in the next quarter. The mining and processing capacity for instance are thus increased after a construction delay.

The third type of object that has been implemented is of the type **buyer**. These objects are no more than sets of attributes of demand curves that can be changed over time. There are two types of buyers: rock buyers and fertilizer buyers. The rock buying party is an aggregated version of rock demand by different processing companies that need rock because they do not have enough phosphate rock coming directly from mines themselves. There is a limit implemented on the retraction of demand by companies of 50% of the previous demand. This prevents excessive cyclic behaviour on the level of the company. An amount of phosphate rock that is directly used is added to this. Size of this demand is fixed at 10% of fertilizer demand. Buyer parameters such as maximum utility – derived from a minimal margin on rock input over processing rock – and amounts needed are translated into an inverse demand function.

The fertilizer buying party is an aggregated buyer representing all demand for P_2O_5-containing fertilizer in a certain region. In normal price ranges demand is highly inelastic. The demand curve is build up of four parameters, which are: (i.) maximum value of lost food production, (ii.) minimum value of lost food production, (iii.) and a relatively stable quantity demanded, and finally (iv.) a maximum quantity demanded. Every quarter, an inverse demand curve is constructed that describes the inelastic demand situation for phosphate fertilizers; this demand curve consists of a linearly sloping piece (describing elastic demand in high price ranges) and an exponentially sloping piece (describing inelastic demand in normal price ranges). The size of the demand parameters can be tailored to exact demand circumstances.

Stock-flow structures for mining and processing

Mining and processing facilities are described as an ageing chain in the system-dynamics sense (Sterman, 2000). They are used to describe each company's capacity to mine rock from the reserve and to process phosphate rock into phosphate fertilizers (these structures are taken directly from Pruyt, 2010). Every company thus also has its own ageing chain structures. Both structures are constituted of two stocks and four flows. The two stocks describe amounts of capacity under construction and in operation respectively. The four flows describe amounts of capacity being planned, being commissioned, being decommissioned because of end-of-lifetime and lastly being decommissioned through the company deciding to divest from mining or processing capacity. The stock-flow structures are directly implemented within the Python programming environment using a set of scripts written by another developer (Herman, 2014). This stock-flow implementation uses a wrapper around an integrator from the scientific computing package SciPy (SciPy Reference, 2016).

Cournot-Nash market clearing mechanism

A Cournot-Nash type market clearing mechanism represents both the fertilizer and the phosphate rock market. In the Cournot-Nash type market companies decide on the amounts they supply in the market assuming that their competitors do not change their outputs. The equilibrium then "describes the set of self-enforcing actions from which no firm would unilaterally wish to deviate" (Shapiro, 1989: 334). Kolstad & Burris (1986) describe both a spaceless and a spatial implementation of the market clearing mechanism, structurally investigating supply quantities and resulting profits as well as conditions for entering an imperfectly competitive market equilibrium. The analytical background to the spatial Cournot-Nash problem is provided in the next appendix.

To solve for the market equilibrium these analytical conditions for finding market equilibrium are translated into a numerical optimisation problem, see also the next appendix. Kolstad & Mathiesen (1991) describe how the Cournot-Nash equilibrium can be found using computational optimisation. They describe the translation of the equilibrium search problem into a sequential linear complementarity problem. This sequential linear complementarity problem actually is an iterative linearization of the non-linear optimisation problem for finding the market equilibrium. The resulting linear complementarity programming problems are translated to quadratic optimisation problems that are implemented and solved using the Python package CVXOPT (Andersen et al., 2015). The optimisation then takes as an input the dynamically changing information on capacities to supply, cost structures and the demand curve of rock and fertilizer buyers. The spatial commodity market model implementation is comparable to implementations used by Paulus (2011) and Salant (1982) which both also use Cournot-Nash equilibria, and is highly related to original work by Enke (1951), Samuelson (1952) and Takayama & Judge (1964) who developed spatial equilibrium finding techniques.

Software implementation

A number of different model building blocks have been combined into one working programming model. A considerable number of Python packages have been used. These include – repeating the ones that were already cited above: Scipy, Numpy and Pandas for data structure, calculation and numerical integration purposes (Numpy Reference, n.d.; Pandas, 2016; SciPy Reference, 2016), a Python implementation of stock-flow structures (Herman, 2014), a symbolic mathematics package for the Cournot-Nash formulation, Sympy (Sympy Development Team, 2016), a convex optimisation package for implementing and solving the Cournot-Nash equilibrium finding problem, Cvxopt (Andersen et al., 2015), a design of experiments package for generating Latin Hypercube Sampling parameters used in running the model, pyDOE (Lee, 2014), and lastly the Python-integrated multiprocessing package for running the model in a parallel core setting speeding up runtime by roughly a factor twelve on the computer setup that has been used to run the model.

2. Model implementation: Cournot-Nash market equilibrium

Both the phosphate rock as well as the phosphate fertilizer market incorporated in the quantitative model is cleared using a Cournot-Nash equilibrium structure. This appendix presents an exemplary analytical setting of the equilibrium problem and shows how a solution can be found – the material below builds strongly on the formulation provided by Kolstad & Burris (1986). A typical Cournot-Nash setting in the quantitative model consists of about five sellers and three buyers in three regional markets. Here an exemplary situation is presented with two regional markets, two producers and two buyers.

Let the two sellers – located in market 1 respectively market 2 – have amounts S_1 and S_2 in storage (amounts in thousands of tonnes); they cannot supply more to market than what they have in store for a typical quarter. The sellers have marginal costs c_1 and c_2 to deliver their produce (cost in $/ton). The buyers are completely characterised by an inverse demand curve which signals price for every amount supplied to the market. Every regional market contains one buyer, let the inverse demand curves be denoted as $P_1(Q_1)$ and $P_2(Q_2)$ with $Q_1 = q_{11} + q_{21}$ and $Q_2 = q_{12}+q_{22}$. Transportation cost between the markets is given by τ_{ij} for i and j in {1,2}. Profits for the two sellers can now be written as:

$$\pi_1 = (P_1(Q_1) - \tau_{11}) \cdot q_{11} + (P_2(Q_2) - \tau_{12}) \cdot q_{12} - c_1 \cdot (q_{11} + q_{12}) - 15 \cdot e^{((q_{11}+q_{12})-S_1)}$$
$$\pi_2 = (P_1(Q_1) - \tau_{21}) \cdot q_{21} + (P_2(Q_2) - \tau_{22}) \cdot q_{22} - c_2 \cdot (q_{21} + q_{22}) - 15 \cdot e^{((q_{21}+q_{22})-S_2)}$$

The last term in each of the profit functions is a soft constraint implementation of the limit on the amount of produce that can in total be supplied to market due to storage constraints. Companies need to pay an artificial oversupply fee if they deliver more then their capacity in storage S_1 respectively S_2.

Conditions for a Cournot-Nash equilibrium are now as follows, we look for a set of supply decisions q_{ij} for i and j in {1,2} such that each seller maximises its profit – under the Cournot conjectural variation assumption that sellers do not take the other sellers supply decisions into account in determining their output. The Kuhn-Tucker conditions for profit maximisation give the following problem (Kolstad & Mathiesen, 1991):

$$-\frac{\partial \pi_i}{\partial q_{ij}} \geq 0 \quad ; \quad \frac{\partial \pi_i}{\partial q_{ij}} \cdot q_{ij} = 0 \quad ; \quad q_{ij} \geq 0 \qquad \forall\, i,j \in \{1,2\}$$

The above problem precisely is a complementarity problem in a mathematical sense and the solution to the Cournot Nash problem can be found by solving this problem through numerical optimisation. In general however the profit function π_i (due to the presence of the oversupply fee and nonlinearities in the inverse demand curve) and the inverse demand curve P_j are nonlinear (due to inelasticity of demand in the market). Thus to swiftly solve the problem it needs to be linearized first. The subsequent linearization of the problem into a linear complementarity problem is done multiple times until a desired convergence is reached. These procedures are elaborately described in Kolstad & Mathiesen (1991).

3. Model implementation: struvite recycling estimates

This appendix holds the background to the estimates used in the parameterisation of the recycling policy measure. The speed with which this technological innovation is rolled out all over Europe is difficult to predict, therefore a feasible rollout path has been estimated by looking at the constituting factors that determine the eventual amount of recycled struvite. According to literature struvite recycling currently is the most feasible method to recover phosphorus flows and reuse them (Kataki et al., 2016; Le Corre et al., 2009). The estimate thus investigates what would be a plausible amount of P_2O_5-equivalent struvite that can be recycled per year by the time it is 2030, under the assumption that policymakers clearly choose to stimulate use of the technology in wastewater treatment plants all over Europe.

Currently, about 510 million people live in Europe, continuing current trends of population growth, about 530 million people will live in Europe by 2030 (Eurostat, 2016). Seen over the whole of Europe, in all parts of the continent at least 70% of wastewater is collected, although it is not always treated that much. In most Northern, Central and Southern countries however up to 90% of wastewater is collected of which over 70% is treated with tertiary methods (European Environment Agency, 2013). A rough estimate of wastewater ending up in the treatment system is thus about 70%. This might easily grow a lot towards 2030 – observing current trends towards more wastewater being treated. According to literature from every cubic metre of wastewater about 1 kg of struvite can be retained (Molinos-Senante et al., 2011). Under the assumption that 20% of water ending is treated for struvite recovery – which would be the results of a conscientious stimulation of use of the technology, the total production of struvite from wastewater can reach 4.4 million tonnes by 2030. This is equivalent to 1.2 million tonnes of P_2O_5 yearly production (using the same conversion factor as Talboys et al., 2016).

