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Will Phosphorite incorporate negative externalities into its market price as it becomes scarcer?

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Acknowledgments

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Abstract

The increasing scarcity of Phosphorite poses a real threat to the world's food production. Global fertilizer production needs a steady phosphorus supply to cater to the global demand. Without Phosphorite, a new source of phosphorus must be found. As it stands today, no other substitute for Phosphorite fills the criteria of being both plentiful enough and economical to extract. Continued population growth and increased wealth also increase demand for both the amount and quality of food. This demand puts a considerable strain on the production of Phosphorite, leading to an over-extraction that is not compatible with economic theory regarding optimal use of non-renewable resources.

Continuing the extraction and beneficiation of Phosphorite creates compounding negative externalities in the form of phosphogypsum stacks and wastewater. These stacks, comprised of toxic and radioactive materials, are incredibly harmful to the environment. Dike breaches and spills from wastewater reservoirs cause irreparable damage to nearby waters and soil and can potentially destroy whole ecosystems if left unmanaged. Because Phosphorite is ultimately used for food production, these negative externalities are under-prioritized over the potential crisis if food demand is not adequately met. Therefore, current environmental policies targeting Phosphorite have no significant bearing on its price.

Today, the price of Phosphorite is dominated by short-term market behavior rather than long-term concerns of scarcity and the environment. This behavior is to be expected, as the production of Phosphorite is still increasing, meaning that a “peak phosphorus” situation is yet to occur. As long as the demand for food is met, there is no incentive to invest long-term, as doing so would lower funds available to invest for short-term profit. This situation will inevitably change once peak production has been reached. At this position, the demand for food can no longer be met, and it will ultimately be more profitable to invest in Phosphorite long-term, as its price must increase.

Around 80% of phosphorus is lost through the journey from extraction to the dinner table. Increasing the efficiency of production and reducing losses is therefore paramount to ensure a longer lifetime of Phosphorite. A longer lifetime of the resource creates more opportunities for technological progress and new methods of production without the looming disaster of a food shortage. This can therefore potentially solve the scarcity problem of Phosphorite in the long run.

Table of Contents

List of figures

List of tables

1. Introduction

Phosphorus is an element that is mainly used along with nitrogen and potassium to make fertilizer, which is vital for producing food worldwide. Phosphorus is concentrated within phosphate rock, also called Phosphorite. Phosphorite must be mined, processed, and transported for further processing before it can be turned into phosphorus. As of January 2021, around 70% of the world's phosphate rock reserves are located in Morocco (U.S. Geological Survey, 2021).

The maximum production rate of Phosphorite is estimated to occur around 2030 (Cordell, Drangert, & White, 2009). This event is nicknamed "peak Phosphorite," aptly drawing inspiration from "peak oil." Furthermore, current global reserves of Phosphorite may be depleted in around 50-100 years (Cordell et al., 2009). Several factors come into play here; First, there are currently no substitutes for phosphorus in agriculture (Tirado & Allsopp, 2012). This means that if the stock of Phosphorite is depleted, more expensive and less effective methods of producing phosphorus must be found. Second, the combined effects of an growing world population and wealth increase food demand and subsequent higher dietary standards (Steen, 1998). Third, as demand increases for food, it is necessary to increase crop yields. This will in turn increase fertilizer demand. The price of Phosphorite is understandably tied to the agricultural market for fertilizer. However, there is no inherent commodity market for phosphorus in its pure form (the Periodic table element). Instead, there is a commodity price on Phosphorite and a commercial and futures market for fertilizer.

The negative externalities in reference to Phosphorite are split into two parts: First, through the agricultural use through phosphorus runoff. Phosphorus runoff causes an increased blooming of harmful algae that reduces oxygen in waterways, resulting in "dead zones" that damage ecosystems. (U.S. Department of Agriculture, 2015). The second negative externality is through the mining and beneficiation process of Phosphorite. This includes air pollution, biodiversity impacts, and water pollution (Worlanyo & Jiangfeng, 2021).

1.1 Short background and motivation

This thesis will deal with Phosphorite, phosphorus and fertilizer. As such, it is crucial to understand the process behind how they are all interconnected. Phosphorus is widely distributed in nature but is rarely found concentrated. To harvest large amounts of it, mining of Phosphorite is required. Phosphorite is a sedimentary rock that has a variable amount of phosphorus content. This ranges from 4% to as high as 30%. To achieve higher ranges of phosphorus content, beneficiation (processing) is required (Zapata & Roy, 2004).

Figure 1.1: A simple diagram showing the process of creating fertilizer

Around 90% of the Phosphorite mined is used for further processing into phosphorus (Zapata & Roy, 2004). This phosphorus is further used as an ingredient together with nitrogen and potassium to produce different kinds of fertilizer. This paper will be concerning DAP fertilizer, which only contains phosphorus and nitrogen. This is done to reduce external factors affecting the price of fertilizers that include all three elements. Further, there is an element of substitutability among fertilizers, meaning that if the price of one type were to skyrocket, buyers would switch to another kind. This means that choosing DAP over another fertilizer (or a basket of fertilizers) will not defeat the intended purpose of analyzing prices and subsequent demand in the overall market.

1.2 Main research question

As the thesis title suggests, the main research question will be: “Will Phosphorite incorporate negative externalities into its market price as it gets scarcer?”. This research question assumes two things: First, it considers that there is an observable price movement tied directly to the scarcity of phosphorous. When phosphorous becomes scarcer, its price should increase, ceteris paribus. Second, it assumes that we can measure the negative externalities connected to phosphate mining, beneficiation, and fertilizer runoff. It also means that one should pinpoint precisely on the price graph for Phosphorite when environmental policies and other factors related to when these negative externalities happened.

1.3 Structure of the thesis

Chapter 2 will go more in-depth on the background and motivation for this thesis. The core problem, hypotheses, and a preliminary look at the empirical data will be undertaken here. This includes the production and price data for Phosphorite and DAP fertilizer, with a quick overview of notable price changes.

Chapter 3 deals with the literary review, which is split into two parts: Natural resource theory and applications, and Phosphorus and negative externalities. Here, the relevant literature will be explained and summarized to make understanding the current research and opinions on this topic more manageable.

Chapter 4 includes a review of the relevant theory, where the Hotelling (price) rule, negative externalities, and scarcity will be the focus. The Hotelling model will be thoroughly reviewed and put in an appropriate context for the case of Phosphorite. The section regarding negative externalities will include both the externalities from Phosphorite production and beneficiation and the externalities connected to fertilizer usage. The section dealing with scarcity will delve into backstop resources and technology, uncertainty, and impact on other commodities.

Chapter 5 deals with the data and methods necessary to conduct the analysis. The data used in this thesis consist of a basket of commodities related to the production and consummation of DAP fertilizer. The methods section describes how the regression model is built and what reasoning is behind its construction. The framework for constructing empirical Hotelling price paths is also included, with examples.

Chapter 6 contains the results from the regression model and empirical Hotelling price path and its implications on the hypotheses. The regression model section will also go through the necessary conditions and assumptions for the model to be reliable.

Chapter 7 discusses these results and more general findings in a broader context. Environmental policies, uncertainty, alternatives to Phosphorite, and possible solutions are discussed in this chapter.

Chapter 8 contains the conclusion of this master thesis and a few words on further research in this field.

2. Background and motivation

2.1 The core problem

The core problem is a two-pronged attack; On the supply side, the stock of Phosphorite is becoming scarcer by the day and will lead to a lower supply of fertilizer when the stock finally runs dry. The demand side is also changing; More people equal more demand for food, and an increase in per capita wealth leads to higher dietary standards. The added demand puts an additional strain on Phosphorite and subsequent fertilizer production.

The demand side effects lead directly to a higher fertilizer price, while the supply side effects lead to a higher cost of Phosphorite, which will also lead to a higher fertilizer price. As food is an essential good, we would expect the same inelastic demand for fertilizer; That is, when prices increase, we expect a small decline in demanded quantity. Subsequently, this will lead to a lower purchasing power for consumers, as more money must be allocated to purchasing food. As their input cost for production increases, fertilizer producers and farmers will also be hurt. This, in turn, leads to money being shifted away from other investment opportunities.

Negative externalities also come from fertilizer use and the mining and beneficiation of Phosphorite. Externalities arise whenever some effects of the production or use of a product are not fully included in market prices. When market prices are closer to the socially optimal prices, the size of externalities declines. For negative externalities, optimal prices are higher than market prices. This may however seem unintuitive in the case of phosphorus, as higher food prices could lead to hunger for the poor, and augment poverty related issues.

2.2 Hypotheses

2.2.1 Hypothesis 1: The price of Phosphorite and fertilizer will rise over time due to increased scarcity

"As time moves on, Phosphorite becomes scarcer due to continued extraction. This means that the price must rise, ultimately leading to lower food production and higher food prices. This is because Phosphorite is an input factor in fertilizer (nitrogen, potassium, and phosphorous are the nutrients needed to make fertilizer)." This hypothesis has several components; The first sentence assumes that the production of Phosphorite will continue over a long period. The second sentence considers that the price correlation between fertilizer and Phosphorite will also be present over the long run.

2.2.2 Hypothesis 2: Population growth leads to increased demand and subsequent price of Phosphorite and fertilizer

"Higher population growth leads to a greater demand for food. This will increase the price of Phosphorite, as it is necessary to create fertilizer." Therefore, the primary analysis in this hypothesis consists of how the price of Phosphorite moves over time. Population growth is continuously increasing, so the cost of Phosphorite should, in theory, also be increasing. This can be analyzed using phosphorite and fertilizer production and price data.

2.2.3 Hypothesis 3: The price of Phosphorite will follow a Hotelling price path

"Optimal resource extraction gradually declines over time (Hotelling price path). Thus, optimal resource price must also rise at the rate of interest until the resource is completely depleted" – The thought is that Phosphorite pricing will follow this idea. This will be in tandem with hypotheses 1 and 2, in that the price should increase with time. The added element in this case is also that production should decline over time. This case calls for a continued "optimal" price that should essentially be constant throughout time. This thesis will therefore test for empirical Hotelling price paths in Phosphorite.

2.3 Preliminary look at the data

2.3.1 The market price and supply of Phosphorite

The price of Phosphorite during the period 01.03.1992 – 01.03.2022 is depicted below in figure 2.1. The price was relatively stable until 2007-2008 when a significant price spike happened due to several factors. Firstly, there was a sharp increase in demand for fertilizer while there was a low international supply of it. This led to a severe imbalance in the market, resulting in high prices. Secondly, nitrogen and potassium prices increased, making it more expensive to produce fertilizer (U.S. Department of Agriculture, 2009). This price increase also affects Phosphorite, as its price is inevitably tied to the price of fertilizer. There are also credit markets and subsidies for purchasing fertilizer in many countries, which further increases the fertilizer price. During this period, the financial crisis (and subsequent) commodity boom also happened, which saw a significant price shock for many commodities.

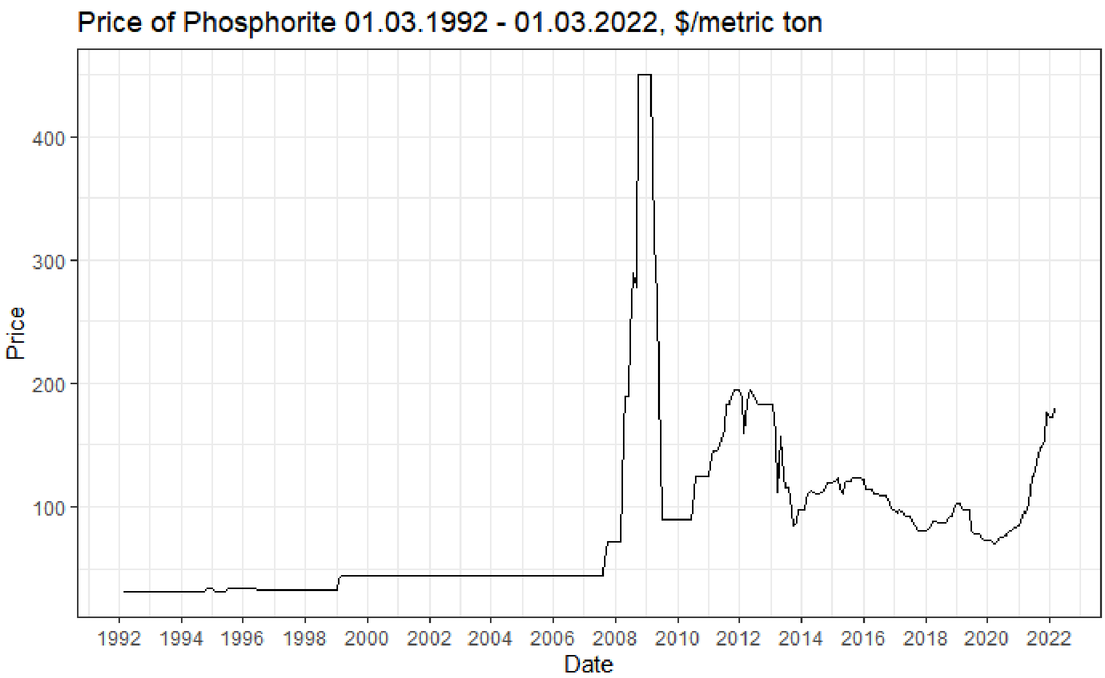

Figure 2.1: Monthly log price of Phosphorite, from 01.03.1992 – 01.03.2022. Source: (Indexmundi, 2021)

After the price spike, we can see that the price enters a period of high volatility from 2010 onwards compared to the period prior to the financial crisis (2008-9). The volatility can be tied to phosphorite entering the market as a properly traded commodity instead of being viewed as a never-ending source of phosphorus in the period 1992-2007. Recent years show a sudden upward trend due to the invasion of Ukraine by Russia and several sanctions, which causes a strain on the production of fertilizer. This will be further discussed in the discussion section (chapter 7).

Figure 2.2 below shows yearly world Phosphorite production from 1900 to 2018. The figure indicates that world production increases around the last half of this timeline, whereas the first half shows a steady production in the early years around 1900-1945.

