Global Phosphorus Recovery
for Agricultural Reuse

A study on fertilizer substitution by struvite precipitants from wastewater

By

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Preface

Global phosphorus insecurity is one of those issues that you are initially indifferent about. Then, after reading two or three articles, you develop a moderate interest. Not much later, before you've realised it's too late, you are wildly passionate about pee, poop and plants, and all the wonderful things they share.

This thesis was written as a graduation project for the degree in the Master in Civil Engineering at Delft University of Technology, The Netherlands. The moment I became involved, I had not imagined that this thesis would end up being much more than just a thesis. The project would carry me across the continent to an internship position at UNESCO's World Water Assessment Programme (WWAP), in Italy. The 2017 World Water Development Report on 'Wastewater: the untapped resource', covers many elements of the thesis' research and concludes with the same message of this research, namely that we need to reassess our view on 'wastewater'. As such, project coordinator, Angela Renata Cordeiro Ortigara, and Director, Stefan Uhlenbrook, were content to receive me as an intern. Once there, I would preoccupy myself with thesis work while doing WWAP assignments on the side. Frequent meetings with Angela, Stefan and Saket kept this difficult project on track, while weekends of exploring Umbria with Saket would soothe the weeks' frustrations. Most troubles arose from the steep learning curve that I was subjected to given the projects' multidisciplinarity. Unfamiliarity with the combined specifics of resources management, economics, agriculture, and sanitary engineering posed significant struggle. With due time investment, however, in reading literature, adapting and revising input data, and running time after time again the model with minor changes, progress was slowly made. In the end, despite the struggles and setbacks, I believe that a meaningful contribution to the pool of knowledge on phosphorus recovery has been made - which is all I could wish for from a project as ambitious as this.

Thank you, Saket, Angela, Stefan and Hubert, for the opportunity and fantastic supervision.

D.D. Kok
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Contents

Abstract

Phosphorus is an element important to all living organisms. It forms a key, structural component of DNA and RNA and, as such, plays an essential role in cell replication. Phosphorus occurs naturally at globally uncertain quantities, in phosphate rock formations. It also concentrates itself in waste and wastewater from urban areas and livestock industries, wherefrom it is often lost as a pollutant. Global food security is dependant on phosphorus as global agricultural production rates are achieved with the application of synthetic phosphate fertilizers. Analysing the phosphorus recovery potential from wastewater in meeting partial agricultural demand can be an important tool in tackling both phosphorus depletion from natural sources and phosphorus pollution of the environment. In this study, a global overview is provided where a selection of P-production and P-consumption sites have been identified through global spatial datasets for 2005. A model is created to consider distances and recovery costs in determining optimal phosphorus market prices and a network of phosphorus trade flows. Results have revealed a maximum anthropogenic recovery potential of 3.3 Mt P for 2005, where a maximum of 19% of that years global fertilizer consumption could be satisfied by recovering all urban excreted phosphorus. However, only 7.3% of that demand could be accommodated economically through competitive, sustainable struvite precipitants. In a scenario where agriculture is completely dependent on recovered phosphorus, only 69% of the demand could be met and phosphate market prices will approximately double. The network maps show that phosphorus recovery is most feasible in Asia and parts of South America, where human and population population densities are high and occur in close proximity to agricultural demand sites that are situated relatively far from phosphate mines. Phosphorus recovery from wastewater will prove an important step in protecting the environment and creating sustainable communities. It is also a step towards prolonging our phosphate rock reserves - granting more time to revise our current phosphorus throughput cycle.

Acknowledgements

List of Definitions

Units	Abbreviation	Conversions
Mega tonne	Mt	10^3 [kt] = 10^6 [t] = 10^9 [kg]
Annum	a	365 days
Heads	h	One individual
Hectares	Ha	1 [km^2] = 100 [Ha]