Continuing to sketch the implications of such a yearly struvite production in terms of economic benefits, estimated market prices from literature can be used. Estimates from literature range between € 188-€763 per tonne (Molinos-Senante et al., 2011). Meaning that possible economic benefits from selling struvite as a fertilizer range broadly between € 830 million and € 3.360 million yearly.

4. Model verification and validation

This appendix discusses the verification and validation to which the quantitative model implementations have been subjected. Both versions of the quantitative model – the aggregated version and the multi-region version – were elaborately verified and validated.

Verification

The verification process that has taken place consists of three steps: (i.) extensive code walkthrough, (ii.) carefully retracing translation of quantitative model criteria, (iii.) mass flow balance analysis. It thus clearly represents a “substantiation that a computerized model represents a conceptual model within specified limits of accuracy” (Schlesinger, 1979: 104).

The code walkthrough has had two goals. Firstly, the code had to be screened for mistakes in the programming implementation. About a dozen minor mistakes have been signalled, after which the code was changed. Types of mistakes that were found were in data handling and in special cases in which model implementation did not do what it was expected to do. Secondly, key sources of instability on the level of the programming code have been signalled. In this way, when experimenting with the model, those parameter combinations for which the model does not work can more easily be identified.

By carefully retracing the process of constructing the quantitative model implementation, the conceptual concessions that needed to be done to be able to implement the model have been found. These concessions are discussed in section 6 and in section 10 of the main text. Key points of attention where the quantitative model(s) deviate from the criteria as set beforehand are in the representation of supplier-buyer negotiations by demand curves, the lack of a market for recycled phosphorus, the lack of being able to take into account dynamic market structure, and the lack of being able to let companies and exporting countries endogenously decide on using market power and export restrictions respectively.

In terms of mass flow balance analyses a number of tests have been done. For this purpose both all rock and all P_2O_5-flows through the model have been analysed. The first check has been to show that the amount of cumulative output from all reserves is equal to the total amount of rock production. Secondly, all produced rock plus rock that processing companies get for free for initialisation purposes minus rock directly used minus rock that is still in the rock storages of the different companies should be equal – up to a factor of 0.3 – to the total production of P_2O_5. A part of these rock flows go through the rock market, total rock supply should equal total rock actual demand. The same mass balance holds for the fertilizer market, thus total fertilizer supply should equal total actual fertilizer demand, again taking into account fertilizer left in storage at end-of-run-time. The model has been verified to be precise up to a large extent.

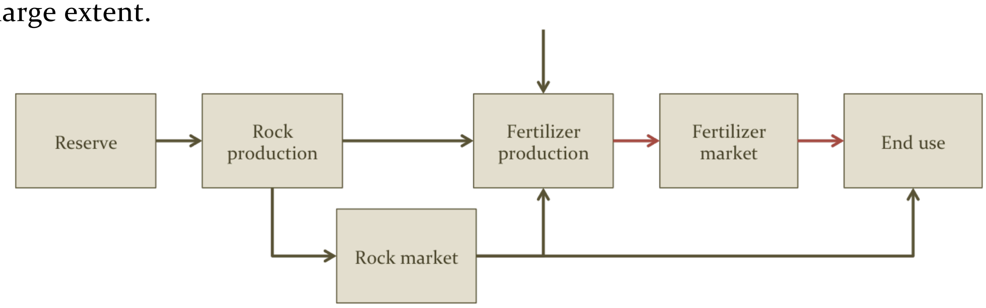

Figure 23 – Rock and fertilizer mass flows through the model

Validation

The validation of the quantitative phosphate market models has been divided in three steps: (i.) checking model input curves, (ii.) checking demand dynamics, investment dynamics and price dynamics, (iii.) checking trade flows (under export restrictions). Thus the validation is a "substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model" (Schlesinger, 1979: 104). The intended application of the quantitative phosphate market models is not such as to be able to predict phosphate market dynamics over time, it is rather to explore determinants of that dynamics as well as provide more understanding about different plausible phosphate market development over time. Validation techniques are discussed summarily; at the same time bounds on the model validity are sketched.

Table 19 – Validation steps

Validation step	Content
i. Checking model input curves	• Inverse demand curves • Extraction cost curves
ii. Checking demand, investment and price dynamics	• Demand growth over time • Investment patterns • Price dynamics comparison with historical data
iii. Checking trade flows (under export restrictions)	• General trade flows • Trade flow change due to restrictions

Checking model input curves has amounted to tracing the validity of demand curves in both the aggregated global market model and the three-region model and tracing the validity of extraction cost curves over time. The main conclusion from this analysis is that the inverse demand curves used in the models are valid for the purpose of the phosphate market modelling study. Demand is indeed inelastic in about the way as literature speaks about it (Gruhn et al., 1995; von Horn & Sartorius, 2009), and total phosphate demand worldwide will be in the order of magnitude of 45-50 million tonnes per year (FAO, 2015). The kink in the demand curve is rightly represented at prices of about 2500 to 3000 $/ton, comparable to DAP prices of 1300 $/ton which is where fertilizer demand reduced in the 2009 price spike (Mew, 2016). In the case of the three-region model the demand curve had to be linearized, thus it has not been possible to fully reflect higher-price dynamics. However, this model is not used for extremely long time scales, thus this is not much of a problem. Regional differences between amounts of phosphate demanded are reflected rightly by the demand curves.

Extraction cost curves as a function of cumulative output have been plotted. Eventual extraction costs have been compared to estimates from literature. Eventual phosphate extraction costs are typically in the order of magnitude of 150 to 250 $/ton with some overshoot, for a cumulative output of 30 billion tonnes. This roughly agrees with the estimates about eventual phosphate rock extraction costs as found by Van Vuuren et al. (2010). Differences between single extraction cost curves also reflect the debate on unimodal versus bimodal curves as reflected in Tilton (2003). In the case of the three-region model, the same analysis has been performed.

The second step in the phosphate market model validation has been to trace the validity of demand, investment and price dynamics. Underlying demand growth in the model is seen to be between 50% and 150% in 2065, which compares nicely to the long-term scenarios as used by Van Vuuren et al. (2010). In the short term, the quantitative model implements a bit too much variation around the estimates by FAO (2015), this is however not much of a problem as in this way implications of differing assumptions on demand can be shown. Regional differences in demand growth are also reflected in the three-region market, for it is broadly recognised that African demand growth is projected to be the largest. Growth in South America and Africa towards 2035 is projected to be approximately 35-60 %, in Europe 10-35 %, while in Middle East, Russia and India growth is then between 20-40 %. These broad demand growth differences are valid for the purpose of this modelling study.

Investigating investment dynamics, it is found that mine capacity and processing capacity do grow under certain circumstances to uphold market balance under conditions of growing demand. At the same time the model does not generate big investment cycles. On the level of single companies, there are sometime some of these cycles to be seen, but this cyclic behaviour is only limitedly present. In capacity utilization patterns there are some cycles, but these typically reflect demand cycles on the basis of a few years period.

Price dynamics generated by the models has been compared to historical price dynamics. All historical data is from World Bank (2016). Firstly orders of magnitude have been compared. Phosphate rock prices generated by the model typically range in the order of 100-400 $/ton, which is comparable to historically observed prices. P_2O_5 prices generated by the model range between 1000 $/ton and 3000 $/ton. Taking into account that DAP only contains about 46% P_2O_5 and using the assumption that other ingredients of DAP do not cost that much these prices can be compared to prices of DAP in the range of 500 $/ton to 1500 $/ton which is right compared to historical price data.

The main tool of comparing the dynamic behaviour is a comparison of the order of magnitude of historical logarithm of price variance over rolling windows of 6 years (a measure that is inspired by Elser et al., 2014). Historical time series were indexed at 1975 prices and thereafter analysed. Model time series have been indexed at 2015 and then analysed, to be able to compare the time series in question. The main conclusion of this analysis is that the model underestimates phosphate fertilizer price dynamics and that it sometimes overestimates phosphate rock price dynamics. Under certain conditions the model phosphate rock price jumps a lot between different quarters. This has to do with vertical integration of the market, see also the analysis in the main body of the text.

Analysing trade flows in the multi-region market it is found that all trade flows are relatively logical. Trade in rock to Europe mainly originates in South America and Africa (i.e. Morocco), which is logical because these markets are relatively close to each other – this has also been reflected in the transport cost governing inter-region trade. Rock produced in region 3 mainly goes to domestic phosphate fertilizer production. It is striking that there is some cross hauling between the regional markets – thus phosphate fertilizer is transported from Europe to other regions as well as from those same regions to Europe at the same time. This phenomenon is however not unheard off in oligopolistic trade models, see for instance Brander & Krugman (1983). From the validation it has become apparent that in the basis that export restrictions have the theoretically expected effects on trade flows between countries. Further analysis is part of the main body of the text.

5. Experimental setup I

This appendix contains all parameter values as used in the model experiments done with the global phosphate market model in section 7. Table 20 shows the values and units of all used variables as well as relevant sources and a short overview explanation. Some further explanation is given below.