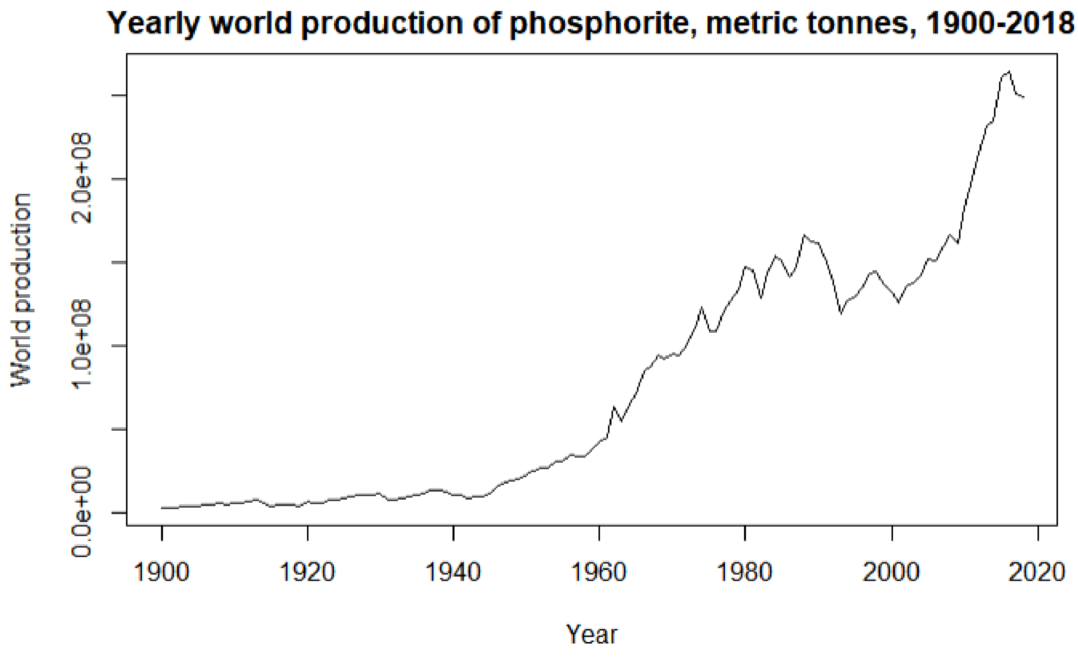

Figure 2.2: Yearly Phosphorite production in the period 1900-2018. Source: (U.S. Geological Survey, 2018).

The production of Phosphorite started to show an upward trend around 1945-1950, forming the initial push that would lead to a very rapid increase in production in the following years. Increasing production means that the resource stock of Phosphorite will also run out sooner with each passing year. This would otherwise be somewhat manageable if the production had been stable. Still, the main problem is that the increase in production is very rapid, doubling in 16 years from 132 million metric tonnes in 2000 to 265 million metric tonnes in 2016.

2.3.2 The market price and supply of DAP fertilizer

In comparison to the price of Phosphorite, the price of DAP fertilizer did not remain stable in the years 1992 to 2006. A steady upward trend is in effect for DAP in the long term, as new plateaus are reached for every price spike. This is evident in the years 2008 and recently in 2022. While on the subject of 2022, the price reached almost the same peak like the one in 2008, which saw the height of the commodity boom. The reason for this is the same as the ones mentioned in section 2.3.1 regarding Phosphorite.

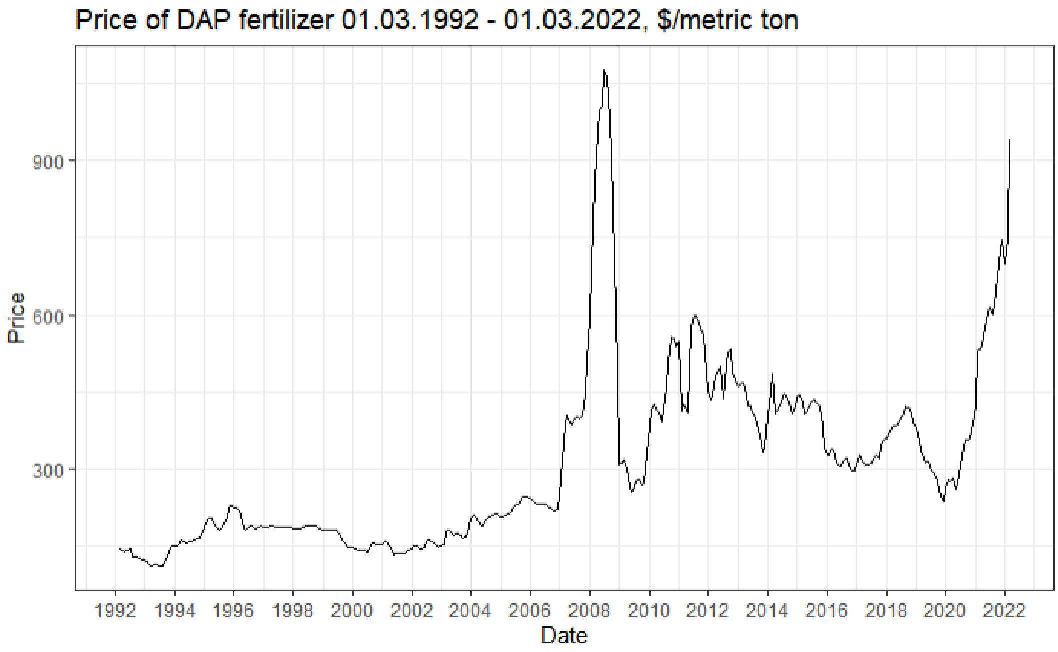

Figure 2.3: Price of DAP fertilizer from 01.03.1992 – 01.03.2022, price is $/metric ton. Source:(Indexmundi, 2022g)..

The price shocks for DAP fertilizer and Phosphorite are similar, which is not surprising considering that Phosphorite is an input factor in producing DAP fertilizer.

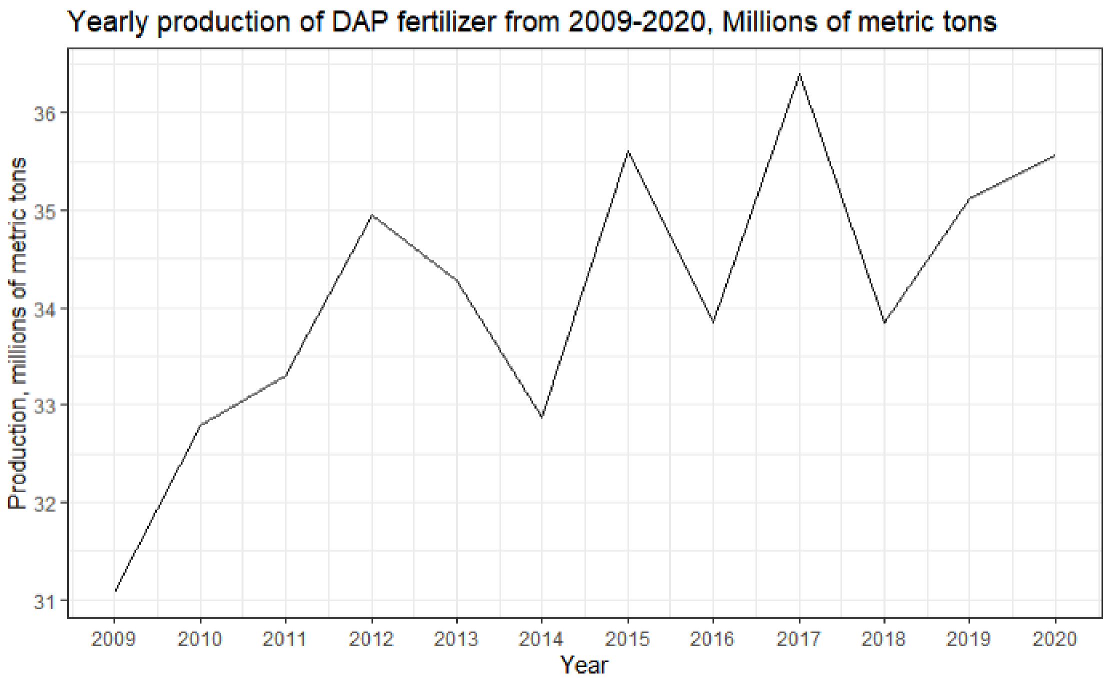

Figure 2.4: Yearly production of DAP fertilizer from 2009-2020. Millions of metric tons. Source:(Statista, 2022b).

The production of DAP fertilizer tells an entirely different tale from the production of Phosphorite, however. The overall increase from 2009 to 2020 is around 4.5 million metric tons, compared to Phosphorites increase of 87 million metric tons in the (closest related) period of 2009-2018. Unfortunately, I do not have the data needed to shed light on these differences. Possible explanations include that extraction rates of a natural resource like Phosphorite are more limited by capacity constraints than fertilizers, or fertilizers are closer to volatile markets than Phosphorite.

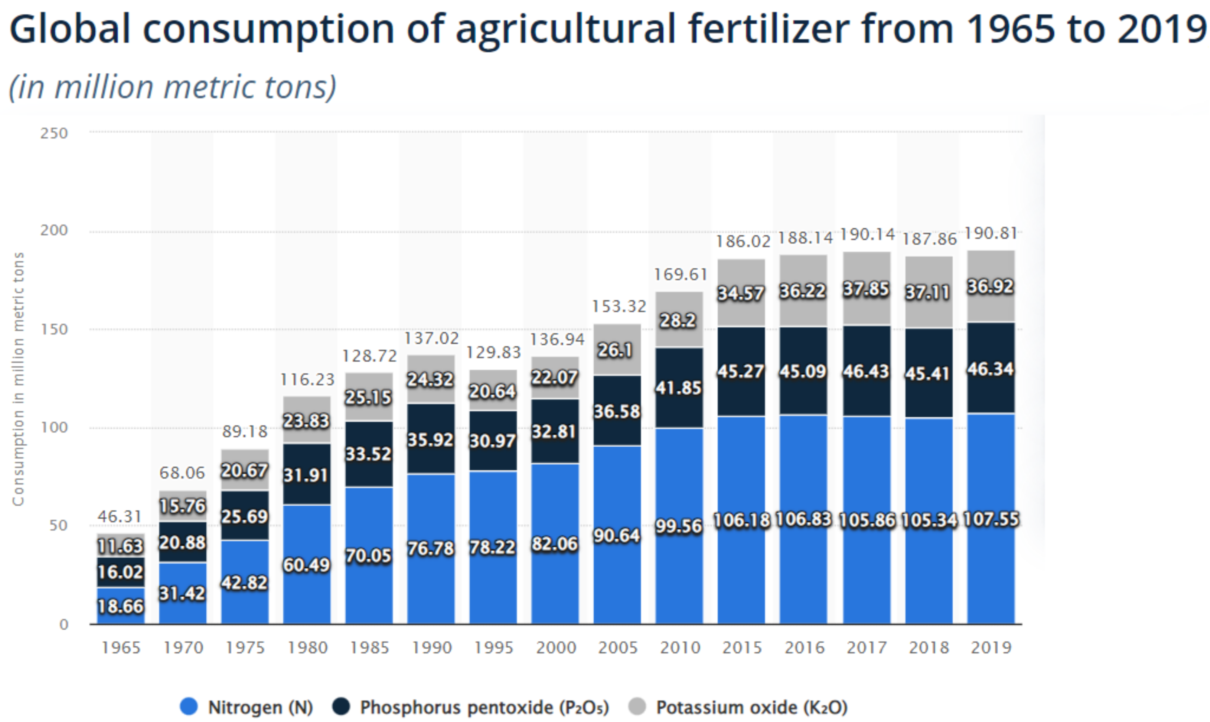

Figure 2.5: Global consumption of fertilizer from 1965-2019 by nutrient. Source: (Statista, 2022a).

The global consumption of agricultural fertilizer also shows a relatively stable growth but slows down from 2015 onwards. The main driver in growth is Nitrogen, with an increase of 88.89 million metric tons from 1965 to 2019. This is compared to 25.29 million metric tons for Potassium and 30.32 million metric tons for Phosphorus in the same period.

2.3.3 The futures market for fertilizer

Fertilizer prices are also affected by futures markets. The Chicago mercantile exchange group (CME) offers futures contracts for different types of fertilizers. A futures contract is a financial contract in which a commodity is purchased for a given price, with delivery at a later date (CME Group, n.d.-a). For fertilizers, futures contracts range from Diammonium Phosphate (DAP) to Urea type fertilizers. The world’s most widely used Phosphorus fertilizer is DAP (International Plant nurtrition institute, n.d.). Therefore, when fertilizer prices and production is mentioned in this paper, it refers to DAP fertilizer.

The primary uses of the futures market are twofold: First, it increases transparency on prices, which enables market participants to make more informed decisions. In a regulated exchange such as the futures market, buyers and sellers put out ask and bid prices which are instantly updated across the globe (CME Group, n.d.-b).

Second, firms, farmers, and others exposed to price movements from fertilizers can hedge their risk. This is done by purchasing futures contracts at a set price when there is a certainty that the market price will clear below the futures market price. Speculators and investors can potentially make money buying futures contracts using the same method.

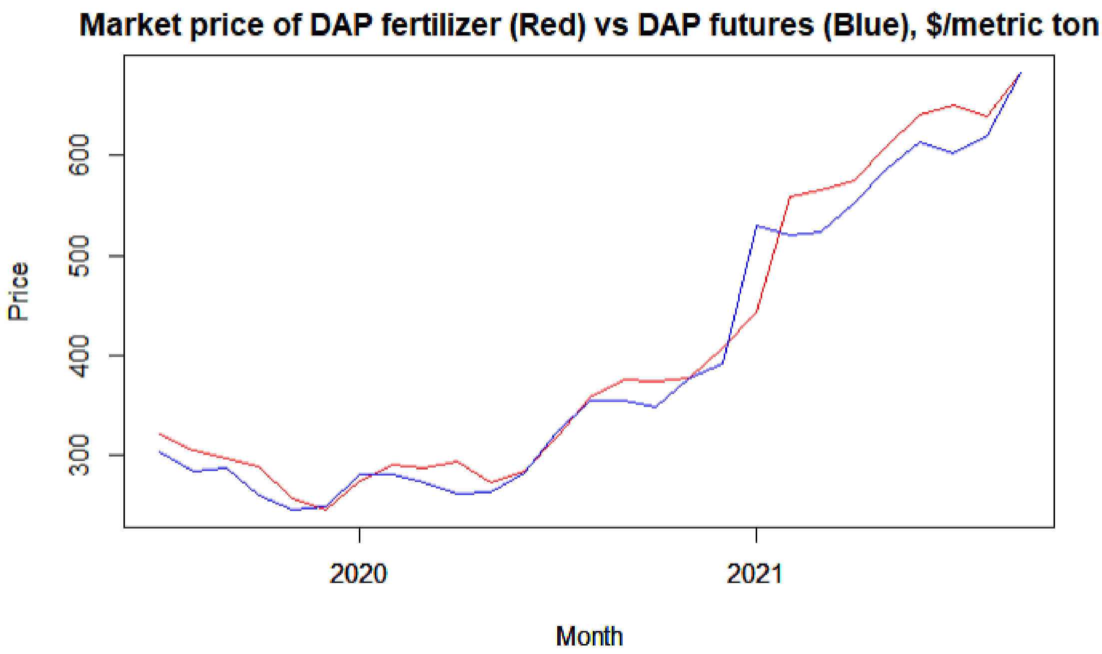

Figure 2.6: Market price of DAP fertilizer (Indexmundi, 2022g) against DAP futures (Barchart, 2022).