Variable Definition	Abbreviation	Formula
Organic phosphorus production	S_{PT}	[kg km^{-2} a^{-1}]
Human population Density	H	[h km^{-2}]
Human P excretion rate	H_{PP}	[kg h^{-1}a^{-1}]
Bovine population Density	B	[h km^{-2}]
Bovine P excretion rate	B_{PP}	[kg h^{-1}a^{-1}]
Poultry population Density	P	[h km^{-2}]
Poultry P excretion rate	P_{PP}	[kg h^{-1}a^{-1}]
Swine population Density	S	[h km^{-2}]
Swine P excretion rate	S_{PP}	[kg h^{-1}a^{-1}]
Estimated recovery efficiency	E_r	[-]
Mass of rock phosphate	M_{RP}	[M]
Phosphate rock grade	R_{grade}	[-]
Mass phosphoric acid	$M_{P_2O_5}$	[M]
Actual yield	Y_a	[kg km^{-2} a^1]
Optimal yield	Y_m	[kg km^{-2} a^{-1}];
Crop coefficient	K_y	[-]
Actual evaporation-transpiration	E_a	[mm a^{-1} Area^{-1}]
Optimal evaporation-transpiration	E_m	[mm a^{-1} Area^{-1}]
Phosphorus Demand	P_{opt}^n	[kg km^{-2} a^{-1}]
Crop specific P-demand	P_{PD}	[kg km^{-2}]
Crop harvested area	A_H	[Ha]
Crop specific max phosphorus price	f_{max}^n	[\$ t^{-1}]
Crop specific optimal yield	Y_{opt}^n	[t ha^{-1}]
Crop specific Fertilizer cost ratio	R^n	[-]
Year specific crop market price	C_a^n	[\$ t^{-1}]
Minimum phosphorus price	f_{min}^i	[\$ t^1]
Magnesium or mining costs per P	M_c^i	[\$]
Base cost of operation	B^i	[\$]
Phosphorus production potential	S_{PT}	[t]
Savings in operational maintenance	S_s	[\$ t^{-1}]
Price of magnesium	P_m	[\$ t^{-1}]
ratio of Mg:P	R_{mp}	[-]
P prop. Mg content of wastewater	C	[t t^{-1}]
Transportation cost from i to n	$T_c^{i,n}$	[\$]
Diesel price	P_d	[\$ L^{-1}]
Fuel efficiency 60 [t] cap. truck	DC_{60}	[L km^{-1}]
Labour wage truck driver	L_c	[\$ h^{-1}]
Average truck velocity	$\bar{V}$	[km h^{-1}]
Distance from i to n	$D^{i,n}$	[km]
Base free for logistic operations	B_c	[\$]
Truck load weight	W_{tr}	[t]
Traded phosphorus weight	W_P	[t]
CO$_2$ emissions in transportation	$E_{CO2}^{i,n}$	[kg]
CO$_2$ per litre of diesel	D_C	[kg litre^{-1}]

Compound/Element	Abbrev./Symb.	Formula	Conversions
Elemental Phosphorus	P	-	-
Phosphate; Phosphoric Acid	P_2O_5	P_2O_5	44% P
Rock Phosphate	RP/PR	-	25-40% P_2O_5
Monoammonium Phosphate	MAP	$NH_4H_2PO_4$	21-27% P
Diammonium Phosphate	DAP	$(NH_4)_2HPO_4$	20-23% P
Triple Super Phosphate	TSP	$Ca(H_2PO_4)_2$	20% P
Single Super Phosphate	SSP	$Ca(H_2OP4)_2$	7-9% P
Dicalcium Phosphate	DCP	$CaHPO_4$	17% P
Monopotassium Phosphate	MKP	KH_2PO_4	17% P
Struvite	-	NH_4MgPO_4	13-14% P
Magnesium	Mg	-	-
Magnesium Chloride	$MgCl_2$	$MgCl_2$	25% Mg

1 Introduction

Phosphorus (P) is a macronutrient and is therefore essential for all living organisms. It forms a key, structural component of DNA and RNA that cannot be substituted for (Childers, Corman, Edwards, & Elser, 2011). Humans and animals acquire most P through metabolism, while crops withdraw it from the soil. However, whereas P-related malnutrition in humans is uncommon, inhibited plant growth due to soil phosphorus deficiency is a much more prevalent issue (MacDonald, Bennett, Potter, & Ramankutty, 2011). Phosphorus has therefore also acquired that status of a being a *limiting nutrient*. Suboptimal plant growth due to limited phosphorus availability translates to suboptimal yields, and as such soil phosphorus deficiency contributes directly to the global cop yield gap (Pradhan, Fischer, van Velthuizen, Reusser, & Kropp, 2015). In achieving higher yields, low levels of soil phosphorus are artificially supplemented through the application of fertilizers. Currently, an estimated 90% of the of global phosphate rock demand is used as fertilizers or as feed additives for food production (OECD, 2011). Although agricultural phosphorus application may have come with improvements to global food security, it also poses a threat to the environment (Ulrich, Malley, & Watts, 2016). One form of improper phosphorus management expresses itself as the over application of phosphorus fertilizer. Through seepage and runoff processes, as well as the discharge of improperly treated wastewater, phosphorus excesses come into contact with open surface waters and cause phosphorus pollution (Sims, Edwards, Schoumans, & Simard, 2000). As a limiting nutrient, the smallest quantities of phosphorus in open surface water can spark the growth of disproportionately large algal blooms. This is of significant concern, as these have a detrimental effect on water based ecosystems in causing eutrophication and thus the essential suffocation of the aquatic life (EPA, 2010).

'Rock phosphate' (RP) is the most widely exploited source of P, despite its very specific, geographic concentration (Cordell & White, 2013)(Figure 1). Rock phosphate formations develop over geological time scales as dissolved and particulate phosphorus in the ocean gradually precipitates or deposits on the ocean floor (Cordell & White, 2011). The rate at which we exploit the ancient rock phosphate formations is far out of proportion to the rate at which they form, which essentially classifies phosphorus as a non-renewable resource. Uncertain estimates on the quantities left in these natural reserves, as well as the increasing demand trends has led many individuals to draw parallels to another group of non-renewable resources, namely of fossil fuels (Cooper, Lombardi, Boardman, & Carliell-Marquet, 2011; Cordell & White, 2011; Edixhoven, Gupta, & Savenije, 2013; Smit, Bindraban, Schröder, Conijn, & van der Meer, 2009). The biggest difference between the two is the availability of greener alternatives for energy, whereas there exists no substitute for phosphorus.