All parameter values governing extraction cost curves have been broadly based upon observed values in the phosphate market, rock cost is about 13 $/ton in Morocco, price currently is about 115 $/ton and initial global reserve is said to be about 70 billion ton (see sources given in the table). These values have been adapted slightly to accommodate for the right model behaviour. Further parameters governing the extraction cost jump have been estimated to work as would be expected from a careful reading of Tilton (2003). Yet swift model implementation was always a leading motive.

The size of global demand has been parameterised such that actual demand over time fits the observed market demand. The model uses two parameters for this purpose – stable demand and maximum demand. The demand curve of the global phosphate market model has a kink at stable demand and minimum value of lost production. This kink has been placed such that price behaviour roughly fits observed price behaviour during the price spike of 2007-2009. According to Mew (2016) fertilizer demand scaled back under rising prices. This is because agricultural application of fertilizer profits from using seasonal soil buffering capacity. See also the explanation in Appendix 0 and in Appendix 4. A broad range of possible demand growth has been used to be able to sample over broad assumptions of demand growth. Resulting values of global demand in the long term have furthermore been compared with values as given in scenarios from literature (Van Vuuren et al., 2010). The cyclic demand patterns have been used to generate broad ranges of plausible model behaviour. Processing cost growth has been modelled such that there is a slightly rising fuel price trend over time.

All market structure and company decision making behaviour parameters are shown in Table 21 and Table 22. These parameters have been chosen such that the implications of different assumptions about phosphate market structure and underlying company decision-making could be made. A number of parameters have also been set such that phosphate market behaviour is about as would be expected from empirical observations – for instance amounts of capacity of mines and processing facilities available in the market.

Table 20 – Global parameters for aggregated phosphate market model

Variable	*Values and unit*	*Relevant sources*	*Explanation*
Initial rock cost	[13,40] [$/ton]	(Gustin & Idoniboye, 2015; Mew, 2016)	Used to parameterise extraction cost curve
Initial rock price	[150,170] [$/ton]	(World Bank, 2016)	Used to parameterise extraction cost curve
Initial reserve	[10,50] [10^9 ton]	(USGS, 2016)	Used to parameterise extraction cost curve
Shape extraction cost curve	No jump/ jump	(Tilton, 2003)	Switch variable for extraction cost curve between unimodal and bimodal cost curve
Extraction cost jump	[10,150] [$/ton]	-	Size of cost jump if extraction cost curve jump is switched on
Extraction cost jump speed	[1/10,1/8]	-	Speed with which the cost jump takes place relative to changes in cumulative output
Value of lost production, high	[2500,3000] [$/ton]	-	Maximum utility from fertilizer demanded, price plafond in market on medium term
Value of lost production, low	[0.8,0.9]	(Mew, 2016)	Vertical coordinate of demand curve kink between elastic/inelastic line piece (multiplied with VOLP, high)
Stable fertilizer	[10,10.5] [10^6	(FAO, 2015;	Stable demand of fertilizer, horizontal

demand	ton/ quarter]	International Fertilizer Association, 2016; United Nations, 2016)	coordinate of demand curve kink between elastic/inelastic line piece
Maximum fertilizer demand	[1.4,1.5]	-	Multiplied with stable demand
Basic demand growth	[0.003,0.007] [1/quarter]	(FAO, 2015)	Basic underlying demand growth rate
Amplitude long cycle	[1/30,1/20]	-	Amplitude of long cycle in demand pattern, multiplied with demand size
Period long cycle	[16,30] [quarter]	-	Period of long cycle in demand
Period shift demand	[0,1]	-	Fraction of the period of the long cycle in demand along which it is shifted
Minimum processing cost growth	[-0.004,-0.002] [1/quarter]	-	Lower bound of processing cost change per quarter, parameter is later on used to determine time series of processing cost
Maximum processing cost growth	[0.004,0.009] [1/quarter]	-	Upper bound of processing cost change per quarter, parameter is later on used to determine time series of processing cost
Life time mine	[20,40] [years]	-	Average life time of mines in the model
Construction time mine	[5,10] [years]	-	Average construction time of mines in the model
Life time processing	[20,40] [years]	-	Average life time of processing facilities in the model
Construction time processing	[5,10] [years]	-	Average construction time of mines in the model

Table 21 – Global parameters used to determine rock and fertilizer market structure

Variable	*Values*	*Unit*	*Explanation*
Number of companies	[5, 6, 7]	[#]	The total number of companies in the market, simulation of an oligopolistic market, not fully realistic
Market type	Integrated/ separated	-	Integrated market type implies more integrated companies, in separated market type there are more specialised companies
Company size distribution	Even/ uneven	-	Even size distribution implies similarly sized companies, uneven implies specialised companies are twice as big
Initial processing relative to stable demand	[1.4,1.5]	-	Multiplication factor of total processing capacity to stable demand
Initial mining relative to processing	[1.05,1.15]	-	Multiplication factor of total mining capacity to processing capacity, also accommodating for rock direct use

Table 22 – Company parameters to govern cost structure as well as decision-making behaviour

Variable	*Values*	*Unit*	*Explanation*
Processing cost	[170,300] / [100,170]	[$/ton]	High range is for integrated companies, processing companies specialise thus have lower cost
P_2O_5buffer capacity	High: [0.75,0.85], low: [0.85,0.95]	-	Preferred buffer capacity of proc. facility, all companies within one experiment have high or low buffers
Rock buffer capacity	High: [0.75,0.85], low: [0.85,0.95]	-	Preferred buffer capacity of mine facility, all companies within one experiment have high or low buffers
Rock input buffer	High: [1.1,1.2], low: [1.0,1.1]	-	Factor to determine actual demand for rock input, all companies within one experiment have high or low buffers
Propensity to invest rock	High: 1,5, Low: 0.5, Uneven: {0.5,1.5}	-	Multiplication factor investment in mines
Propensity to invest P_2O_5		-	Multiplication factor investment in processing facilities
Propensity to divest rock		-	Multiplication factor divestment in mines
Propensity to divest P_2O_5		-	Multiplication factor divestment processing facilities
Minimal margin on input	High: [1.25,1.75]/[1.5,2], Low: [1,1.5]/[1.25,1.75]	-	Margin factor over rock input to produce P_2O_5, higher parameter = higher margin, low value bounds are for processing companies, they must cope with a lower margin
Expectation type	Memory/ adaptive	-	Mechanism type to determine expected demand for own produce in next quarter
Expectation parameter	0.5 if adaptive/4 if memory	[-]/ [q.]	Adaptive: amount of change with which expectation is updated, memory: number of q. that is looked at

6. Experimental setup II

This appendix contains all parameters of which the value is in principle dependent on regional circumstances. Some other parameters had to be changed to make sure that also the 3-region model is computationally tractable. By varying the parameters found in Table 23 the essential differences between the three regions that are modelled are reflected. Market structural characteristics are sampled in about the same way as in the aggregated global phosphate market model. Relevant market structural parameters are again shown in Table 24. The only company parameter that was changed was the margin over rock input that companies prefer. Due to the dynamics of the rock market in the 3-region market, this parameter is sampled in [1,1.25] for processing companies and in [1,1.5] for all other companies.

Table 23 – Regional parameters for three-regional phosphate market model

Variable	*Region 1 – South America & Africa*	*Region 2 - Europe*	*Region 3 – Middle East, Russia & India*	*Unit*	*Relevant sources*
Initial rock cost	[25,50]	[50,100]	[50,100]	[$/ton]	(Gustin & Idoniboye, 2015; Mew, 2016)
Initial rock price	[120,170]			[$/ton]	(World Bank, 2016)
Initial reserve	[10,50]	-	[2, 6]	[10^9 ton]	(USGS, 2016)
Shape extraction cost curve	No jump/jump			-	(Tilton, 2003)
Extraction cost jump	[10,150]			[$/ton]	-
Extraction cost jump speed	[1/10,1/8]			-	-
Value of lost production, high	[2500,3000]			[$/ton]	(Mew, 2016)
Stable fertilizer demand	[8.2/4,8.4/4]	[2.5/4,2.7/4]	[9.4/4,9.6/4]	[10^6 ton/ quarter]	(FAO, 2015; International Fertilizer Association, 2016)
Maximum fertilizer demand	[1.2,1.4]			-	-
Basic quarterly demand growth	[0.005,0.007]	[0.002,0.004]	[0.003,0.005]	[1/quarter]	(FAO, 2015)
Amplitude long cycle demand	[1/30,1/20]			-	-
Period long cycle demand	[16,30]			[quarter]	-
Period shift demand	[0,1]			[-]	-
Minimum processing cost growth	[-0.004,-0.002]			[1/quarter]	-
Maximum processing cost growth	[0.005,0.009]			[1/quarter]	-
Life time mine	[20,40]			[years]	-
Construction time mine	[5,10]			[years]	-
Life time processing	[20,40]			[years]	-
Construction time processing	[5,10]			[years]	-
Number of companies	[2,3]	2	[2,3]	[#]	-

Table 24 – Global parameters used to determine rock and fertilizer market structure

Variable	*Region 1*
Market type	Integrated/separated
Company size distribution	Even/uneven
Initial processing relative to demand	[1.05,1.10]
Initial mining relative to processing	[0.9,0.95]

7. Time series clustering

In analysing the model results time series clustering methods have been used. The goal of a clustering algorithm is to group a large set of time series into a number of homogenous sets of time series. The method that was used is an agglomerative, hierarchical dynamic time series-clustering algorithm based on the mean squared error-distance (Liao, 2005). The algorithm was parameterised such that cut-off happens at a fixed number of clusters – for instance 10. These 10 clusters are then taken as representing the whole set of time series, that has typically consisted of about 2000 time series in this research. Others have developed the scripts that were used, see Yücel & Kwakkel (2011). These scripts have for instance also been used in Kwakkel et al. (2013).