Price movements between spot and short-term futures are often tightly linked. This is not surprising as these prices have the same underlying information structure. Moreover, as the futures contract nears expiration, it will converge with the spot price. Both prices follow an upward trend from mid-2020 onwards from the graph above. Backwardation seems to mark most of the period, save from the last months of 2019 to early 2020, and the previous months of 2020 to early 2021. Backwardation implies that there has been more demand for short-time delivery rather than long-time delivery of DAP fertilizer. It can also mean a shortage of the good in the spot market, which also relates to the convenience yield; When inventory levels of fertilizer are low, there is an inherent benefit to owning it (CME Group, n.d.-c).

Cost-of-carry is also a factor that comes into play. It is measured by taking the spot price less the futures price and signifies the cost of storing the commodity. Typically, this includes insurance, purchasing of physical storage space, and potential losses due to long-time storage. It is possible to store fertilizer for a long time, so losses due to storage are unlikely to have an effect.

3. Literature review

This chapter presents the literature I deem most relevant. The literature will be split into two sections: The first deals with theory regarding natural resources, which I choose to group into Hotelling price paths, optimal resource extraction, and scarcity. There are also empirical applications of theory, consisting of papers that have tested theories like the Hotelling price path on empirical data.

The second deals with Phosphorus and negative externalities, which will provide an insight into how the whole process of fertilizer production works from start to finish. This section investigates the negative externalities connected to Phosphorite, phosphorus, and fertilizer production. Literature regarding commodity markets is also included here and will mainly consist of background information on futures markets and specific market relations in regard to Phosphorite and fertilizer.

3.1 Natural resource theory and applications

Natural resource and Environmental Economics (Perman, Ma, McGilvray, & Common, 2003):

This book is the starting point for many master’s students in environmental and resource economics. It deals with many relevant theories regarding natural resources: This includes topics in scarcity, optimal resource extraction, and different market structures concerning natural resources. It also contains models related to Hotelling price paths and resource depletion. This book delves into many aspects of whether the theories can be connected to the real world and gives suggestions for dealing with these.

Theoretically, it is possible to sustain the use of an essential resource by having its use decline asymptotically to zero across a finite time. The problem in the case of Phosphorite is that the production of it is always increasing, meaning that the use of the resource is also growing. This implies that for the continued use of fertilizer to take place, measures must be taken to make Phosphorite extraction sustainable over a long period. Possibly the most obvious economic approach to increase the lifespan of Phosphorite is an extraction tax.

On the Empirical Significance of the Hotelling Rule (Livernois, 2009):

This paper summarizes many essential aspects of bringing the Hotelling rule into real life. Many studies have indeed been done on several commodities, but the problem is that many of these studies were done in the 1970s and 80s when concerns about the scarcity of these resources were less pronounced. This leads to an analysis of goods dominated by short-term profit instead long-term optimal resource extraction.

Livernois (ibid.) remarks that for a basket of eleven resources in the period 2001-7, prices increased far more than what can be explained by Hotelling's rule alone. The commodity prices were also extremely volatile during this period, which he claims will disturb any expectations in the future. Since 1990, the situation was the opposite, as the basket of resources experienced a downward trend for a decade. This creates a U-shaped price path for the resources because of technological change being beaten by the rising scarcity rent. In other words, the reduction in marginal cost from technology is lower than the increase in market price because the scarcity rent dominated it for some years. Livernois also created a simulated price path, which is not unlike many found empirically.

Phosphorus availability in the 21st century: Management of a non-renewable resource (Steen, 1998):

This paper delves into the empirical data connected to phosphorus. It is rather old, but many of its points still apply: Depleting phosphate rock quality will inevitably increase production costs, as beneficiation and mine capacity must be expanded to keep the same production rates. Another problem is that heavy metal contaminants will become more present as quality declines. At certain levels, this means not being able to sell the product as certain European countries apply limits to the amount of cadmium present in the fertilizer. According to Steen (ibid.) the removal of cadmium requires more processing costs equivalent to around 2-10% of phosphate fertilizer prices. These numbers are not updated, but they still give an insight into how stricter legislation on Cadmium contents may affect fertilizer prices.

Steen (ibid.) mentions that prices will also be affected when countries with significant reserves become conscious of the scarcity. This is an aspect that is mainly overlooked, but it will most likely become an essential factor in trade going forward. As countries become more aware of the scarcity, they may begin to withhold phosphate rock, favouring domestic supply and ensuring food safety. This will also be a factor in increased prices for phosphate rock due to reduced exports.

3.2 Phosphorus and negative externalities

Use of phosphate rocks for sustainable agriculture (Zapata & Roy, 2004):

This publication provides background information on how phosphate rock functions, how it is mined, what content of phosphorus is included, and several other facts that are necessary to give a good introduction. It also has several aspects that could help prevent negative externalities related to Phosphorite mining and fertilizer application, by directly applying Phosphorite to farms instead of creating phosphorus.

Zapata and Roy (ibid.) also discuss how the pricing policy for phosphate rock adoption should be carried out. Proper incentives need to be in place to encourage correct fertilizer use, as too much or too little will harm soil quality. The pricing policy should be such that it is profitable for farmers to work in the field rather than find another job. They bring forward two arguments for using fertilizer subsidies: First, one must realize that only large-scale farms can achieve economies of scale. This ties in with the fertilizer demand never increasing to the necessary levels to reduce production prices. The cost of production also does not decrease by a lack of demand. This creates a cycle that can only be improved by increasing demand, which subsidies do pretty efficiently.

Second, they argue that a subsidy will help preserve a social optimum; This is because the benefit to society of having fertile soils exceeds the pure individual incentive of farmers. In other words, the effect of having fertile soils is considered a positive externality and, as such, should be subsidized to avoid a market failure. Their support for a subsidy is contrary to the results in Vatn et al. (1996) that is presented later in this review chapter.

Policies for reduced Nutrient losses and erosion from Norwegian Agriculture (Vatn et al., 1996):

This report contains several applicable models and calculations related to phosphorous and nitrogen runoff from fertilizer usage in Norway. It also includes several policy measures which are highly relevant to this thesis. This includes input taxes, emission fees, fertilizer quotas, and mandated catch crops. There is also a discussion around uncertainty connected to the topic. Even though they focus on Norwegian conditions, many of their principal points are generally valid. For this thesis, a discussion of input taxes is perhaps most relevant, as it is directly related to phosphorus.

Input taxes on fertilizer is a mechanism to incentivize farmers to lower their use (of fertilizer), thereby reducing fertilizer runoff and emissions. The input tax is a crucial tool to mention, as the optimal factor used may in some cases be much lower than what it currently is. However, according to the authors' calculations, there are several problems with such a tax: Up until a certain point, fertilizer has a net-zero effect on emissions. This means that fertilizers are favorable for the environment up to this level, as the cultivation of crops provides a positive benefit. Therefore, introducing an input or fertilizer tax will significantly affect farmers producing under the “net-zero fertilizer level”. Vatn et al. (ibid) claim that there is only a fragile relationship between the input use of phosphorus in fertilizer and emissions, which only adds to input taxes not being a solution to the problem of Phosphorus use. Increased availability and use of fertilizers containing less Phosphorus are in line with their report. However, for Nitrogen, input taxes are more closely tied to nitrate leaching (Vatn et al. ibid.).

World Phosphate Rock Reserves and Resources (Van Kauwenbergh, 2010):

This paper is akin to a guideline as to what phosphate rock is. It contains necessary details to understand and discuss the process from start to finish; From geology to manufacturing to fertilizer. This paper also delves into the prospect of estimating phosphate rock reserves and how long they will last, adding to the overall discussion. He claims no indication of a peak phosphorus event in 20-25 years (2010 calculations). Instead, based on the production rates and data from 2010, he claims that phosphate rock of suitable quality will be available long into the future. This will be further discussed in the discussion section of this thesis.

Van Kauwenbergh (ibid.) also comments on other phosphorus sources: bone meal, guano, and several other phosphate sources, which are not commercially used due to a higher cost per nutrient than phosphate rock. The potential supply that these alternate sources can provide is also only a tiny fraction of the quantities needed to cover the world’s phosphate fertilizer demand.

Van Kauwenbergh (ibid.) also brings into attention the increasing vertical integration of phosphate rock mining and processing. This indicates a shift in the market structure surrounding phosphate rock mining, which stems from increasing excavation and production costs. Vertically integrating these processes further increases economies of scale and reduces costs related to transport and production. For a sector such as mining, which requires enormous capital investments, vertical integration might alleviate much of the risk by ensuring that extraction and processing are secured in a single supply chain. This will make previously uneconomical excavation possibilities feasible, which will be discussed further in the discussion chapter.

Evaluating the environmental and economic impact of mining on post-mined land restoration and land use (Worlanyo & Jiangfeng, 2021):

This paper serves as the baseline for negative externalities connected to Phosphate rock mining. In particular, the general concepts of land destruction, pollution, and harm to ecosystems are essential subjects covered by the paper.

They also look into land restoration and reclamation, clearly defining specific guidelines to create a fair and realistic land rehabilitation. Land reclamation goes through two processes: Earth-battering, which is used to combat land compaction due to prolonged use of heavy machinery. The second process deal with chemical and biological methods to aid in the restoration of land fertility and microbial growth; Examples of which include compost, synthetic fertilizer, nanoparticles, and biochar.

These methods are costly but will provide a proper land reclamation to sustain many years of agriculture. Whether these costs should be placed on mining companies, consumers or governments is another discussion that is highly relevant in the context of this thesis.

Phosphate rock costs, prices, and resources interaction (Mew, 2016):

This paper discusses the price movements of phosphate rock and how this relates to production costs. It also discusses the inadequate accessibility to phosphorus for farmers in landlocked countries. Lack of access is an aspect that ties into transportation and handling costs. According to Mew (ibid.), the leading price spike events around 1970 and 2008 can be related to increased investment costs to create new mine capacity. These investments cause an observable factor that can raise prices in the future when the mine capacity is increased. This is under the constraint that there is a possibility to increase it in the first place.

Based on this paper, the volatility in phosphate rock prices is more likely to impact food prices than the production costs of phosphate rock. The reason is caused by a shift in investment for mining companies; They are incentivized to invest more into phosphorus recycling when increasing mine capacity becomes too expensive. The authors also note that as the cost of mining increases, an economic push toward recycling phosphorus will become more critical than a legislative one.

What Killed the Diammonium Phosphate Futures Contract? (Bollman, Garcia, & Thompson, 2003):

Even though DAP (diammonium phosphate), FOB (free on board) NOLA (New Orleans Louisiana) futures exist today, they initially only lasted six years, from 1991-to 1997. Bollman (2003) explains why the futures contract was delisted and provides essential insight into how the underlying market mechanisms of a DAP futures market work. It also shows how introducing a mechanism to aid price discovery can fail.

The failure of these futures contracts stems from several effects happening at once. Firs, the contract itself was seen as not providing any additional risk management beyond what already existed in the market. Second, contract contained a specification that led many to consider its delivery rate relatively high. This unusually high rate reduced the initial participation in this contract, as most actors do not use the futures market for the physical delivery aspect, but rather for risk management. Low participation in the futures contract leads to low liquidity and sporadic price speculation. This situation ultimately made it a poor hedging tool and practically useless to keep listed in the Chicago Board of Trade (now merged with CME).

A successful futures contract is a combination of long-term and short-term participation. Speculators will become discouraged from participating without participation on both fronts, and the market will lose liquidity. A market without liquidity will become tough to enter and will eventually lose market participants as the barrier of entry becomes too high.

4. Theory

4.1 Non-renewable natural resource management

4.1.1 Optimal resource extraction and price

Because non-renewable resources have a finite stock, an optimal extraction path must be developed to ensure efficient use of the resource throughout time. The most essential efficiency condition is the Hotelling rule: It states that the value of the resource (discounted) should be the same in all periods (Perman et al., 2003). This means that the net price of the resource should grow with capitalization factor for a set discount rate over time. Intuitively, mining companies would instead leave the resource unmined today if they could get a better price for it tomorrow. Likewise, companies would mine more today if they would earn less for the resource tomorrow. Along a Hotelling price path there is absence of arbitrage possibilities.

Therefore, a potential pitfall would be overexploitation or exhaustion of a resource if one could sell it for a high price today, knowing the price would drop tomorrow. This would lead to no profits when the resource is exhausted, meaning it is not a competitive equilibrium. The Hotelling rule counteracts this by implementing the fundamental theory of discounting, where future profits are worth less than the profit earned today. The firm must sacrifice current total profits but gain increased marginal profit over time. Because the net price increases with a discount rate, the price must increase exponentially, leading to a situation where demand for the resource should drop in the long run, all other things equal. However, with the resources necessary for producing food, external shocks may create market imbalances that could lead to significant, short-term price fluctuations.

However, the Hotelling rule is not sufficient to ensure an optimal price path (and, by extension, an optimal extraction); It is possible that multiple price paths can follow the Hotelling rule from different initial prices, but only one of these paths can be optimal. This is because initial prices can be too high or too low, leading to either a waste or under usage of resources.

The optimal price path must also fulfill the criteria of static efficiency. Static efficiency requires that in each instance where the resource is used, “the marginal value of the services from it should be equal to the marginal value of that resource stock in situ” (Perman et al., 2003). This achieves two things: First, it ensures that the services created do not have a lower value than the resource stock in situ, meaning that we do not lose value by creating services from it. Second, it ensures that all possible uses have the same net marginal benefit to society, reminiscent of Pareto efficiency. No use of the resource could be better applied without making another use worse.

Please note that external shocks could lead to deviations from the Hotelling price path. In the case of agriculture, unexpected weather events or other external shocks could lead to different prices than those expected by Hotelling's rule.

4.1.2 Optimal resource extraction in different market structures

Resource extraction in a perfectly competitive market will, ceteris paribus, follow the same efficiency conditions as the previous chapter 4.1.1. This means that with equal and constant marginal costs, and a fixed selling price at any point in time, each firm would select an extraction rate so that the discounted marginal profit would be the same at any given time (Perman et al., 2003). This means that the net price increase should equal the interest rate, i.e., as given by the Hotelling rule.

In a monopolistic market, the selling price is not fixed but depends on the monopoly's amount of output. This means that monopoly price will be higher than the marginal revenue, and the monopolist maximizes profits by adjusting quantity so that marginal revenues are equal to marginal costs. Instead of net price, the monopolistic marginal profit should increase at a set rate of interest to obtain the maximum discounted profit over time (Perman et al., 2003).