In the main body of the text the ten representative dynamic scenarios are extracted from the results found from the global phosphate market model. A dendogram of inter cluster distances shows the relative characteristics of the clusters. Every root branch of the dendogram presented in Figure 24 represents one cluster of time series. It is seen that there is one extreme outlier: the run with experiment number 1402. Distances within the cluster are at maximum about 600 in terms of mean squared error. Some of the larger clusters – for instance the ones having more than 400 members – might be separated in multiple clusters. Yet, for the current purpose the 10 representative time series found suffice.

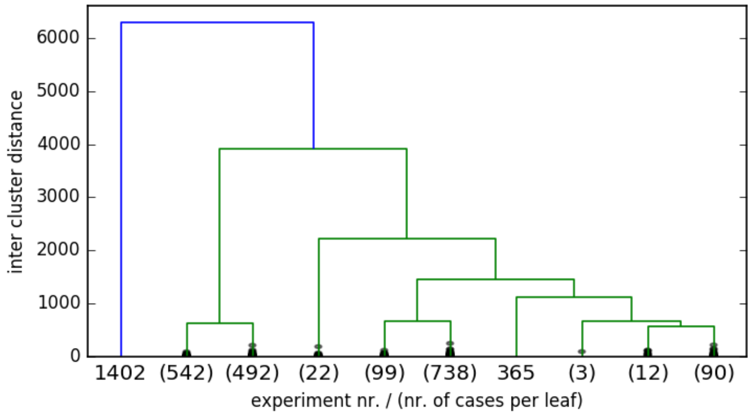

Figure 24 – Dendogram of inter cluster distances between the 10 clusters that were found from the results of the model experiments with the global phosphate market model. On the x-axis every root of the tree represents the time series within one cluster – two clusters consist of only one time series. On the y-axis is the inter cluster distance with respect to the mean squared error metric

Time series clustering is also used in representing the dynamic time series that result from the three-region market model, see appendix 9. In these analyses, a behavioural type distance metric is used that is based upon the metric proposed by Yücel (2012), that was in turn partially based on original work by Ford (1999). The clustering is performed on the time series for the European rock price. The cut-off value for the number of clusters has been fixed in these analyses.

8. Further analysis of model results I

This appendix contains some further analysis of phosphate scarcity building on the results of the global phosphate market model experiments found in section 7.3. The analysis provides more depth into the different types of phosphate scarcity that can arise on the market.

The analysis of dynamic scenarios over time has shown that it is plausible that phosphate market balance is preserved. Yet, multiple types of scarcity characterise the market. Next to the ratio of demand and supply of fertilizer, there is the ratio of demand and supply of phosphate rock, see a comparison over time for the ten representative dynamic scenarios in Figure 25. From the figure it is seen that scenarios in which there is phosphate fertilizer scarcity induce abundance on the phosphate rock market; the value for ratio of demand and supply tends to decrease below 0.5. It is found that sudden oscillatory behaviour in processing capacity (see Figure 11 in the main body of the text) induces a stark increase in phosphate scarcity – as occurs in for instance the scenario represented by the black line. In that case the rock market dries up.

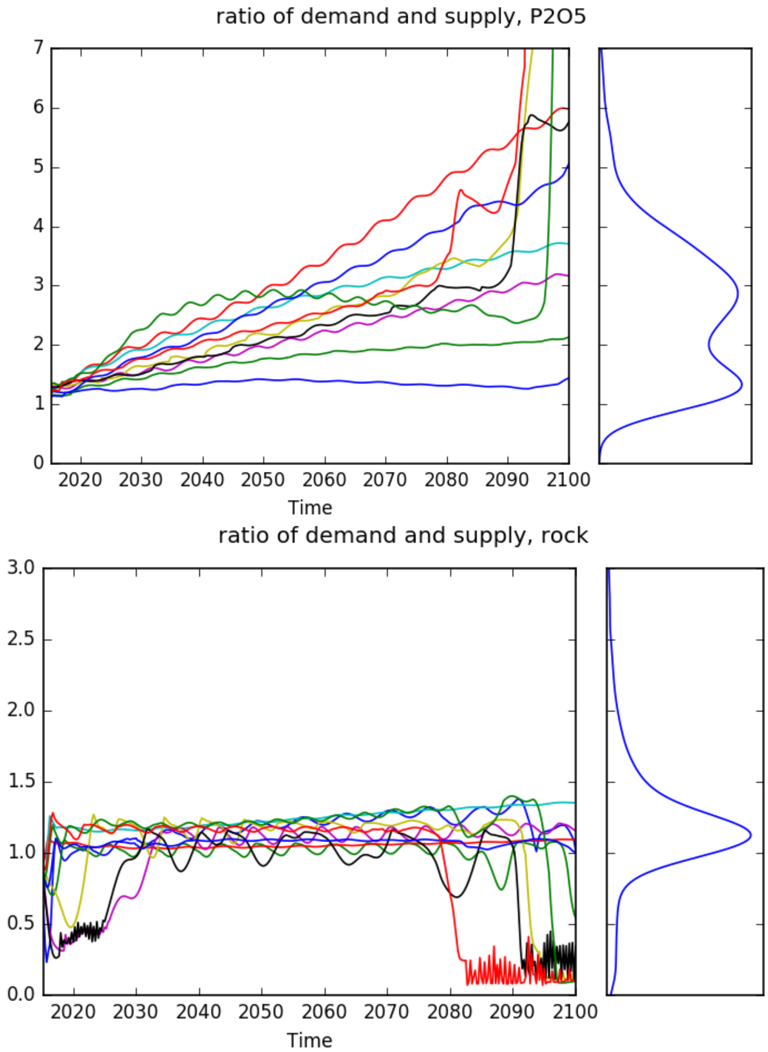

Figure 25 – Ten representative scenarios for ratio of demand and supply for phosphate and rock to 2100. Kernel density estimates are shown for the end values

A distinction must also be made between the ratio of demand and supply on the one hand and the ratio of demand and capacity on the other hand, see Figure 26. Using this distinction the emergence of imbalances in terms of supply and in terms of capacity can be better understood. The difference is most pronounced in the model experiments that show strongly oscillatory behaviour. Take for instance the scenario represented by a black line. Oscillatory behaviour is far more pronounced in the ratio of demand and capacity than it is in the ratio of demand and supply, cf. with the black line at the left of Figure 25.

This cross-comparison shows by example that capacity available in the market changes far less than does supply in the market. In the case of a scarcity of capacity – which directly implies a scarcity of supply – investment in processing facilities shall need to be started up. Producing extra fertilizer only has a limited delay – a quarter year in the model – whereas investments only come online in about 5 to 10 years. This creates market inertia that can only be overcome after a processing capacity investment delay. When companies do not pick up on the trend towards scarcity, it increases over time. This clearly happens in some scenarios.

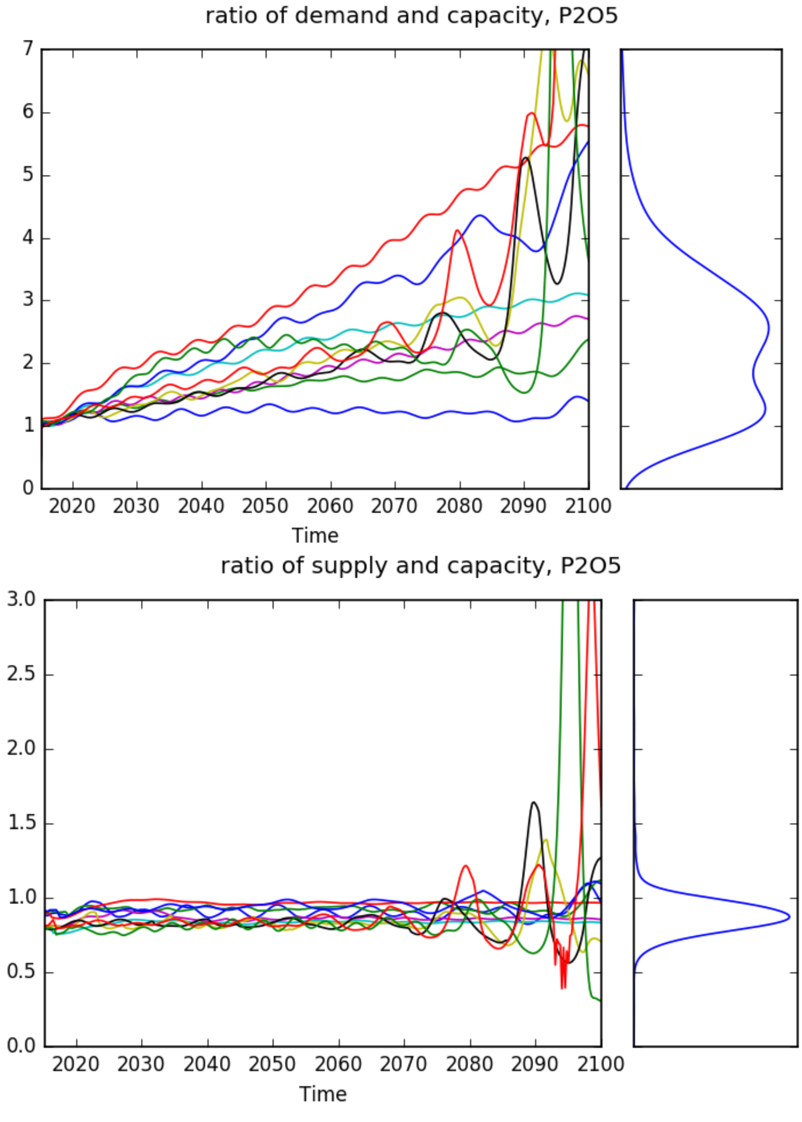

Figure 26 – Ten representative scenarios for ratio of demand and capacity for phosphate, and for ratio of supply and capacity for phosphate to 2100. Kernel density estimates are shown for the end values

9. Further analysis of model results II

This appendix provides background to the analysis of the effect of export and production restrictions as provided in section 9. Firstly, the underlying numbers of the violin plots given in the main body of the text is shown. Some insight into dynamic model behaviour and the dynamic analysis of the effect of individual restrictions on Europe is given. The effect of restrictions is analysed from the point of view of the region where the restriction takes effect. Throughout this appendix use is made of statistical methods to compare distributions over simulation runs, background information on these methods is in appendix 10.

Detailed analysis of individual restrictions from a European perspective

The detailed background of the numbers used in the main text to investigate the individual export restrictions from a European perspective is shown in Table 25. Key indicators for effects of the individual restrictions on price dynamics, trade dynamics and regional scarcity in Europe are given. Distribution indicators for price effects are in Table 26t.

*Table 25 – Results summary of experiments with individual export restrictions from a European perspective, 10%, 50% and 90%-quantiles of change in key indicators between Q4 2019 and Q1 2021 are shown, quantiles of runs without restrictions are shown in grey. Every row reflects 200 model runs. Results are significantly different from the reference distribution at the 1 %-level, except at **

European perspective *From Q4 2019-Q1 2021*	*Effect on price dynamics* Change in rock price differential			*Effect on trade dynamics* Change in rock imports			*Effect on regional scarcity* Change in regional phosphate scarcity		
Exporter measure	10%-q	50%-q	90%-q	10%-q	50%-q	90%-q	10%-q	50%-q	90%-q
No measure	-6.9 $/ton	+0.2 $/ton	+9.9 $/ton	-33.7 %	+2.0 %	+74.4 %	-3.6 %	+2.1 %	+9.7 %
Export tax rock (*100 $/t. by region 1*)	+9.9 $/ton	+17.8 $/ton	+30.0 $/ton	-41.2* %	-3.1* %	+63.8* %	-4.5* %	+1.5* %	+8.4* %
Production limit on rock (*0.7 in region 3*)	-8.3 $/ton	+2.1 $/ton	+26.6 $/ton	-57.9 %	-9.5 %	+63.8 %	-1.5 %	+4.8 %	+15.4 %
	Change in phosphate price differential			Change in phosphate imports			Change in regional phosphate scarcity		
No measure	-23.0 $/ton	-1.5 $/ton	+11.8 $/ton	-10.2 %	-1.5 %	+7.3 %	-3.6 %	+2.1 %	+9.7 %
Export tax P_2O_5 (*300 $/t. by region 3*)	+2.0 $/ton	+26.5 $/ton	+50.5 $/ton	-14.0 %	-4.6 %	+2.7 %	-1.1 %	+3.6 %	+10.9 %
Production limit on P_2O_5 (*0.7 in region 3*)	-13.5 $/ton	+14.0 $/ton	+49.3 $/ton	-24.3 %	-12.2 %	-2.5 %	+3.2 %	+13.1 %	+23.0 %

Table 26 – Price changes over time on the European market during production restrictions, 10%, 50% and 90%-quantiles of change in key indicators between Q4 2019 and Q1 2021 are shown. Comparison is made with runs in which no measure was implemented. Results are significantly different from the reference distribution at the 1 %-level. The results of every row are based on 200 model runs

From Q4 2019-Q1 2021	Change in European rock price		
Exporter measure	10%-q	50%-q	90%-q
No restriction (*number for rock*)	-213.4 $/ton	+15.5 $/ton	+238.2 $/ton
Production limit on rock (*by region 3*)	-114.1 $/ton	+75.3 $/ton	+293.5 $/ton
	Change in European phosphate price		
No restriction (*number for phosphate*)	-89.5 $/ton	+47.7 $/ton	+185.6 $/ton
Production limit on fertilizer (*by region 3*)	+49.2 $/ton	+157.6 $/ton	+289.1 $/ton

Dynamic analysis of individual restrictions from a European perspective

The model behaviour of the three-region phosphate market is shown in Figure 27. Representative scenarios have been found by using the time clustering algorithm again. Five clusters were found using the European rock price and a behavioural distance metric, see also appendix 7. Kernel density estimates show that end values of all shown metrics are comparable to the values seen in the global phosphate market model. There is already a slight, endogenous trend towards phosphate scarcity. Rock price dynamics is also quite large.

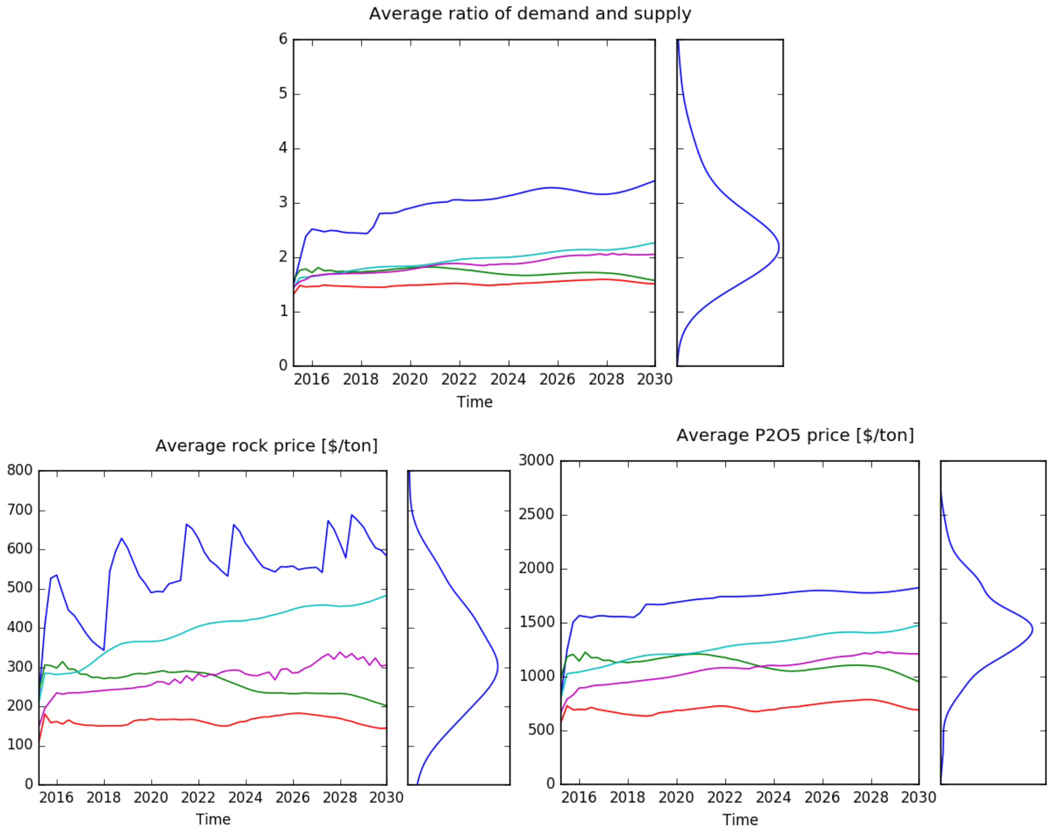

Figure 27 – Five representative scenarios for average rock price [$/ton], average phosphate price [$/ton] and average ratio of demand and supply for phosphate to 2030. Kernel density estimates are shown for the end values

The scenarios in which export taxes are implemented on phosphate rock and phosphate fertilizers are primarily characterised by a price increasing effect in Europe. Figure 28 shows the dynamic effect of these taxes on rock price differential respectively phosphate price differential in Europe. The price differential increasing effect of the export taxation can clearly be observed from the presented representative time series. Both sets of distributions are statistically significantly different at the 1 %-level, see appendix 10. From this dynamic point of view, it can also clearly be seen that price differential increases are not constant over the time of implementation of the taxes. Endogenous market dynamics are still also at work during the period in which the tax is implemented.