To compare these two market structures, we can draw a few conclusions. The initial net price will be higher for monopolies than in a perfectly competitive market, but the price increase will be lower. This follows standard theory for most monopolies, as setting marginal revenue equal to marginal cost leads to a higher price in the market than in a perfectly competitive equilibrium. This means that resource extraction will be slower initially but faster as the resource is depleted (Perman et al., 2003). In this way, it can be argued that monopolies are better suited to conduct resource extraction if the goal is to extend the lifetime of the resource.

4.2 Scarcity

4.2.1 Types of scarcity

Following (Perman et al., 2003), scarcity can be measured in two different ways; absolute and relative. Relative scarcity for consumers means an opportunity cost exists to acquire one extra unit of a good. For producers, more demand triggers an increase in supply, and resources must be reallocated to produce more of the good. Even if producers cannot meet the required demand, they can still produce a minimal amount. Therefore, under relative scarcity there is no underlying resource stock that runs out.

Absolute scarcity refers to the fact that there is an underlying limited supply stock that can run out. That is there is only a fixed resource stock available, and the maximum quantity that can be extracted equals the available resource stock. Therefore, one cannot reallocate resources to produce more when the stock has run out.

Phosphorite fits into the second category, but there are some problems associated with labeling it as such: There is the uncertainty of reserves and, therefore, the total stock available. A McKelvey box captures the nature of this problem:

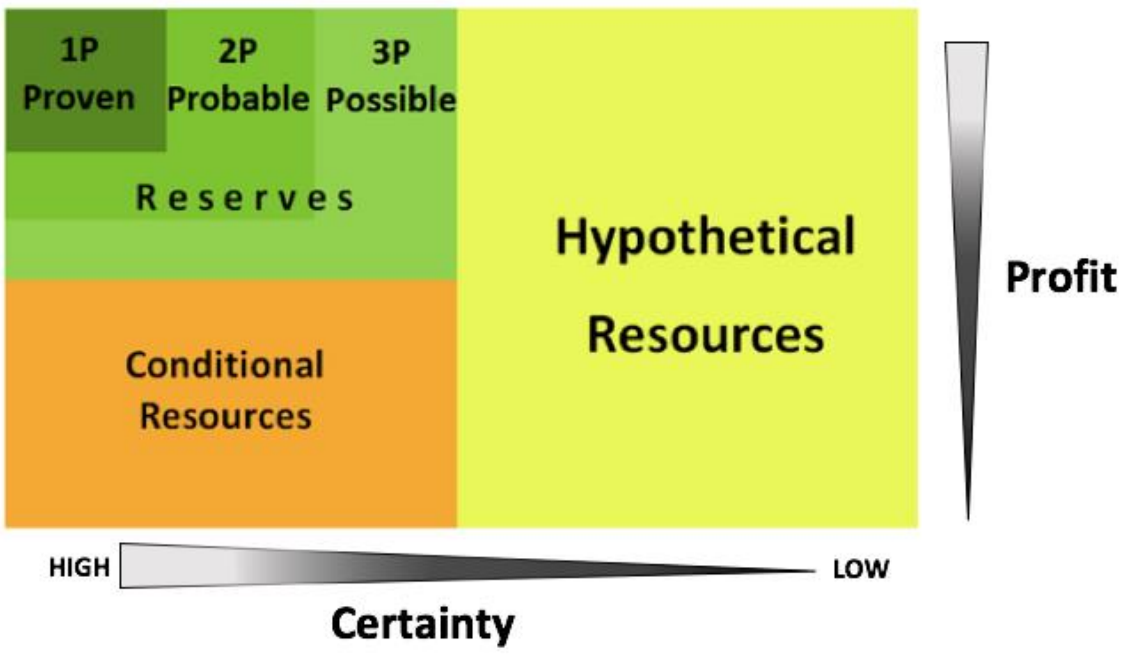

Figure 4.1: McKelvey box relating to natural resources. Source: (Afework, Hanania, Stenhouse, & Donev, 2019).

In this diagram, known reserves are on the left-hand side, while undiscovered and hypothetical resources are on the right. Conditional resources serve as a “backup,” but only if the more profitable reserves have been exhausted first. This applies to Phosphorite, as the number of reserves is unknown, thus making it hard to truly know how scarce the resource is.

4.2.2 Backstop technologies and resources

Technological advances can also make the resource less scarce through more efficient means of production, requiring fewer resources to produce the same amount of goods. Technology can also allow for an alternative resource to be used or the possibility to manufacture the resource itself. Both options could alter the scarcity of the original resource. The problem is that foreseeing technological advances is not possible, and thus the only information usable is the one available in the present day.

Theoretically, it is possible to use other methods for producing phosphorus: Guano mining has historically been the method of obtaining fertilizer until modern synthetic fertilizers were created. Guano is the excrement of different types of seabirds and bats, rich in phosphates, nitrogen, and potassium (Karkanas, 2017). It is possible to create “guano farms” consisting of seabird islands for harvesting guano, but the yield is meager compared to modern mining methods of phosphate rock. Questions also arise as to whether these guano farms are sustainable in the long run; An increase in seabird activity can severely affect the ecosystem of nearby waters, resulting in eutrophication and harming biodiversity due to the introduction of predators. Overfishing in surrounding waters and lack of maintenance could also cause severe harm to endangered bird species (Schnug, Jacobs, & Stöven, 2018). However, because it is a method of creating phosphorus, it falls under conditional resources.

4.2.3 General effects of phosphorus scarcity on the price of agricultural commodities

Because Phosphorite is used in fertilizer production, the price movements for both of these goods are inherently connected. This means that if the price of Phosphorite increases, so too must the fertilizer price, as it is an input factor for production. As fertilizer prices increases, so must several agricultural commodities as well, as they require fertilizer. The initial effect of Phosphorite scarcity will therefore have several implications on the price of agricultural commodities. Cereals are the primary “consumers” of fertilizer, where wheat, rice, and maize made up 41% of the world’s fertilizer usage in 2014-2015 (Heffer, Gruère, & Roberts, 2017). Soybeans also make up a sizable portion at 9.7%. The rest of the consumption is split among many sub-groups, including fruits, vegetables, tubers, and oilseeds.

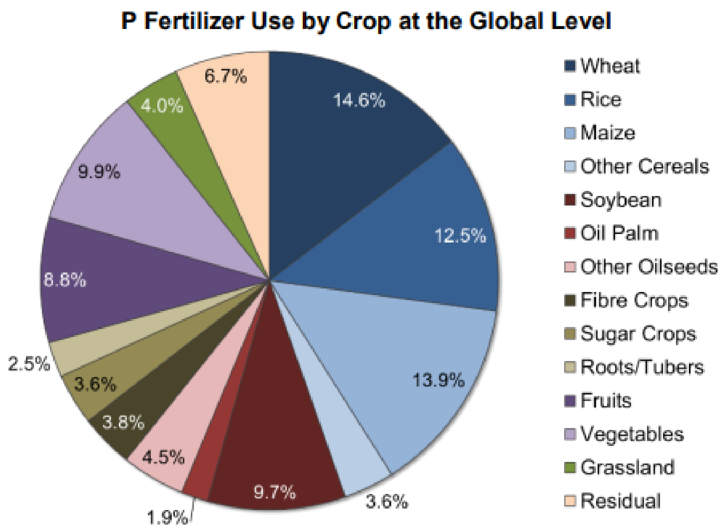

Figure 4.2: Phosphorus Fertilizer use by crops at the global level. Source: (Heffer et al., 2017), page 3.

Increased phosphorus scarcity will have two main effects on agricultural goods: First, increased scarcity will lead to an increased fertilizer price as it is an input factor for producing it. This implies that Cereals and soybeans are the main crops subject to price changes in fertilizer. Consequently, corn, wheat, and soybeans are among the most traded agricultural commodities in the futures markets (Investopedia, 2022). Second, when speculators are aware of increased scarcity, expectations will shift towards investing in futures. An increased flux of speculators, combined with fertilizer producers and farmers having increased input costs, will inevitably lead to increased volatility in the market.

4.3 Negative externalities connected to phosphorus

A negative externality is an economic activity of production or consumption that harms a third party, not reflected in the market price (Gayer & Rosen, 2013). A classic example of this is pollution, where a firm pollutes a nearby river as a byproduct of production, thereby harming the welfare of the people using the river.

4.3.1 The impact of mining

The mining process causes damage to the immediate area through several means; Especially in open mines and strip mining, the mined land is taken possession of and essentially destroyed. This displaces animals and plants and makes it difficult to restore the original habitat. Digging up deep and extensive plots of land can also cause contamination of the surrounding area, as aquifers can get damaged or radioactive rock may leach (Worlanyo & Jiangfeng, 2021). Soil quality is also significantly damaged from mining. After the mining is finished, most sites cannot correctly support crop production due to severe soil erosion or soil compaction from heavy machinery (Worlanyo & Jiangfeng, 2021).

These damages depend on location-specific characteristics, the method in which the Phosphorite is mined, and the country-specific policies to deal with such damages. Policies that keep mine owners or operators accountable for damages create incentives to perform responsible mining. In contrast, a lack of such policies may lead to environmental degradation or negative impacts on mineworkers or locals. On top of these policies, increased excavation and production costs may make it uneconomical to continue operating, discussing how dynamic these policies should be. This will be further discussed in the discussion section.

4.3.2 Phosphorite processing

After mining is completed, large amounts of water are used either in situ or transported to a nearby plant to create a "matrix." This consists of a slurry made up of phosphate rock, sand, and clay. The matrix is then separated and treated with sulfuric acid, resulting in phosphoric acid, the product needed to create fertilizer. There are two byproducts of this production: Phosphogypsum and wastewater. Phosphogypsum is radioactive, acidic, and contains numerous heavy metals, such as arsenic and lead (Belair, 2021). Storage of phosphogypsum consists of piling it up in "mountainous stacks that are hundreds of acres wide and hundreds of feet tall" (Lopez, n.d.).

The resulting wastewater is stored in reservoirs with liners (Bausback, 2021). However, these reservoirs are vulnerable to dike breaches and overflow due to rain. Potential spills, breaches, or mishandling of phosphogypsum can result in the bloom of red algae, which can severely harm the surrounding waters. One such leak happened at Piney Point, Florida, in March of 2021: Wastewater in this site has been stored 20 years after operations were halted. A tiny leak in the reservoir lining released thousands of gallons of toxic wastewater every day until it was discovered. More than 200 million gallons of polluted water were pumped into the surrounding bay to prevent flooding (Bausback, 2021).

4.3.3 Fertilizer production and usage

Creating fertilizer produces emissions, most notably through transport, production, and use. According to YARA, however, growing plants using fertilizer will increase yield, reducing the cultivation of new land. Cultivating new land means clearing native vegetation like rainforests, accounting for 20% of world GHG emissions (YARA, 2022).

Fertilizer and phosphorus runoff causes eutrophication in nearby bodies of water. This increase in nutrients promotes the growth of harmful algae that creates "dead zones" by depleting waterways of oxygen (U.S. Department of Agriculture, 2015). The runoff itself is usually caused by rainfall or melting snow. This runoff and the damage caused by wastewater breaches are therefore similar in nature.

5. Data, Methods and Preliminary Findings

This chapter will serve as an introduction to this thesis's empirical work. The data is presented first, giving insight into the basis for further analysis. This includes price data for several commodities, as well as production. The methods will then be presented, with some introduction to theory and then the empirical analysis. All data for commodity prices collected has a start date of February 1992 and ends in November 2021.

5.1 Data on commodity prices

5.1.1 Phosphorite

The spot price for Phosphorite is collected from Indexmundi, which compiles data from World Bank, Fertilizer Week, and Fertilizer International. This price data is based on Moroccan-produced Phosphorite, with a phosphorus concentration of 70% (Indexmundi, 2022h). Compared to what was presented in the introduction, this concentration is very high. This suggests a large amount of beneficiation is done to the Phosphorite before it is introduced into the market. The price itself is denominated in US Dollars per Metric Ton. Historical production of Phosphorite is collected from U.S. Geological Survey (U.S. Geological Survey, 2018).

5.1.2 DAP fertilizer

The spot price of DAP fertilizer is also collected from Indexmundi. The price is denominated in US Dollars per Metric Ton. The product's name is DAP FOB NOLA, which stands for Diammonium Phosphate, Free on board, New Orleans, Louisiana (Indexmundi, 2022f). Under an FOB contract, the buyer is responsible for transport costs and insurance. In the case of the alternative, CIF (Cost, insurance, and freight), the seller is instead responsible for transport costs and insurance. NOLA refers to the entry and exit point of fertilizer in the U.S.

5.1.3 Oil

The spot price for Oil is collected from Indexmundi. In comparison to the other two commodities, Oil is straightforward in terms of contracts; The name of the spot price product is Crude oil. Oil products are differentiated by where they are produced and the amount of sulfur they contain. The two most common types are Western Texas Intermediate (WTI) and Brent. WTI is a light oil more commonly used for gasoline. Brent is extracted in the North Sea, and its distribution is more global than WTI. This means that Brent is a better index for oil prices, as it contains price relationships from more economic regions than WTI (Investopedia, 2021). However, price changes between these two oil varieties are almost identical. Choosing one over the other in this analysis will yield little difference in results, as the log form of prices is used. The price is in U.S. Dollars per barrel. A barrel is equivalent to 42 U.S. Gallons, or 159 liters (Indexmundi, 2022a).

5.1.4 Natural gas

Prices for natural gas are collected from Indexmundi. There are several types of Natural gas, depending on location. Russian natural gas and Indonesian Liquified natural gas are examples of this. The price data for this thesis is based on Henry Hub, located in Louisiana, United States (Indexmundi, 2022b). The price is denominated in U.S. Dollars per million metric British thermal units.

5.1.5 Wheat

The price data for wheat is collected from Indexmundi. The price is based on the export price “delivered at the US Gulf port for prompt or 30 days shipment” (Indexmundi, 2022i). The price is in US dollars per metric ton. Wheat is split into six classes in the U.S: Hard red winter, hard red spring, soft red winter, soft white, hard white, and durum. Each of these has unique characteristics and is used for different products. The price data from Indexmundi is based on Hard red winter, which is the most commonly grown wheat variant in the U.S. (U.S. Wheat Associates, 2013a). Wheat can also contain varying amounts of protein (U.S. Wheat Associates, 2013b). The set quality of “ordinary protein” is used for this price data.

5.1.6 Corn (Maize)

Price data for Corn is also collected from Indexmundi. Corn comes in several varieties, just like wheat. The six major types are dent, flint, pod, sweet, flour, and popcorn (CFAES Ohio state university, 2015). The price data collected is based on “yellow no.2”, the dent variety. It is FOB, and the price is US dollars per metric ton (Indexmundi, 2022e).

5.1.7 Rice

Price data for Rice is collected from Indexmundi. The price refers to Thailand-produced rice, with a standard set at 5% broken white rice (Indexmundi, 2022c). 5% broken refers to the amount of fragmented rice, not defective. Milling rice creates around 15% broken or immature rice kernels, which sell for less, but is just as nutritious as normal rice (U.S.

Department of Agriculture, 2002). The price is FOB and is denominated in U.S. Dollars per metric ton.

5.1.8 Soybeans

Price data for Soybeans are collected from Indexmundi. Soybeans come in several different grades from 1 to 4 (best to worst), where each grade contains minimum and maximum limits of specific attributes. These are attributes such as damaged kernels, foreign material, and animal waste (U.S. Soybean export council, 2012). The price data uses grade no. 2, which means second best in terms of grading factors. The price is FOB, based on the Gulf of Mexico. The price is U.S. Dollars per metric ton (Indexmundi, 2022d).

5.1.9 Data adjustments

Because the data starts at differing periods, they must all be cut to the same size for regressions and analyses. All data mentioned in this section has been cut to 357 observations, starting from 01.03.1992 and ending on 01.11.2021. This yields a combined dataset that lasts four months short of 30 years.

5.2 Effect of other commodity prices on fertilizer prices

This section gives an overview of the linkages between prices for important agricultural commodities and fertilizer prices. A preliminary model is also added in this section to provide more context. The model is exploratory and seeks to identify main linkages. It is based on economic theory and contains several relationships that are explained below. The preliminary model also contains ordinary and autoregressive seasonal terms, where only the significant autoregressive terms are included in both the preliminary and final model. The variables with “X” in their name are removed in the final model:

```
MODEL INFO:
Observations: 346 (11 missing obs. deleted)
Dependent Variable: dap2$Price
Type: OLS linear regression

MODEL FIT:
F(35,310) = 830.45, p = 0.00
R² = 0.99
Adj. R² = 0.99

Standard errors: OLS
```

	Est.	S.E.	t val.	p
Intercept	-0.16	0.10	-1.51	0.13
Trend	0.00	0.00	1.85	0.07
Spring	-0.01	0.01	-1.51	0.13
Summer X	0.01	0.01	0.64	0.52
Fall	-0.01	0.01	-1.01	0.31
Lag 1 of DAP	1.29	0.05	25.02	0.00
Lag 2 of DAP	-0.38	0.05	-6.99	0.00
Lag 12 of DAP	-0.05	0.02	-2.12	0.03
Phosphorous	0.01	0.04	0.32	0.75
Lag 1 of Phosphorus X	0.01	0.05	0.18	0.86
Lag 2 of Phosphorus X	-0.03	0.04	-0.69	0.49
Lag 12 of Phosphorus X	-0.00	0.01	-0.21	0.83
Oil	0.01	0.03	0.28	0.78
Lag 1 of Oil X	0.07	0.05	1.33	0.18
Lag 2 of Oil X	-0.08	0.03	-2.15	0.03
Lag 12 of Oil X	0.00	0.02	0.06	0.95
Wheat	-0.04	0.05	-0.68	0.49
Lag 1 of Wheat X	0.07	0.08	0.91	0.36
Lag 2 of Wheat X	-0.00	0.06	-0.07	0.94
Lag 12 of Wheat X	-0.02	0.03	-0.88	0.38
Corn	-0.06	0.07	-0.89	0.37
Lag 1 of Corn X	0.13	0.10	1.33	0.18
Lag 2 of Corn X	-0.08	0.07	-1.15	0.25
Lag 12 of Corn X	-0.00	0.03	-0.08	0.93
Rice	0.09	0.06	1.62	0.11
Lag 1 of Rice X	0.03	0.09	0.35	0.72
Lag 2 of Rice X	-0.10	0.06	-1.66	0.10
Lag 12 of Rice X	0.03	0.02	1.51	0.13
Soy	0.03	0.07	0.47	0.64
Lag 1 of Soy X	0.07	0.10	0.71	0.48
Lag 2 of Soy X	-0.01	0.08	-0.18	0.86
Lag 12 of Soy X	0.01	0.04	0.20	0.84
Natural gas	0.03	0.02	1.49	0.14
Lag 1 of Natural gas X	-0.01	0.03	-0.22	0.83
Lag 2 of Natural gas X	-0.02	0.02	-1.00	0.32
Lag 12 of Natural gas X	0.02	0.01	1.56	0.12

```
[1] "AIC: -1009.15145791802"
[1] "Residual Variance: 0.00285550624759202"
```

Table 5.1: Preliminary regression model. “X” marks removal for the final model.

A trend dummy variable is added to check for any apparent trends within the regression. Similarly, the current price of DAP will naturally be based on the previous price of DAP, so the first two lags and lag 12 are added as independent variables in the model. In the preliminary model, three lags (1, 2 and 12) are added for each commodity to identify any significant linkage of past commodity prices on the current price of DAP fertilizer. Seasonal dummies will also be added, where one season must be omitted. In this case, both Summer and Winter will be omitted as they are not significant. The estimates for Spring and Fall will therefore be weighed against the sum of Summer and Winter.

Phosphorus is an input factor in fertilizer, and as such, the price of Phosphorite should affect the price of fertilizer. This means that an increased price of Phosphorite will increase the fertilizer price because it would make it more costly to produce.

Wheat, rice, corn, and soybeans make up around half of DAP fertilizer usage (Heffer et al., 2017). Therefore, it is reasonable to assume that if the demand for these commodities increases, the demand for fertilizer will also increase as farmers will increase or switch production from other commodities over to wheat, rice, corn, and soybeans. The price will increase as fertilizer is an input factor in producing these commodities. This effect also works the other way around, so it will cost more to produce these four commodities if the demand for fertilizer increases.

Nitrogen, one of the other input factors in fertilizer, is tied to oil prices (Ostendorf, 2021). This must inherently mean that the fertilizer price itself will have a relationship to oil prices, either through proxy or directly. Oil prices also link to electricity markets, as oil and natural gas are close substitutes in power generation (Bencivenga, Sargenti, & D'Ecclesia, 2010).

Natural gas is the primary source of hydrogen in the Haber-Bosch process to make anhydrous ammonia. This means that natural gas is essential in the production of nitrogen fertilizers, accounting for 70-90% of variable production costs in the synthesis process (Westra, 2022). Therefore, it is natural to include Natural gas in the analysis both for this reason and the connection to the electricity markets.

Removing insignificant lag variables and keeping the commodities give the simplified main equation:

$$\begin{aligned} DAP_t = \beta_0 + \beta_1 Trend_t + \beta_2 Spring_t + \beta_3 Fall_t + \beta_4 DAP_{t-1} + \beta_5 DAP_{t-2} + \beta_6 DAP_{t-12} \\ + \beta_7 Phos_t + \beta_8 Oil_t + \beta_9 Gas_t + \beta_{10} Wheat_t + \beta_{11} Corn_t + \beta_{12} Rice_t \\ + \beta_{13} Soy_t + u_t \end{aligned}$$

In the equation all prices are in log form. In this equation form, DAP_{t-1} refers to the first lag of DAP, DAP_{t-2} refers to the second lag of DAP, and DAP_{t-12} refers to the 12^{th} lag of DAP. This model will be used as the baseline for further analysis. Adding this amount independent variables will cause the degrees of freedom to drop by 13, but as the fitted data has 357 observations, it does not pose a serious problem.

5.3 Estimating empirical Hotelling price paths

The equation for a Hotelling price path is $P_t = P_0 * e^{rt}$, where P_t is the price at the time *t*, P_0 is the starting price, *r* is the resource rent, and *t* is time. Because we have all the elements except *r*, it is possible to solve for it and thus create empirical Hotelling price paths. If the price at period 1 is 100 and the price at period 2 is 150, the resulting equation is:

$$150 = 100 * e^{r*2} \rightarrow \ r = 0.202733$$

When the scarcity rent is obtained, it is possible to use the formula backward and solve for any price P_t. Because this is an exponential function, running it across multiple periods is possible to obtain a graphical line, which essentially is the Hotelling price path. In this way, it is possible to estimate a simple Hotelling price path empirically. This does not consider any extraction cost or technological change, but it will still give us important insight into how the price of Phosphorite moves compared to a Hotelling price path.

There is also a choice about where to start the hotelling price paths. The simplest solution is to solve the equation above for only one period and keep that scarcity rent for the rest of the analysis. Using only a few time periods to estimate the interest rate involves a risk of too high or low estimates for *r*. For example, for a too high estimate of *r*, the computed prices 10-20 time periods into the future will be much higher than what they should be due to the exponential form behind the Hotelling price path.

Moreover, current Phosphorite prices do not follow an exponential form. It is therefore unrealistic to apply this method to analyse how it deviates from a Hotelling price path. Another solution must therefore be produced to ensure that the analysis does not get stuck in this dead end.

One approach is to split the Hotelling price paths into intervals, where a price path is created for every *n* number of months or years. This will give different scarcity rents and provide more insight into how the price paths change as time moves on. This is a more analytical approach and will contain a price path for every *n* time interval that can be compared. As mentioned in 4.1.1, multiple Hotelling price paths can be present, but only one of them is truly optimal.

The empirical Hotelling price paths in this thesis will be based on Phosphorite prices ranging from 2007-2021. This will include multiple Hotelling price paths dependent on an interval of 3 years. This gives approximately 14 years’ worth of yearly data to work with, which should provide plenty of space to conduct a proper analysis. Any data earlier than this would not yield any feasible Hotelling price path, as the price of Phosphorite is relatively stable across the period from 1992-2006, as discussed in 2.3.1.

5.4 Choice of modelling program

The data is processed, tidied, and analyzed using R Studio version 1.4.1106. Plots in this thesis are made through the package *ggplot2*. The packages *zoo* and *lubridate* are used in conjunction with *tidyverse* to clean up dates and make proper adjustments to the dataset so that it is possible to model it. Regressions and modelling are done through the use of the package *stats*.

6. Results

Several regression models have been tested in this thesis, each with its own set of specifications. As is frequently the case for time series data, there also had to be adjustments to get error terms that signalled that all information in the data had been reasonably well utilized. Finally, the end model includes commodity prices, lag 1, 2, and 12 of DAP, trend and season dummies. The other models contained several problems specific to each model; A model with only commodities fails all linear regression assumptions except normality. A model containing the first difference for every commodity (normal prices + first difference) becomes overfitted. The problem is that having a first difference alone does not provide much intuitive explanation but instead creates noise to the other explanatory variables. Results of these model are included in appendix B. The AIC for these models are also significantly lower than the simpler end model used for the analysis.

The model with a mixture of commodity prices, lags for DAP, and the dummies provide a stable starting point and are easier to interpret; therefore, it is natural to choose this model. The problem with this model, however, is that the R-squared will become highly inflated and unreliable, but this does not affect variable estimates.

6.1 Preliminary regression model results

Depicted below in table 6.1 is an OLS regression in which the log price of a basket of relevant commodities plus lags, trend, and seasons are regressed on the log price of fertilizer. Keep in mind that this is a preliminary model, and the stable model with proper standard errors will be reviewed in sub-chapter 6.2.5. As a refresher, the model that is estimated can be written in the equation form as follows:

$$\begin{aligned} DAP_t = {} & \beta_0 + \beta_1 Trend_t + \beta_2 Spring_t + \beta_3 Fall_t + \beta_4 DAP_{t-1} + \beta_5 DAP_{t-2} + \beta_6 DAP_{t-12} \\ & + \beta_7 Phos_t + \beta_8 Oil_t + \beta_9 Gas_t + \beta_{10} Wheat_t + \beta_{11} Corn_t + \beta_{12} Rice_t \\ & + \beta_{13} Soy_t + u_t \end{aligned}$$

```
MODEL INFO:
Observations: 346 (11 missing obs. deleted)
Dependent Variable: dap2$Price
Type: OLS linear regression

MODEL FIT:
F(13,332) = 2169.55, p = 0.00
R² = 0.99
Adj. R² = 0.99

Standard errors: OLS
-----------------------------------------------------
                        Est.   S.E.    t val.      p
------------------ ------- ------ -------- ------
Intercept              -0.12   0.08     -1.40   0.16
Trend                   0.00   0.00      2.51   0.01
Spring                 -0.02   0.01     -2.49   0.01
Fall                   -0.01   0.01     -1.83   0.07
Lag 1 of DAP            1.32   0.05     26.89   0.00
Lag 2 of DAP           -0.43   0.05     -8.74   0.00
Lag 12 of DAP          -0.05   0.02     -2.96   0.00
Phosphorite            -0.01   0.01     -0.45   0.65
Oil                     0.01   0.01      1.04   0.30
Natural gas             0.02   0.01      1.84   0.07
Wheat                   0.03   0.02      1.17   0.24
Corn                   -0.01   0.03     -0.39   0.70
Rice                    0.07   0.02      3.08   0.00
Soy                     0.08   0.03      2.42   0.02
-----------------------------------------------------
[1] "AIC: -1019.3953230211"
[1] "Residual Variance: 0.00293952369321594"
```

Table 6.1: Regression of various commodity prices on fertilizer prices.

The model fit is significant at a <0.001 level. This means that this model has a better fit than an intercept model alone. An alternative way of phrasing this is that the null hypothesis of an intercept alone being a better fit is rejected. The Akaike information criterion (hereafter AIC in tables) is -1019.39. This number is indicative of the quality of the model and can be seen as a wellness-of-fit of our model. Alone, this is not very indicative, but it becomes more relevant when compared to another model. The lower, the better, and it is an absolute value. From the model, it is evident that Trend, Spring, the lags, rice, and soy is significant at the < 0.05 level. Oil is also significant at a 0.05 level, and Fall is significant at a 0.06 level. All significant Commodities have a positive estimate, which makes intuitive sense. Having a commodity with a negative estimate would indicate that a price increase for the commodity reduces the cost of fertilizer (for agricultural goods: Its input factor).

The model itself has an adjusted R-squared of 99% and residual variance of roughly 0.0029. However, as mentioned initially, these R-squared numbers are inflated and unreliable. This is because the lags of the dependent variable have been added, and we end up with variations of the dependent variable on both sides of the equation. However, it is necessary to do it this way, as past prices will determine the current prices of DAP, so leaving this out creates an omitted variable bias.