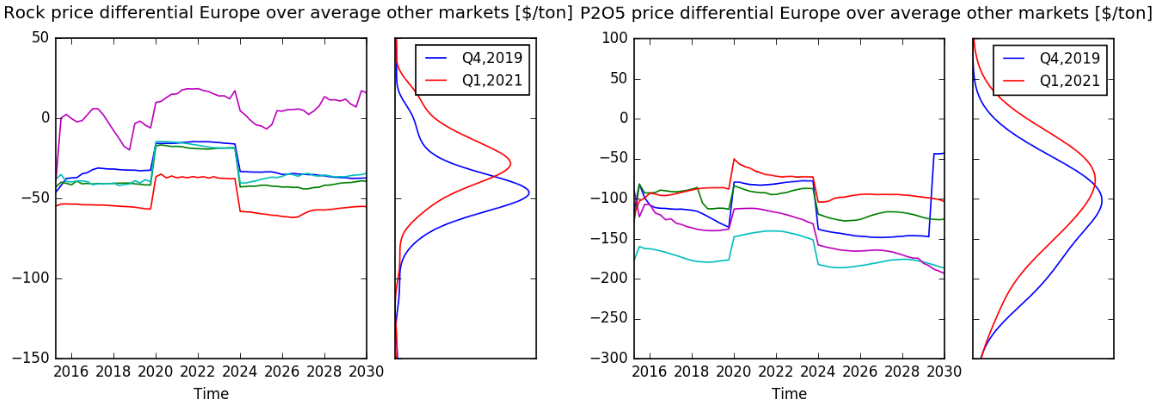

Figure 28 – Primary effects of export taxation on Europe. Left: five representative scenarios for rock price differential Europe – under an export tax of 100 $/ton implemented by region 1 – to 2030. Right: five representative scenarios for phosphate price differential Europe – under an export tax of 300 $/ton implemented by region 3 – to 2030. Kernel density estimates show the distribution of price differential values right before tax implementation (Q4, 2019) and after one year of implementation (Q1, 2021).

The scenarios in which there is an exogenous limit on mine capacity respectively processing capacity are characterised by strongly rising scarcity on the European market. Figure 29 shows these effects. In the left graph it is seen that under a rock production restriction of 30% in region 3, scarcity increases in some of the representative scenarios. Seen over all model runs, phosphate scarcity increases between 2019 and 2021, as exemplified by the statistically significantly different end-value distributions. This increase is however also already seen when no production restriction is implemented. See the analysis in the main body of the text.

The scarcity increasing effect is seen far stronger when processing facilities in region 3 are restricted in their production. All representative scenarios show a considerable increase in European phosphate scarcity at the start of 2020, this is clearly seen from the difference in the distributions shown on the right. These distributions are statistically significantly different at the 1 %-level. Yet, there are runs – see the light blue representative scenario – in which the market can recuperate from this negative effect.

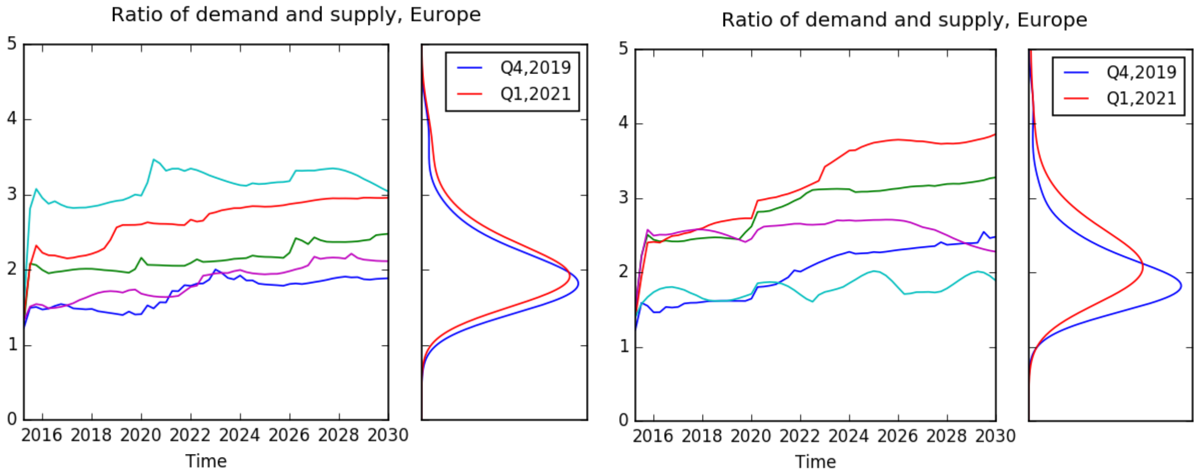

Figure 29 – Primary effects of production restrictions on Europe. Left: five representative scenarios for ratio of demand and supply in Europe – under a rock production restriction at 70% effectuated in region 3 – to 2030. Right: five representative scenarios for ratio of demand and supply in Europe – under a phosphate production restriction at 70% effectuated in region 3 – to 2030. Kernel density estimates show the distribution of phosphate scarcity values right before tax implementation (Q4, 2019) and after one year of implementation (Q1, 2021)

Individual restrictions from phosphate exporter perspective

By changing actor perspective insight is gained in the rationale for instating export restrictive measures. Also, the effects of production restrictions are felt strongest on the regional market where that restriction is active. Table 27 shows a results summary from the perspective of the region that implements the export restriction. In the case of the rock export tax this is region 1. In the case of the phosphate export tax this is region 3.

From the point of view of the implementing region a 100 $/ton export tax decreases rock price differential strongly, see also Figure 30. Median rock price differential change in region 1 is -34 $/ton between Q4, 2019 and Q1, 2021. At the same time, less rock is exported over the same period: median rock trade differential increases by almost 10%. An export tax on phosphate rock has an impact on phosphate scarcity in region 1: median scarcity tends to increase by about 1 %-point less. This scarcity effect is however not statistically significant at the 1 %-level. From the point of view of a phosphate rock exporter, it might still be positive to implement export taxation. Although, a rock price decrease of course means that mining companies within the country get less value for their products. In the case of a 300 $/ton export tax on phosphate fertilizer implemented by region 3, the fertilizer price differential decreases by about 75 $/ton. Median phosphate trade differential increases by more than 90 %: thus far less fertilizers are exported. Therewith, the trend of rising phosphate scarcity in region 3 can be held limited. Phosphate scarcity decreases marginally; the difference is statistically significant.

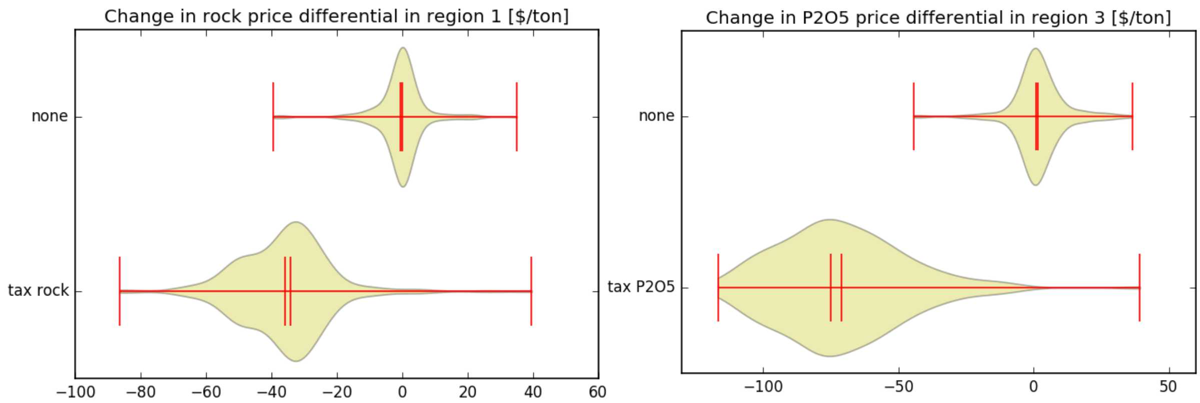

Figure 30 - Violin plots for the effect of export taxation on domestic market price. Change between Q4 2019 and Q1 2021 is shown in: rock price differential in region 1 [$/ton] and in phosphate price differential in region 3 [$/ton]. Kernel density estimates shown are based on 200 runs. Red lines show position of mean, median and extrema

*Table 27 – Overview of the results of experiments with individual export restrictions from the perspective of phosphate exporting countries, 10%, 50% and 90%-quantiles of change in key indicators between Q4 2019 and Q1 2021 are shown. Comparison is made with runs in which no measure was implemented. All results are significantly different from the reference distribution at the 1% level, except: * indicates significance at the 10 %-level. The results of every row are based on 200 model runs*

From Q4 2019-Q1 2021	*Effect on price dynamics*			*Effect on trade dynamics*			*Effect on regional scarcity*		
	Change in rock price differential of implementing region			Change in rock trade differential of implementing region			Change in regional phosphate scarcity of implementing region		
Exporter measure	10%-q	50%-q	90%-q	10%-q	50%-q	90%-q	10%-q	50%-q	90%-q
No tax (*number in region 1)*	-7.7 $/ton	0.0 $/ton	+4.3 $/ton	-71.2 %	+0.1 %	+45.2 %	-3.3 %	+2.4 %	+11.0 %
Export tax rock (*100 $/t. by region 1)*	-51.0 $/ton	-34.1 $/ton	-24.3 $/ton	-19.2 %	+9.4 %	+74.2 %	-4.1* %	+1.5* %	+9.7* %
	Change in phosphate price differential of implementing region			Change in phosphate trade differential of implementing region			Change in regional phosphate scarcity of implementing region		
No tax (*number in region 3*)	-5.9 $/ton	+0.9 $/ton	+11.1 $/ton	-36.6 %	-3.6 %	+23.3 %	-3.2 %	+2.8 %	+10.2 %
Export tax fertilizer (*300 $/t. by region 3*)	-87.7 $/ton	-75.0 $/ton	-58.3 $/ton	+1.9 %	+91.7 %	+264.3 %	-5.8 %	-0.4 %	+5.6 %

A rock capacity utilisation limit causes phosphate rock to become more expensive on the domestic market in region 3. Median rock price increase is almost 80 $/ton. This is of course due to the decrease of rock production caused by the restriction: the median of rock production changes between 2019 and 2021 is -31%. Rock production might even come to a complete standstill due to the production restrictions. Phosphate scarcity increases by 5 %, 2 %-point more than without the production restriction. In the case of a limit on fertilizer production the price increase is 146 $/ton in the median, although price increases of up to 250 $/ton were observed in the model results. Reduction of fertilizer production is between 10 and 30 %. Phosphate scarcity takes a sharp blow, by increasing by an extra 6-12 % on top of endogenous market development. Thus, both the rock production restriction and the fertilizer production restriction cause severely negative effects on the market of region 3.