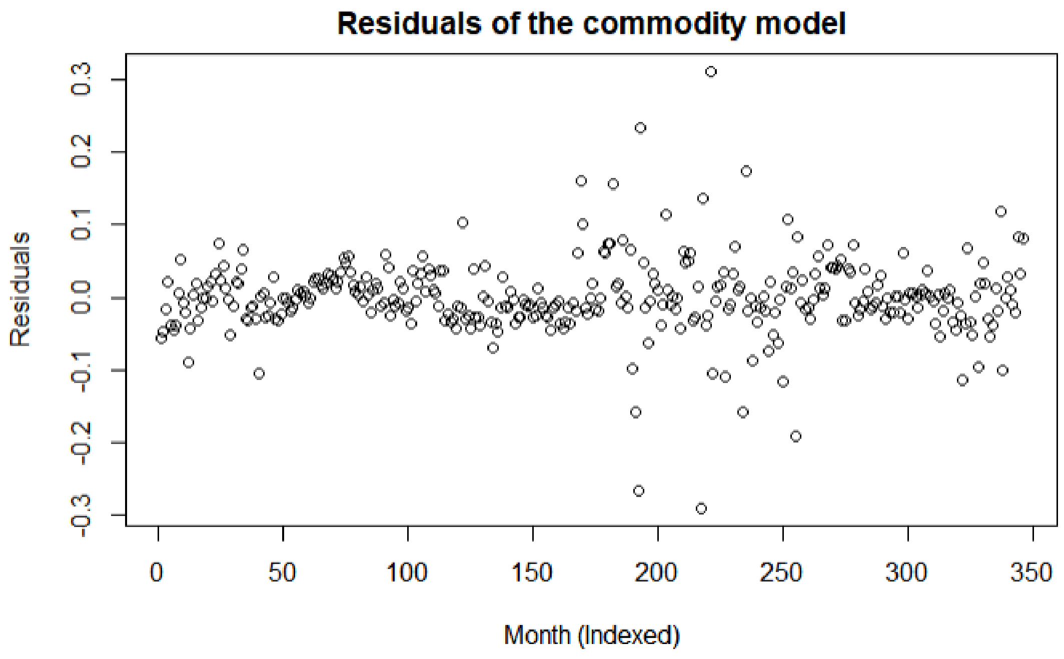

Figure 6.1: Plot of the residuals, commodity model. Start: 03.1992.

The residuals of the commodity model are centered chiefly around zero, except for months 180-250 (2006-2008 equivalent), where large dispersions are found. However, this is consistent with the commodity boom, where significant price volatility was in effect. There also seems to be a pattern of dispersion of the residuals in recent months from 300-to 350, indicating a more significant deviation from the regression line. This may also indicate increased price volatility, which is also something that is observed by looking at the price data for the basket of commodities.

6.2 Linear regression assumption tests for the commodity model

The following four assumptions are needed for the linear regression to provide unbiased and effective estimates in this case: (i) Normal distribution of variables, (ii) Linear relationship between DAP and the independent variables, (iii) homoskedasticity, and (iv) independence of predictors.

6.2.1 Tests of normality

The assumption of normally distributed data can be tested graphically using a Q-Q plot and tested using four different normality tests: Shapiro-Wilk, Kolmogorov-Smirnov, Cramer-von Mises, and Anderson-Darling. Below in figure 6.2 is a Normal Q-Q plot of the model:

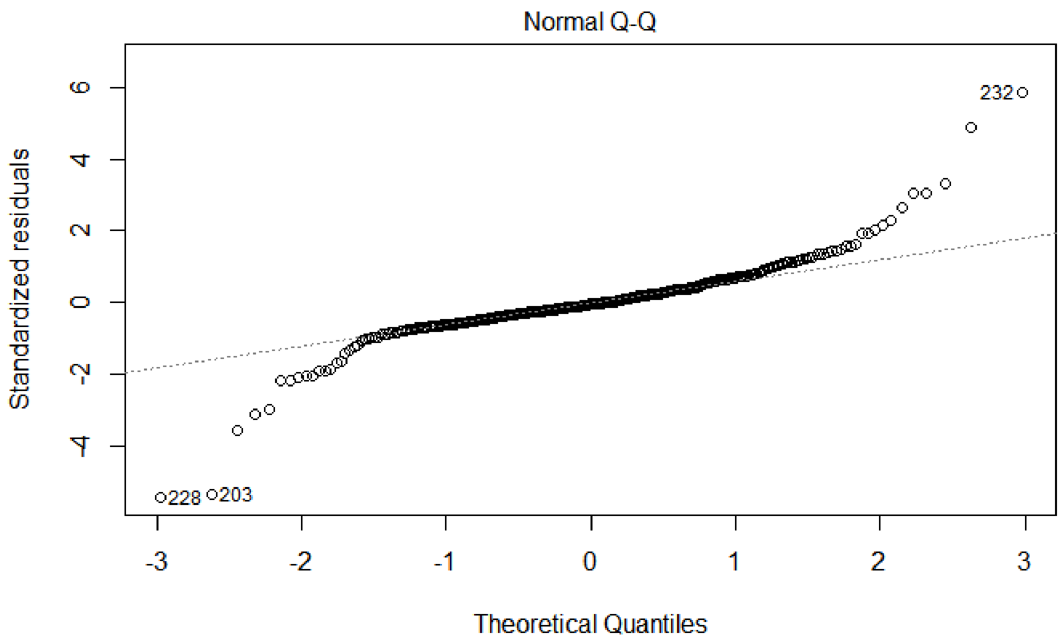

Figure 6.2: Normal Q-Q plot of the commodity model

As the points are distributed along a diagonal line, it is safe to assume graphically that the data is normally distributed. The points from x-axis -3 to -2 seem to fall out of this assumption, but the rest of the data falls neatly in a straight diagonal line. The points that fall out of the normal distribution correspond to around 2008-2009.

Test	Statistic	pvalue
Shapiro-Wilk	0.8655	0.0000
Kolmogorov-Smirnov	0.127	0.0000
Cramer-von Mises	105.3977	0.0000
Anderson-Darling	10.0901	0.0000

Table 6.2: Table of normality tests on the commodity model

From Table 6.2 above, we reject the null hypothesis of non-normality of the residuals for all tests. We can therefore claim normality in our data.

6.2.2 Tests of linearity

Testing the linear relationship between DAP and the commodity basket can be done graphically by plotting residuals against fitted values. Ideally, the data points should be randomly spread around the graph, and the red line should be horizontal at zero on the y-axis.

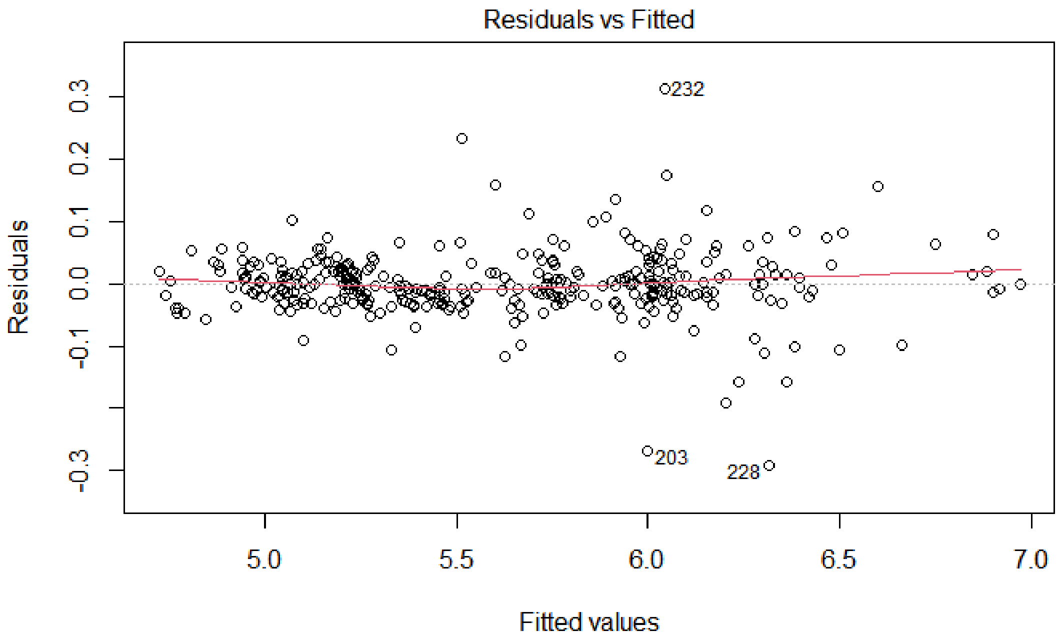

Figure 6.3: Residuals vs. Fitted values of the commodity model

In our case, we achieve both. The data points are randomly spread out, and the red line is mainly centered around zero. This indicates that we have a linear relationship between DAP and the commodity prices.

6.2.3 Test of homoskedasticity

To test for homoskedasticity in this model, a Breusch-Pagan test is used. The null hypothesis states that there is insufficient evidence to claim heteroscedasticity in the model.

```
        studentized Breusch-Pagan test

data:  m4
BP = 67.214, df = 13, p-value = 2.604e-09
```

Table 6.3: Studentized Breusch-Pagan test for the commodity model

Because the p-value is below 0.05, we can reject the null hypothesis and claim that there is heteroskedasticity in the model. However, this is easily remedied by applying White robust standard errors at the end to correct this issue. The model with these standard errors will be used for reviewing estimates.

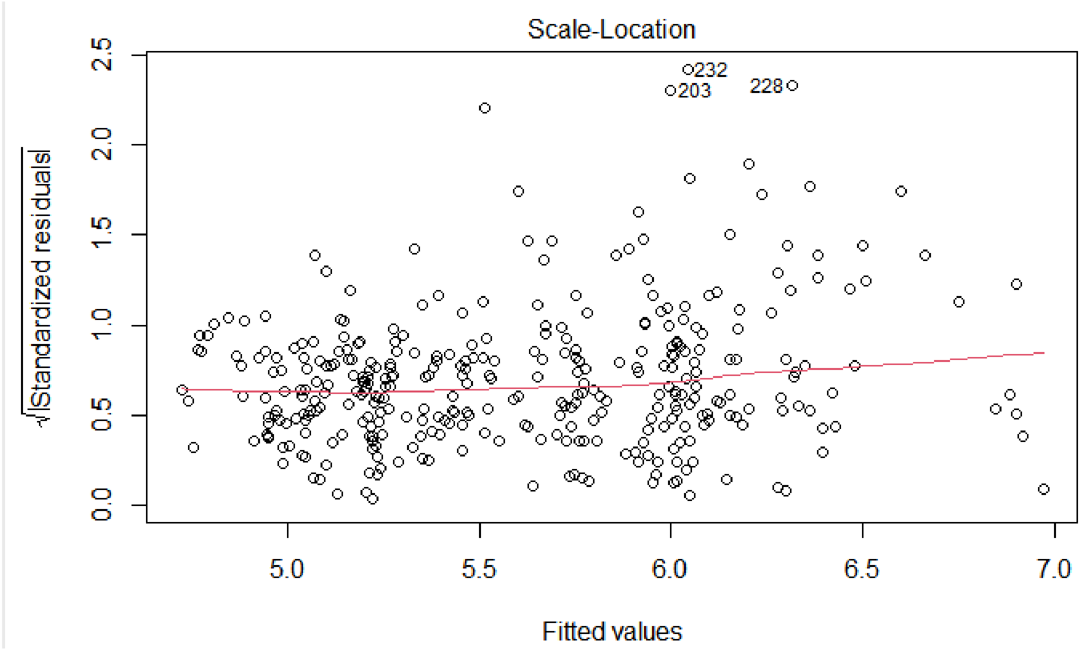

Figure 6.4: Scale-location plot for the commodity model

The scale-location plot shows conflicting results. However, the Breusch-Pagan test is the safest option to follow in this case.

6.2.4 Test of independent predictors (no autocorrelation)

To for autocorrelation in the chosen specification, a Durbin-Watson test is performed. The null hypothesis of this test states that there is no correlation among the residuals.

```
lag Autocorrelation D-W Statistic p-value
  1    -0.002797764      1.995334    0.52
Alternative hypothesis: rho != 0
```

Table 6.4: Durbin-Watson test results on commodity model.

Because the p-value is above 0.05, the null hypothesis is not rejected, and we can state that the model does not contain any correlation among the residuals. Graphically we can also see the same result:

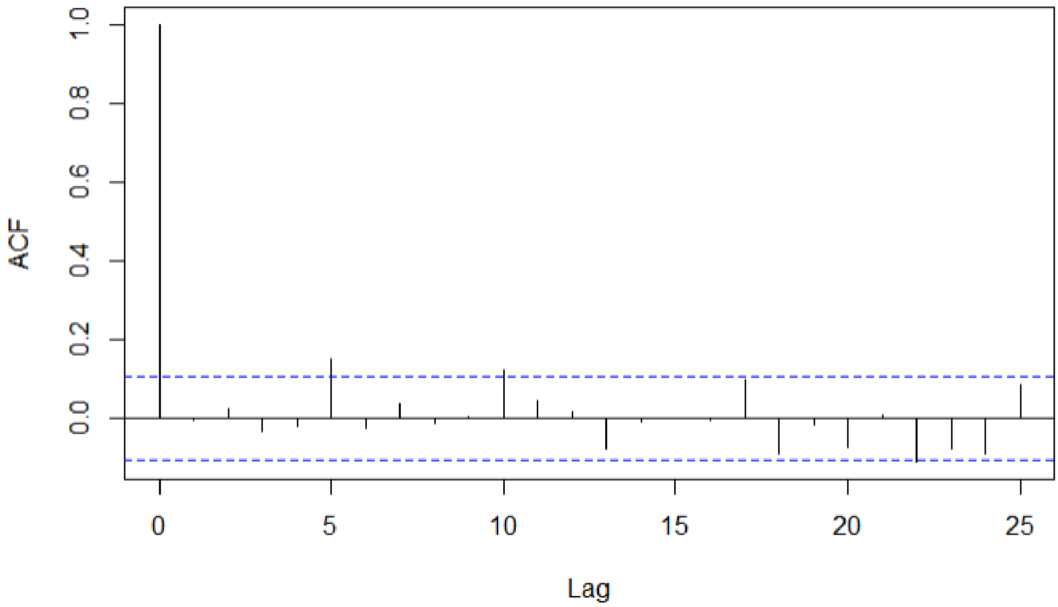

Figure 6.5: Autocorrelation graph with lags.

The model has no autocorrelation because the ACF instantly drops down after lag 0 and stays within the blue dotted lines. We can therefore claim that our model contains independent predictors.

6.2.5 Regression model estimates and discussion

The new model with corrected white robust standard errors is as follows:

```
Residuals:
      Min        1Q    Median        3Q       Max
-0.291440 -0.023280 -0.003083  0.020258  0.312800

Coefficients:
                Estimate Std. Error t value Pr(>|t|)
Intercept     -1.165e-01  8.243e-02  -1.414  0.15842
Trend          1.527e-04  5.819e-05   2.625  0.00907 **
Spring        -1.794e-02  6.956e-03  -2.579  0.01035 *
Fall          -1.332e-02  5.807e-03  -2.293  0.02245 *
Lag 1 of DAP   1.324e+00  1.061e-01  12.473  < 2e-16 ***
Lag 2 of DAP  -4.323e-01  9.760e-02  -4.429 1.29e-05 ***
Lag 12 of DAP -4.733e-02  1.460e-02  -3.242  0.00131 **
Phosphorite   -5.763e-03  1.712e-02  -0.337  0.73667
Oil            1.279e-02  1.497e-02   0.855  0.39341
Natural gas    1.832e-02  1.219e-02   1.503  0.13384
Wheat          2.808e-02  2.311e-02   1.215  0.22512
Corn          -1.140e-02  3.643e-02  -0.313  0.75443
Rice           6.738e-02  2.458e-02   2.741  0.00645 **
Soy            7.604e-02  2.771e-02   2.744  0.00639 **
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.05422 on 332 degrees of freedom
  (11 observations deleted due to missingness)
Multiple R-squared:  0.9884,    Adjusted R-squared:  0.9879
F-statistic:  2867 on 13 and 332 DF,  p-value: < 2.2e-16

Note: Heteroscedasticity-consistent standard errors using adjustment hc0
```

Table 6.5 Regression model with White Robust standard errors to correct for heteroskedasticity.

The equation is rewritten to fit the estimates. This equation now becomes:

$$
\begin{aligned}
DAP_t = -0.165 + 0.00015Trend_t + (-0.01794Spring_t) + (-0.01332Fall_t) + 1.324DAP_{t-1} \\
+ (-0.4323DAP_{t-2}) + (-0.04733DAP_{t-12}) + (-0.005763Phos_t) \\
+ 0.001279Oil_t + 0.01832Gas_t + \ 0.02808Wheat_t + (-0.01140Corn_t) \\
+ 0.06738Rice_t + 0.07604Soy_t + u_t
\end{aligned}
$$

The confidence intervals are also included for the variables in this model:

	2.5 %	97.5 %
Intercept	-2.803785e-01	0.0473258107
Trend	3.307515e-05	0.0002724128
Spring	-3.209942e-02	-0.0037750667
Fall	-2.763936e-02	0.0010021571
Lag 1 of DAP	1.227012e+00	1.4207091291
Lag 2 of DAP	-5.295631e-01	-0.3349951261
Lag 12 of DAP	-7.883238e-02	-0.0158245861
Phosphorite	-3.090331e-02	0.0193768387
Oil	-1.137531e-02	0.0369629636
Natural gas	-1.230991e-03	0.0378626135
Wheat	-1.923487e-02	0.0753957820
Corn	-6.914008e-02	0.0463319421
Rice	2.432988e-02	0.1104345553
Soy	1.422319e-02	0.1378533690

Table 6.6: Confidence interval of the variables in the regression model.

The model's intercept is significant at the 0.05 level, and the estimate is -0.165. This number indicates the mean effect of the variables not included in this regression model.

The trend variable is positive and significant, indicating an upward trend. Because the trend is not in log form, it had to be exponentiated, subtracted from 1, and multiplied by 100. For every one-unit increase in *Trend*, the price of DAP increases therefore by 0.0033% on average. This means that a minor upward trend is in effect for DAP.

Spring and Fall are significant at the 0.05 level. The estimates are negative, at -0.0179 for Spring and -0.01332 for Fall. Because Winter and summer are omitted and insignificant, the estimates for Spring and Fall are related to the sum of Winter and Summer. Spring, therefore, has a -1.79% decrease in DAP price in comparison to Winter and Summer, while Fall leads to a -1.33% decrease in DAP price in comparison to Winter and Summer.

Lag 1 of DAP is significant at the < 0.01 level, with an estimate of 1.324. This means that for every 1% increase in Lag 1 of DAP, the DAP price itself rises by about 1.32%. This indicates that the DAP price increases more rapidly than Lag 1 of DAP. However, this increase aligns with theory, as current prices will be based on past prices. When past prices increase, the current prices must increase more, indicating an upward trend.

Lag 2 of DAP is also significant at the < 0.01 level, with an estimate of -0.4323. This means that for a 1% increase in Lag 2 of DAP, the DAP price is decreased by around 0.43%. This is also in line with theory, as an increased price two periods ago will not last long in the market due to mean reversion. An increased price two periods ago will lead to a decline in price two periods later.

Lag 12 of DAP is significant at the 0.01 level. The 12th lag captures the yearly variation, which captures seasonality outside the spring and fall dummy variables. The estimate is -0.04733, meaning that for every 1% increase in the 12th lag of DAP, the DAP price itself is decreased by roughly 0.04%.

Phosphorite is not significant in the model, but this is most likely due Phosphorite prices having been almost stagnant for 14 years (1992-2006). This means Phosphorite was relatively cheap and experienced little to no volatility in terms of price movements. However, in the last 16 years, Phosphorite has become more volatile and affected by the market. This means that as DAP prices have experienced highs and lows in those initial 14 years from 1992-2006, Phosphorite prices have remained stable and thus have no direct effect on the price of DAP.

Oil and Natural gas are also not significant in the model, and this might be because the primary factors driving change in these commodities are not the same as the ones that drive change in the price of DAP. The factors connecting Oil and Natural Gas to DAP may therefore not be enough to warrant significant price changes.

Wheat and corn are also not significant. A possible reason is that wheat and corn are critical staple foods that producers fertilize based on expected yields. In contrast, actual yields may vary due to variable growing conditions.

Rice and Soy are significant at the < 0.01 level. A 1% increase in rice increases the DAP price by roughly 0.067%. A 1% increase in Soybeans increases the DAP price by roughly 0.076%. This is in line with the theory described in chapter 5.

6.3 Modelling empirical Hotelling price paths on Phosphorite

All calculations for Hotelling price paths in this chapter are included in Appendix A. Each Hotelling price path is created using 3-year intervals, meaning that each equation is solved by plugging in the data from the respective periods. Seven price paths were made over 15 years, from 2007 to 2021. Starting the price paths earlier would not yield any good results as the price increase between each year from 1992-to 2006 would be negligible. The first two price paths were removed as they were too high above the Phosphorite price, which stems from the fact that they were based on the commodity boom in 2007-2009 (high starting value).

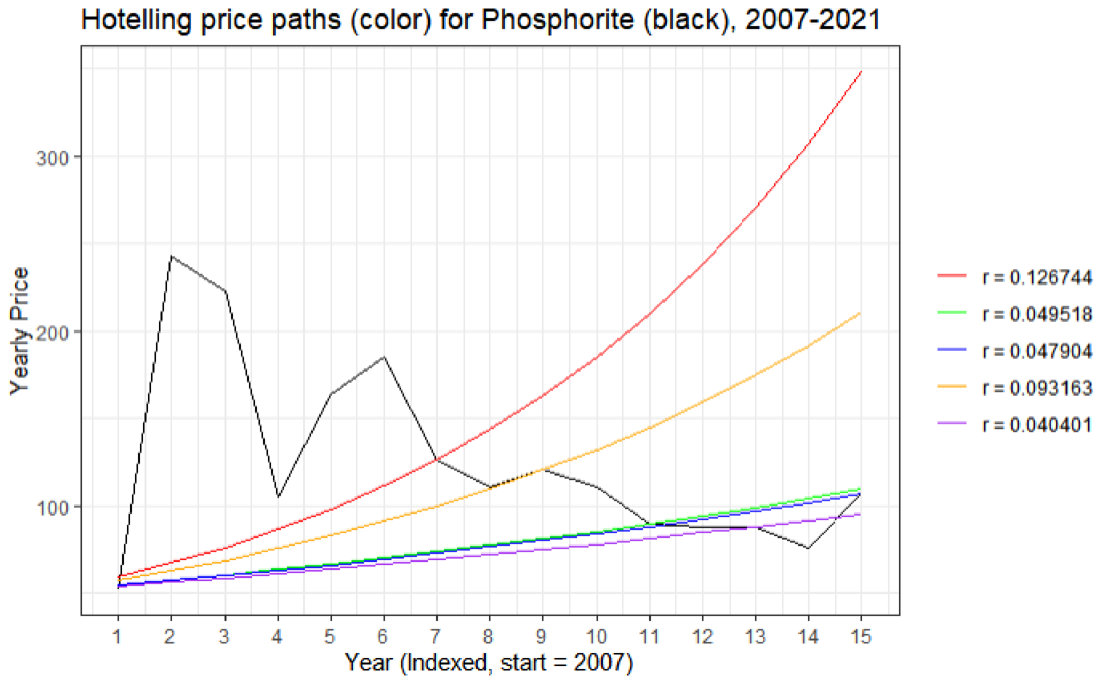

Figure 6.6: Hotelling price paths for Phosphorite, created using the period 2007-2021.

The remaining five Hotelling price paths are divided into different colors to differentiate them easier. The red price path is created using the years 2011-2013. The yellow price path is based on 2013-2015, green from 2015-2017, blue from 2017-2019, and Purple from 2019-2021. This means that the price paths based on later years are much lower than those based on the commodity boom. Keep in mind that even though all the price paths are based on "future prices" (after 2007), I have layered them so that they start simultaneously in the graph. This makes it easier to compare them instead of having price paths all over the figure. Figure 6.8 shows that the red and yellow price paths overshoot the price of Phosphorite. However, the green, blue, and purple price paths are more reasonable; These have much slower growth and will better represent how the actual price of Phosphorite might become in the future.

The problem with this method becomes evident when the price paths are layered on top of the Phosphorite price. As these price paths are based on 3-year intervals, it will be hard to draw credible conclusions as one can argue that a new interval will always be better than the last as it draws from a newer price history. The price of Phosphorite does not follow any of the price paths to a fault, and the main reason lies in the fact that the market participants are more concerned with short-term expectations and risk rather than investing long-term. This means that the scarcity factor, which one anticipates being in place for nonrenewable resources with a short expected remaining lifetime, does not come into play because market participants favor short-term profit.

Market participants also must consider external shocks that affect the price. These shocks create high-risk, high reward situations that long-term investment could not. Shocks can also leave the price in new plateaus, meaning that refusal to adjust short-term may leave investments on a downturn. Therefore, it is intuitive that market participants prioritize short-term market behavior rather than investing over the long term. This is in clear contrast to the optimal extraction theory, where the price should rise at a set discount rate. This conflict may point to an over-extraction of Phosphorite, as the price is volatile but reverts to a set mean rather than steadily increase. A price that follows its mean with ever-increasing production means that the net effect will be over-extraction until production can no longer increase. In that case, prices must rise to cater to the increased demand. This price increase might be explosive, seeing as market participants know that the peak production has been achieved and thus may invest as much as possible in Phosphorite, seeing as the price has no other choice than to increase.

6.4 Result effects on hypotheses

To summarize, the model gives a different result than what is in line with the theory. Most importantly, the Phosphorite price has no significant effect on the DAP price. This, in turn, cuts off the link in hypothesis 1, which states that there is a price correlation between Phosphorite and DAP fertilizer. As explained, however, the Phosphorite price is only in the recent decade that it began to be affected by the market, which may cause an increased effect on the DAP price going forward.

Hypothesis 2 states that the price of Phosphorite should be ever-increasing as the population is increasing and the demand for better quality food is also rising. However, this is canceled out because the supply of Phosphorite can keep up with the increasing demand for Phosphorite, essentially maintaining an equilibrium in the market. It is only when Phosphorite's production can no longer increase that we will see ever-increasing prices of Phosphorite, as the supply no longer can keep up with the demand.

Hypothesis 3 claimed that the Phosphorite price would follow a Hotelling price path. However, this is not the case. The collected price data showed no signs of following a Hotelling price path, instead showing signs of volatility. The constructed Hotelling price paths also did not fit the data, characterized by too much dependence on short-term corrections. If the corrections were not implemented, the Hotelling price paths would quickly overshoot or undershoot the Phosphorite price. Over the long run, the Phosphorite price also seems to follow mean reversion and thus is not ever-increasing.

These results also point toward Phosphorite prices being dominated by short-term market behavior, as aligned in the previous section. If production increases, the increased demand can be met, and the Phosphorite price will be determined by hedging, speculation, and other commodities.

7. Discussion

Much of the econometric analyses in this thesis have dealt with understanding the price generating processes for Phosphorite and DAP fertilizer. These processes are affected by several factors addressed in this chapter.

7.1 The case of weakly targeted environmental policies

Unchecked pollution from nitrogen and phosphorus causes severe environmental damage in the form of eutrophication. This pollution is already exceeding safe planetary boundaries, posing a threat to the climate and life on Earth (European Comission, 2022).

Environmental policies connected to Phosphorite must target the process before or during extraction and beneficiation. Policies that target the process before extraction include land conservation laws and regulations and land reclamation at the expense of the extractors. These policies are enacted to either conserve the land and biodiversity, make extraction unfeasible, or increase the cost of starting the extraction process. Such strict policies will no doubt increase the cost of extraction and increase search and discovery costs as mining companies must find new sites to extract Phosphorite. Land conservation regulations also keep the reserves of Phosphorite under lockdown, which creates an artificial barrier in supply, as extraction may no longer be possible.

Policies that target the process during extraction and beneficiation are related to taxation and penalties. Such policies can be akin to the minerals resource rent tax Australia implemented in 2012 but later repealed. This tax set out to control parts of the mining industry by taxing supernormal profits earned by mining companies (Parliament of Australia, 2011). Another policy can be penalties if the mining companies fail to adhere to specific standards. An example of this could be a penalty due to nearby waters becoming polluted because of the mining operation. Such policies increase the cost for mining companies as they must be cautious of not overstepping any boundaries lest they get penalized. Current policies targeting Phosphorite seem to have little effect in terms of price change, even though the extraction and beneficiation process is quite harmful to the environment. Questions regarding phosphogypsum storage and subsequent leakage of radioactive material are also of great concern.

The increase in the amount and the strength of policies connected to Phosphorite mining and beneficiation should be expected moving forward. The negative externalities connected to

Phosphorite are also cumulative; Phosphogypsum stacks in Florida alone increase by 30 million new tons every year (Florida Polytechnic University, n.d.). There have been several attempts to use phosphogypsum for road construction and agriculture, but because of the lifetime of radiation, potential homeowners settling on the farmland or road far into the future would face too significant a risk of contracting cancer (Florida Polytechnic University, n.d.). These scenarios have led to the EPA banning the widespread use of phosphogypsum for road construction. Phosphogypsum is, however, used in agriculture but may not exceed 0.37 Bq/g (10 pCi/g) (U.S. Environmental Protection Agency, 2021).

Policies aimed at reducing the harmful environmental effect of extracting and beneficiating Phosphorite will cause an increased fertilizer price. This connection will also cause food prices to rise as fertilizer is a vital input factor in generating higher yields per hectare. The policies would also combat scarcity concerns but would do so chaotically and unpredictably. Instead of incentivizing research and development in phosphorus production through subsidies and more predictable means, it will be pushed by the market. When the market in question relies on a non-renewable resource essential for producing a necessary good, price changes will become highly volatile. This will lead to a desperate push toward alternative methods of producing phosphorus.