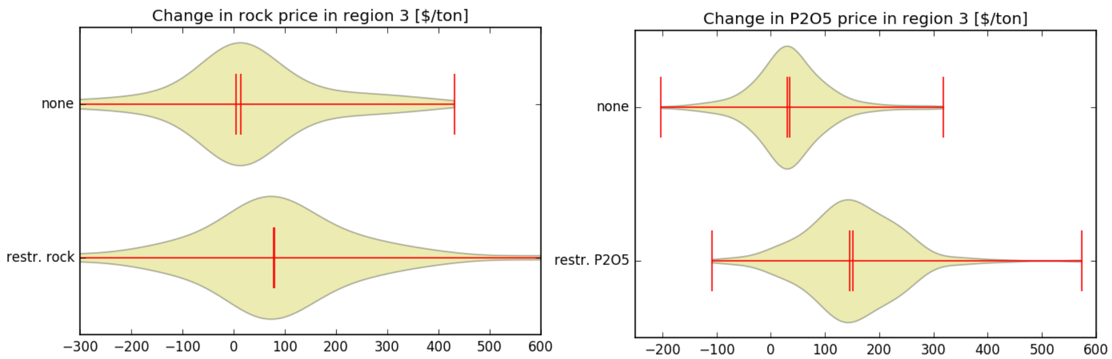

Figure 31 – Violin plots for the effect of production restrictions on domestic market price. Change between Q4 2019 and Q1 2021 is shown in: rock price, region 1 [$/ton] and phosphate price, region 3 [$/ton]. Kernel density estimates shown are based on 200 runs. Red lines show position of mean, median and extrema

Table 28 – Overview of the results of experiments with production restrictions from the perspective of exporting countries, 10%, 50% and 90%-quantiles of change in key indicators between Q4 2019 and Q1 2021 are shown. Comparison is made with runs without restrictions. All results are significantly different from the reference distribution at the 1% level. The results of every row are based on 200 model runs

From Q4 2019-Q1 2021	*Effect on price dynamics*			*Effect on production dynamics*			*Effect on regional scarcity*		
	Change in rock price implementing region			Change in rock production implementing region			Change in phosphate scarcity implementing region		
Exporter measure	10%-q	50%-q	90%-q	10%-q	50%-q	90%-q	10%-q	50%-q	90%-q
No measure (*number in region 3 for rock*)	-205.7 $/ton	+14.4 $/ton	+232.8 $/ton	-5.0 %	-0.3 %	+4.3 %	-3.2 %	+2.8 %	+10.2 %
Production limit on rock (*0.7 in region 3*)	-118.7 $/ton	+77.8 $/ton	+282.1 $/ton	-100.0 %	-31.2 %	-11.1 %	-1.3 %	+5.0 %	+14.4 %
	Change in phosphate price implem. region			Change in phosphate prod. implem. region			Change in phosphate scarcity implem. region		
No measure (*number in region 3 for P_2O_5*)	-42.1 $/ton	+31.0 $/ton	+108.7 $/ton	-12.7 %	-1.0 %	+7.5 %	-3.2 %	+2.8 %	+10.2 %
Production limit on P_2O_5 (*0.7 in region 3*)	+42.1 $/ton	+145.6 $/ton	+248.2 $/ton	-29.6 %	-22.1 %	-10.6 %	+3.8 %	+13.3 %	+21.5 %

Detailed analysis of scenarios and policies

Below are three tables containing detailed numbers on the effects of scenarios of export and production restrictions and importer policies on the European market. In Table 29 the effects on European rock prices are shown, in Table 30 the effects on European phosphate prices and in Table 31 the effects on European phosphate scarcity. The numbers from these tables are extensively used in the analysis provided in the main body of the text. In the tables below asterisks are used to provide more information on the statistical differences between distributions on the given indicators.

*Table 29 – Results of experiments with coherent scenarios from a European perspective, 10%, 50% and 90%-quantiles of ratio of demand and supply in 2018, 2024 and 2030 are shown. All results are significantly different from the reference distribution at the 1% level, except: * indicates there is no statistically significant difference compared to the reference distribution at the 1 %-level, ** indicates significance at the 2.5 %-level. Every row reflects 200 model runs*

Scenario of under-capacity and tax	Phosphate scarcity in Europe in Q1 2018			Phosphate scarcity in Europe in Q1 2024			Phosphate scarcity in Europe in Q1 2030		
Importer measure	10%-q	50%-q	90%-q	10%-q	50%-q	90%-q	10%-q	50%-q	90%-q
No policy & no scenario	1.51	1.82	2.52	1.60	1.99	3.03	1.57	2.14	3.49
No policy	1.50*	1.80*	2.51*	1.82	2.15	3.56	1.74	2.27	4.15
Recycling	1.48*	1.81*	2.53*	1.76	2.15	2.98	1.56**	2.27**	4.10**
Strategic buying	1.47*	1.76*	2.40*	1.28	1.55	2.16	1.74	2.28	3.44
Scenario of tit-for-tat export taxation	Phosphate scarcity in Europe in Q1 2018			Phosphate scarcity in Europe in Q1 2024			Phosphate scarcity in Europe in Q1 2030		
Importer measure	10%-q	50%-q	90%-q	10%-q	50%-q	90%-q	10%-q	50%-q	90%-q
No policy & no scenario	1.51	1.82	2.52	1.60	1.99	3.03	1.57	2.14	3.49
No policy	1.49*	1.83*	2.52*	1.55*	1.93*	2.99*	1.51*	2.06*	3.58*
Recycling	1.49*	1.80*	2.50*	1.50**	1.87**	3.11**	1.41	1.96	4.15
Strategic buying	1.50*	1.85*	2.40*	1.11	1.40	2.17	1.53*	2.10*	3.75*

*Table 30 – Results of experiments with coherent scenarios from a European perspective, 10%, 50% and 30%-quantiles of rock price [$/ton] in 2018, 2024 and 2030 are shown. All results are significantly different from the reference distribution at the 1% level, except: * indicates there is no statistically significant difference compared to the reference distribution at the 1 %-level, ** indicates significance at the 2.5 %-level. Every row reflects 200 model runs*

Scenario of under-capacity and tax	Rock price in Europe in Q1 2018 [$/ton]			Rock price in Europe in Q1 2024 [$/ton]			Rock price in Europe in Q1 2030 [$/ton]		
Importer measure	10%-q	50%-q	90%-q	10%-q	50%-q	90%-q	10%-q	50%-q	90%-q
No policy & no scenario	41.0	239.7	415.0	125.5	260.7	457.0	121.1	287.7	521.3
No policy	58.7*	217.4*	395.7*	194.3	394.6	530.0	186.6	419.5	574.4
Recycling	45.9*	203.8*	377.4*	171.8	403.3	520.0	86.2	389.8	581.3
Strategic buying	58.2*	223.3*	392.7*	180.8	430.7	538.2	231.4	431.4	553.5
Scenario of tit-for-tat export taxation	Rock price in Europe in Q1 2018 [$/ton]			Rock price in Europe in Q1 2024 [$/ton]			Rock price in Europe in Q1 2030 [$/ton]		
Importer measure	10%-q	50%-q	90%-q	10%-q	50%-q	90%-q	10%-q	50%-q	90%-q
No policy & no scenario	41.0	239.7	415.0	125.5	260.7	457.0	121.1	287.7	521.3
No policy	34.7*	209.5*	418.2*	133.9*	285.5*	453.0*	130.3*	270.4*	497.4*
Recycling	-12.7*	226.7*	379.2*	103.6*	292.0*	436.1*	14.4	239.9	420.9
Strategic buying	29.9*	240.9*	417.8*	79.3	317.9	523.9	66.9*	295.4*	520.1*

*Table 31 – Results of experiments with coherent scenario from a European perspective, 10%, 50% and 90%-quantiles of phosphate price [$/ton] in 2018, 2024 and 2030 are shown. All results are significantly different from the reference distribution at the 1% level, except: * indicates there is no statistically significant difference at the 1 %-level compared to the reference distribution, ° indicates the distribution is significantly different at the 5 %-level, ** at the 10 %-level. Every row reflects 200 model runs*

Scenario of under-capacity and tax	P_2O_5 price in Europe in Q1 2018 [$/ton]			P_2O_5 price in Europe in Q1 2024 [$/ton]			P_2O_5 price in Europe in Q1 2030 [$/ton]		
Importer measure	10%-q	50%-q	90%-q	10%-q	50%-q	90%-q	10%-q	50%-q	90%-q
No policy & no scenario	943	1235	1607	1035	1371	1826	985	1467	1932
No policy	910*	1210*	1604*	1259	1491	1947	1171	1540	2086
Recycling	889*	1219*	1674*	1182	1494	1872	983	1537	2106
Strategic buying	892*	1197*	1604*	1319	1560	1911	1132	1545	1945
Scenario of tit-for-tat export taxation	P_2O_5 price in Europe in Q1 2018 [$/ton]			P_2O_5 price in Europe in Q1 2024 [$/ton]			P_2O_5 price in Europe in Q1 2030 [$/ton]		
Importer measure	10%-q	50%-q	90%-q	10%-q	50%-q	90%-q	10%-q	50%-q	90%-q
No policy & no scenario	943	1235	1607	1035	1371	1826	985	1467	1932
No policy	896*	1230*	1654*	977*	1333*	1822*	950*	1393*	1914*
Recycling	913*	1205*	1660*	968**	1302**	1860**	800	1338	2039
Strategic buying	872*	1241*	1652*	1083°	1428°	1905°	947**	1414**	1993**

Effects of importer policies on exporting countries

By changing actor perspective a last time, the effects of the importer policies recycling and strategic buying on other regional markets than Europe can be sketched. In Table 32 and Table 33 the effects of the scenarios and European importer policies on phosphate scarcity in region 1 and 3 are sketched. Background on statistical significance of the differences between distributions of key indicators over the simulations runs is also given. Recycling is found to have a marginally negative effect on phosphate scarcity in both Africa & South America and in Middle East, Russia & India in 2030. Strategic buying has a negative effect on phosphate scarcity in 2024 in these regions. Median phosphate scarcity in both regions increases by an extra 2 to 7 % on top of the effect of the scenarios.

The effect of strategic buying is also seen in rock and phosphate prices. Median rock price in 2024 in region 1 under both scenarios is about 20 $/ton higher when Europe implements strategic buying. Median phosphate price in 2024 in region 1 is also between 20 and 80 $/ton higher when Europe implements strategic buying. Recycling does not have this price increasing effect on the markets of phosphate exporting countries.

*Table 32 – Results of experiments with coherent scenario from the perspective of region 1, Africa & South America, 10%, 50% and 90%-quantiles of ratio of demand and supply, in 2018, 2024 and 2030 are shown. Results are significantly different from the reference distribution at the 1% level, except: * indicates there is no statistically significant difference at the 1 %-level compared to the reference distribution. Every row reflects 200 model runs*

Scenario of under-capacity and tax	Phosphate scarcity in Africa & South America in Q1 2018			Phosphate scarcity in Africa & South America in Q1 2024			Phosphate scarcity in Africa & South America in Q1 2030		
Importer measure	10%-q	50%-q	90%-q	10%-q	50%-q	90%-q	10%-q	50%-q	90%-q
No policy & no scenario	1.71	1.98	2.71	1.81	2.20	3.64	1.80	2.38	4.21
No policy	1.69*	1.97*	2.70*	2.11	2.48	3.96	2.02	2.66	4.98
Recycling	1.65*	1.98*	2.77*	2.09	2.49	3.69	2.05	2.72	5.27
Strategic buying	1.67*	1.96*	2.75*	2.15	2.57	4.00	2.04	2.61	4.35
Scenario of tit-for-tat export taxation	Phosphate scarcity in Africa & South America in Q1 2018			Phosphate scarcity in Africa & South America in Q1 2024			Phosphate scarcity in Africa & South America in Q1 2030		
Importer measure	10%-q	50%-q	90%-q	10%-q	50%-q	90%-q	10%-q	50%-q	90%-q
No policy & no scenario	1.71	1.98	2.71	1.81	2.20	3.64	1.80	2.38	4.21
No policy	1.67*	2.01*	2.68*	1.79*	2.17*	3.44*	1.71*	2.29*	4.00*
Recycling	1.67*	1.96*	2.68*	1.75*	2.12*	3.62*	1.75*	2.35*	5.08*
Strategic buying	1.69*	2.05*	2.72*	1.81*	2.27*	3.50*	1.75*	2.33*	4.36*

*Table 33 – Results of experiments with coherent scenario from the perspective of region 3, Middle East, Russia & India, 10%, 50% and 90%-quantiles of ratio of demand and supply, in 2018, 2024 and 2030 are shown. Results are significant at the 1% level, except: * indicates there is no statistically significant difference at the 1 %-level compared to the reference distribution. Every row reflects 200 model runs*

Scenario of under-capacity and tax	Phosphate scarcity in Middle East, Russia & India in Q1 2018			Phosphate scarcity in Middle East, Russia & India in Q1 2024			Phosphate scarcity in Middle East, Russia & India in Q1 2030		
Importer measure	10%-q	50%-q	90%-q	10%-q	50%-q	90%-q	10%-q	50%-q	90%-q
No policy & no scenario	1.69	1.96	2.73	1.78	2.16	3.52	1.77	2.35	3.94
No policy	1.67*	1.94*	2.66*	2.04	2.46	3.95	1.98	2.57	4.65
Recycling	1.66*	1.96*	2.70*	2.05	2.46	3.53	2.01	2.78	4.95
Strategic buying	1.64*	1.92*	2.63*	2.14	2.49	3.59	2.03	2.61	4.05
Scenario of tit-for-tat export taxation	Phosphate scarcity in Middle East, Russia & India in Q1 2018			Phosphate scarcity in Middle East, Russia & India in Q1 2024			Phosphate scarcity in Middle East, Russia & India in Q1 2030		
Importer measure	10%-q	50%-q	90%-q	10%-q	50%-q	90%-q	10%-q	50%-q	90%-q
No policy & no scenario	1.69	1.96	2.73	1.78	2.16	3.52	1.77	2.35	3.94
No policy	1.65*	1.98*	2.68*	1.76*	2.10*	3.46*	1.69*	2.24*	4.04*
Recycling	1.66*	1.91*	2.63*	1.73*	2.10*	3.78*	1.73*	2.32*	5.04*
Strategic buying	1.65*	2.02*	2.78*	1.79*	2.25*	3.61*	1.70*	2.31*	4.08*

10. Statistical testing of distribution differences

In analysing the model simulation results, statistical testing of distribution differences has been extensively used. This appendix shows which techniques from mathematical statistics have been used in these analyses. A typical situation of comparing distributions on a key model indicator is provided as well as the type of conclusions that have been drawn. The mathematical background to this appendix is in Govindarajulu (1976) and in Scholz & Stephens (1987).

In all analyses of simulation run distribution differences two different statistical tests were used: the 2-sample Kolmogorov-Smirnov test, the k-sample Anderson-Darling test. Both of these tests are implemented in the SciPy-library (SciPy Reference, 2016). The former of these methods tests the null hypothesis that two independent samples are drawn from the same underlying continuous distribution. The result of the test can be found by looking at the resulting p-value, if that value is low the null hypothesis is rejected. The latter of these methods tests the null hypothesis that k samples are drawn from the same underlying population, without having to specify the probability distribution of that population. The result of the test is found by comparing the value of test statistic to specific critical values also given by the algorithm.

A simple example of a statistical test looks again at the effect of an export tax on rock on Europe, see also Figure 32. The distributions for change in rock price differential between 2019 and 2021 are tested with both statistical methods: the Anderson-Darling test statistic is 127.5 and thus larger than the critical value for rejection of the null hypothesis at the 1 %-significance level, the Kolmogorov-Smirnov p-level is in the order of magnitude of 10^{-57}. The distributions are found to be different. The rock export tax has a measurable impact on rock price differential on the European market.

The distributions for change in European phosphate scarcity between 2019 and 2021 are also tested with both statistical methods: the Anderson-Darling statistic is -0.50, smaller than all critical values given, the Kolmogorov-Smirnov p-value is 0.45, too large to reject the null hypothesis. The distributions are not found to be different. The rock export tax does not have a measurable impact on scarcity in Europe.

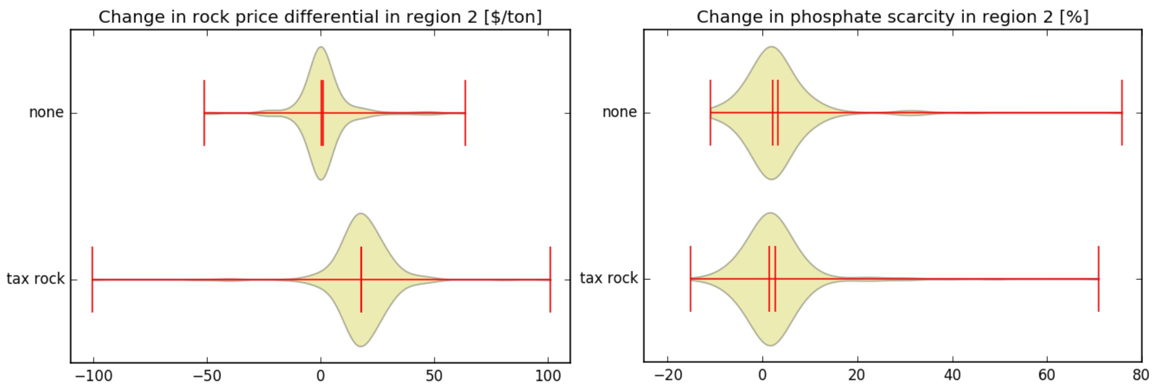

Figure 32 - Violin plots for the effect of a 100 $/ton rock export tax implemented by region 1. Change between Q4 2019 and Q1 2021 is shown on key indicators: rock price differential [$/ton] and phosphate scarcity [%]. Kernel density estimates shown are all based on the results of 200 simulation runs. Red lines show position of median, mean and extrema