7.2 Short-term profit dominating long-term sustainability concerns

The log price of Phosphorite (black) and DAP fertilizer (Blue) is depicted below in figure 7.1:

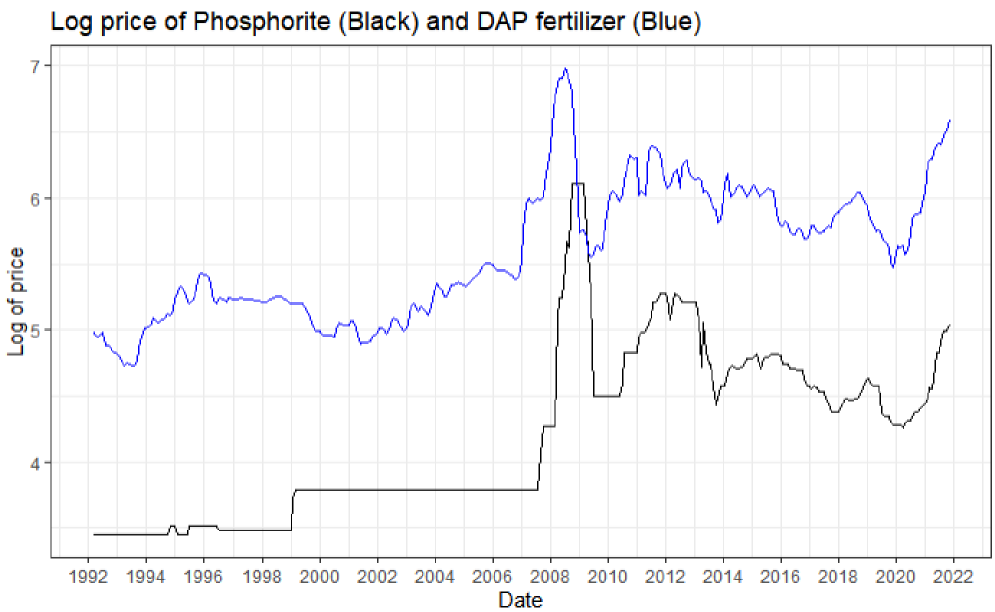

Figure 7.1: Log price of Phosphorite and DAP fertilizer

The price of Phosphorite and DAP fertilizer both seem to increase steadily from 2020 onwards. The initial push can be attributed to supply chain disruptions during the Covid-19 pandemic and was further propelled by Russia's invasion of Ukraine. Following Westra (2022), a "perfect storm" of trade disputes and sanctions also affects the current market for fertilizer.

- Sanctions have been placed on Belarus, responsible for 20% of global potash exports.
- China has applied an export ban on phosphate to aid in increased domestic use and higher price of production. This has a significant effect on the market as China is responsible for 25% of the world's phosphate fertilizer exports.
- Russia is a significant exporter not only of natural gas but also of nitrogen, phosphate, and potash. Therefore, the current geopolitical situation puts heavy pressure on fertilizer and phosphate prices.

This is another indication of the market for Phosphorite being dominated heavily by short-term shocks and market behavior. Long term sustainability concerns and scarcity does not reflect in the current price of Phosphorite, which comes down to two main reasons:

First, producing food causes a "necessary evil" paradigm to trump environmental policies aimed at reducing the production and beneficiation of Phosphorite. This is because producing food provides a more significant societal benefit than reducing negative externalities. The problem with this method becomes apparent when the compounded negative externalities become so large that significant environmental damage occurs. The remedy, in this case, must either come from new technologies, methods of production, or use for the waste products.

Second, a sudden introduction of harsh policy measures would heavily disturb the market, causing an increase in price for Phosphorite, DAP fertilizer, and subsequent soft commodities, but will also send a message that the market for Phosphorite is under scrutiny. This will further garner attention to the scarcity situation, and subsequently cause an even more volatile situation in the market.

However, because the production of Phosphorite is still ever-increasing, there appears to be no widespread short-term concern of scarcity. This, in turn, is reflected in the market behavior because investing long-term in this market would lead to a loss of potential profit if the price were volatile and production had not reached its peak.

7.3 Uncertainty regarding peak phosphorus

Several sources state that peak phosphorus will happen within 2030; see 1-2 references. Discoveries of reserves, technological change, and more efficient production possibilities would prolong the expected lifetime of reserves. What is certain is that the population is increasing, and wealth is increasing, leading to an added stress on phosphorus production. This means that we cannot assume stable production in the future but rather an increasing production to cater to the increasing food demand.

According to the International fertilizer development center (IFDC), there is no indication of a nearby peak phosphorus event given 2010 levels of production and reserves. Instead, they estimate that Phosphorite reserves will be available 300-400 years into the future (Van Kauwenbergh, 2010). This statement is based on the presumption that production levels stay constant throughout this period, which is unlikely. As seen in figure 2.2 in chapter 2.3.1, production levels increase rapidly each year. Production levels in 2010 were 183 million metric tonnes and increased to 265 million metric tonnes just six years later in 2016. Given this increase, doubling 2010's production would cut the IFDC's estimate down to 150-200 years. Another doubling would cut it down to 75-100 years. Therefore, expectations surrounding production and reserves are changing rapidly and lead to uncertainty about when peak phosphorus occurs.

It is valid to assume that as extraction costs of Phosphorite increase, previously unprofitable reserves now become a viable option. When these reserves also become unprofitable, the next step in the ladder is considered. This cycle continues until extraction costs become too high or reserves are too thin. At that point, the most reasonable option for mining companies is to reallocate resources into research and development to ensure the company's future survival. This means that as phosphorus mines either run dry or the quality decreases to the point where it is unprofitable, the mining company would instead invest in new technologies than extract the last amount of unprofitable Phosphorite.

On a side note, a misconception will most likely arise as Phosphorite quality drops during reduced resource stocks as time moves on; Beneficiating low-quality rock will enter a point where it is so costly that the only option is to market Phosphorite at a lower percentage of Phosphorus than what is done today. This means that the price will most likely remain stable or drop, but this should not be associated with the price of Phosphorite rock marketed today. The Moroccan Phosphorite marketed today is beneficiated at around 70% before it is marketable. An example of what could happen in the future is that the beneficiation is dropped to 50%, and the price will subsequently drop or be stable. Ideally, this should lead to new classifications of Phosphorite so as not to confuse past prices with new gradings.

7.4 Problems and limitations of the Hotelling price path

The Hotelling price path does not consider external shocks into its equation and thus will make the analysis distorted. This makes it hard to choose an optimal path and claim that Phosphorite will follow that path over a more extended period. The commodity boom and financial crisis in 2008 is an example of this, where the price spike only lasted roughly a year, but creating a Hotelling price path based on this information will lead to a path that is way above average prices. The regression model also suffers heavily from including short-term shocks, bringing with it issues of heteroskedasticity and unreliable estimates. These issues would not be present if not for the external shocks, as the bundle of agricultural commodities mostly follows the same patterns in the realm of seasonality and substitutability.

Therefore, removing such effects will create a more stable environment to conduct analyses and tests. There are, however, several problems with doing this. The most obvious is that it manipulates the data and creates a biased analysis. The second is finding an appropriate definition of external shocks. Removing every price peak will eventually remove average price volatility, leading only to a stable straight price line. This causes the removal of external shocks not to be a feasible option.

The simplest form of the Hotelling model does not consider rising extraction costs as the resource stock becomes depleted. Because it is not considered, the price growth will be higher than what is genuinely optimal (Livernois, 2009). In practice, the original model will lead to an underusage of resources, as it proposes a situation in which it is too costly to extract them. Inclusion of extraction costs also brings backstop resources into attention, as it is not economically feasible to extract a resource if the extraction price is too high. A remedy for this is to use a Hotelling model that accounts for these factors. However, there are inherent problems related to the unobservability of both the resource net price and discount rate (Perman et al., 2003). This creates a situation where analyzing Hotelling price paths through proxies occurs, which further causes uncertainty as to how well these price paths reflect the price generating processes.

7.5 Current alternatives to Phosphorite and possible solutions to scarcity

Around 80% of mined phosphorus is lost on the journey from the extraction phase to the dinner table (Cordell, 2010). This leaves enormous potential for reducing losses and will significantly help improve the lifetime of Phosphorite if corrected. Increased efficiency in production also leads to less usage of nutrients, meaning that more fertilizer can be produced by using less phosphorus. Methods of recycling phosphorus, either through organic farming or wastewater treatment, could also help in this regard. These solutions will not work for the longer term as recycling rates would be below one. However, they will significantly increase the lifetime of phosphorite, leading to more time and resources being used to find alternative ways of producing phosphorus.

Demand-side solutions and alternatives also exist; where an example would be a push for foods that are less phosphorus-intensive in their production. Reducing the over-consumption of food would also help in this regard, as it would lower the demand for food production. This kind of framework would also have the added benefit of reducing pollution and greenhouse gasses (Cordell et al., 2009). This would not solve the initial problem but would, together with the supply-side solutions, also help ensure a longer lifetime of phosphorite.

Guano mining was historically used to harvest phosphorus but declined at the end of the 19th century both due to exhaustion of guano and a switch towards artificial fertilizer (Cordell et al., 2009). Artificial guano islands could be made to create a source of phosphorus potentially, but the amount of guano needed would be immense to cater to today’s demand for phosphorus. Around ten tons of fish are required to produce a ton of guano (Schnug et al., 2018). If guano islands were to take over phosphorus production, several hundreds of million metric tons (current phosphorite production) would have to be produced every year to match the demand. This information alone questions if this is possible and what kind of environmental damage such a massive undertaking would cause.

8. Conclusion and further research

The main finding in this thesis is that the Phosphorite prices are dominated by short-term market behavior and shocks rather than long-term sustainability and scarcity concerns. The price of Phosphorite did not follow a standard Hotelling price path and required frequent adjustments to account for new market behavior. The data are inconsistent with an optimal long-term price path (and, by extension, optimal extraction) over time. Because the price of Phosphorite is volatile, it essentially results in an over-extraction compared to the Hotelling price path. Moreover, Phosphorite production is increasing everywhere in the data used in this thesis, which is inconsistent with the theory of optimal extraction of non-renewables due to discounting.

The regression model for DAP fertilizer showed clearly that Phosphorite prices did not significantly affect the price of DAP fertilizer. This is due to Phosphorite prices being relatively stable for roughly 15 years before entering a volatile stage. If Phosphorite prices had been climbing steadily (e.g., following a Hotelling price path across the whole 30-year period), the cost of producing DAP fertilizer would also increase relative to the price of Phosphorite, and a more apparent connection between these two prices would be evident. This is another indication that scarcity of Phosphorite is not yet kicking in by affecting the price, even though the problem of peak phosphorus is well-known.

Current environmental policies and targeted remedies for negative externalities seem to have little to no effect on the price of Phosphorite. Phosphorite extraction and its use are seen as “necessary evils” to ensure adequate food production. This implies that current policies are not plentiful or strong enough to incentivize a cleaner production or investment in new technologies. Therefore, the negative externalities connected to Phosphorite are currently being trumped by the necessity of producing food. However, pushing forward policies can heavily disrupt the market for Phosphorite and create a very volatile and chaotic situation.

However, these findings may change over time due to the increased compounding of negative externalities from extraction, use, and the inability to increase the production of Phosphorite when the resource stock inevitably runs out. Further research on this topic will most likely depend on time, as scarcity and environmental policy measures against the negative externalities will dominate the price of Phosphorite in the future.

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10. Appendices

Appendix A – Hotelling price paths calculation

Period	**Initial price**	**End-of-period price**	**Resulting r**
2007-2009	52.02083	222.75	0.484802
2009-2011	222.75	163.5525	0.229098
2011-2013	163.5525	126.32417	0.126744
2013-2015	126.32417	120.315	0.093163
2015-2017	120.315	89.68833	0.049518
2017-2019	89.68833	87.95833	0.040401
2019-2021	87.95833	106.72	0.047904

Note: Initial prices can be higher than end-of-period prices, but r is still positive as the equation ($P_t = P_0 * e^{rt}$) must be solved for the exponent (r) through logarithms. The Hotelling price path can not be negative by design, as this would imply exponential decay in the resource's price.

Appendix B – Results from the first difference and commodity- only model

First difference model

```
MODEL INFO:
Observations: 356 (1 missing obs. deleted)
Dependent Variable: dap2$Price
Type: OLS linear regression

MODEL FIT:
F(15,340) = 221.26, p = 0.00
R² = 0.91
Adj. R² = 0.90

Standard errors: OLS
----------------------------------------------------------
                                Est.   S.E.   t val.      p
--------------------------- ------- ------ -------- ------
Intercept                      -0.74   0.23    -3.19   0.00
Diff 1 of DAP                  -0.00   0.00    -1.26   0.21
Phosphorous                     0.20   0.03     7.01   0.00
Diff 1 of Phosphorus            0.00   0.00     7.87   0.00
Oil                             0.06   0.03     1.90   0.06
Diff 1 of Oil                  -0.00   0.00    -0.37   0.71
Natural gas                     0.15   0.03     5.76   0.00
Diff 1 of Natural gas           0.01   0.01     0.45   0.65
Wheat                           0.12   0.06     1.93   0.05
Diff 1 of Wheat                 0.00   0.00     2.95   0.00
Corn                            0.10   0.08     1.22   0.22
Diff 1 of Corn                 -0.00   0.00    -0.13   0.90
Rice                            0.41   0.05     7.97   0.00
Diff 1 of Rice                  0.00   0.00     1.25   0.21
Soy                             0.27   0.09     2.99   0.00
Diff 1 of Soy                   0.00   0.00     0.30   0.77
----------------------------------------------------------
[1] "AIC: -298.192190237686"
[1] "Residual Variance: 0.0241127126177679"
```

Commodity- only model

```
MODEL INFO:
Observations: 357
Dependent Variable: dap2$Price
Type: OLS linear regression

MODEL FIT:
F(7,349) = 384.05, p = 0.00
R² = 0.89
Adj. R² = 0.88

Standard errors: OLS
------------------------------------------------
                      Est.   S.E.   t val.      p
----------------- ------- ------ -------- ------
Intercept            -0.92   0.24    -3.80   0.00
Phosphorous           0.17   0.03     5.96   0.00
Oil                   0.06   0.03     1.95   0.05
Natural gas           0.17   0.03     6.19   0.00
Wheat                 0.12   0.07     1.80   0.07
Corn                  0.12   0.09     1.28   0.20
Rice                  0.41   0.06     7.35   0.00
Soy                   0.31   0.09     3.36   0.00
------------------------------------------------
[1] "AIC: -236.286337037463"
[1] "Residual Variance: 0.029378273771113"
```

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