Figure 1. Estimated global phosphorus reserve distribution (USGS, 2017).

1.1 Research Problem

The human impact on the natural phosphorus cycle is unsustainable and threatens future food security (Schröder, Cordell, Smit, & Rosemarin, 2010). The dwindling of rock phosphate reserves will reduce future phosphorus production, while phosphorus demand continues to rise as populations grow and living standards improve (Mew, 2016). Some studies predict a complete exhaustion of phosphate reserves to occur within the next 50-100 years (Smil, 2000; Steen, 1998; van Vuuren, Bouwman, & Beusen, 2010), while others predict the reserves lasting us another good 300-400 years (van Kauwenbergh, 2010). Despite this, much phosphorus is being wasted through wastewater streams which result in the pollution of open surface waters and their dilution in the ocean where they are inevitably lost. A study on the estuary of Chesapeake Bay, near Washington D.C., reveals that 41% of the phosphorus pollution was caused by agricultural runoff, and another 16% by wastewater discharges (University of Maryland & State of Maryland, n.d.). Urban centres, livestock industry and agriculture are thus, and will become more so, major contributors to excess phosphorus loads in open surface waters. These pollution loads can effectively and efficiently be reduced with the introduction of phosphorus recovery technologies for wastewater and the adoption of new nutrient management practices in agriculture, yet the adoption of recovery technologies is inhibited by (perceived) economic infeasibility or lacking economic incentives.

The economic feasibility of phosphorus recovery, however, is not globally static but varies spatially and temporally. The global widespread availability and accretion of phosphorus in wastewater streams provides recovered products with location-defined competitive advantage over the geographically concentrated rock phosphate mines. Also, the gradual depletion of rock phosphate reserves and the resultant rising price trends for non-sustainable phosphatic fertilizers, increase the appeal for recovery over time.

Transition to a more sustainable phosphorus cycle is hampered by the absence of global studies that identify the locations and conditions for economically feasible phosphorus recovery. Given that the will, the technology and the knowledge are there to fundament the transition to a market of sustainably recovered phosphorus products, it is therefore important that investigation is done as to under what economic conditions such a transition may occur and what such a development at global scale may come to look like. Only then can policy regulate it in such a way that maximum benefit is achieved for both the environment and the urban community, as well as the livestock and agricultural sectors.

1.1.1 Research Objectives and Approach

Exploring the dynamics of the phosphorus market and identifying the points that allow for economically competitive phosphorus recovery requires an integrated approach that can be summarized in multiple objectives:

- Geographical identification of high phosphorus production and demand areas.
- Approximation of the potential contribution of recovered phosphorus to global phosphorus demand.
- Evaluation of the emissions that come with the transportation of recovered vs. mined phosphorus.
- Evaluation of the effects of different financial and policy measures on the created network.
- Determination of areas where there is an economic feasibility for phosphorus recovery.

The objectives are addressed through the employment of Geographic Information System (GIS) tools and a Python built model. These tools allow for the identification of recovered, and conventional, phosphorus

flows and prices at a global scale. Major urban, livestock and agricultural sites for phosphorus production and consumption are identified spatially through GIS. These are then linked to a model built network based on the distances and costs so that a market price of phosphorus may be approximated. Different scenarios, by current and future market supply characterizations, are then simulated. Finally, financial parameters are tweaked to evaluate the effects of financial policy measures on the modelled phosphorus market. This is followed up by a brief analysis on the effects of these variations and a final summary of concrete findings in addressing the study objectives.

1.1.2 Implications

Answers to the research question and study objectives will reveal where a more sustainable relationship with phosphorus may develop, under what circumstances, and what this development may come to look like. This offers research-based argument for or against phosphorus recovery at specific sites, which in turn may influence the strategy and rate of efficiently transitioning the current phosphorus cycle to a more sustainable alternative thereby improving the phosphorus- and food security. The study's identified areas of high phosphorus recovery potential also create incentive for more accurate, site specific research. As such, this study can serve as a tool that may accelerate research within the subject field of phosphorus recovery and implementation. Also, this identification may contribute in discrediting the misperception of the general, global economic infeasibility of phosphorus recovery.

More generally, the implications of an accelerated and more efficient transitioning of the phosphorus cycle by the above-mentioned impacts can best be summarized in the addressing of the Agenda 2030 for Sustainable Development (UN General Assembly A/RES/70/1) goals:

- **Ending Hunger (2):** where wastewater recovery will improve the access of isolated farmers to phosphorus fertilizers, further helping to close the yield gap.

- **Clean Water and Sanitation (6):** By alleviating wastewater treatment costs through the remarketing of recovered phosphorus and the reduction in maintenance costs related to struvite-scaling.

- **Sustainable Cities and Communities (11):** By creating a circular economy where wastewater materials are recovered and recycled.

- **Responsible consumption and production (12):** Where we reduce our dependency on open cast phosphate mines, and diversify our sources to more sustainable alternatives.

- **Healthy life below water (14):** By further reducing the phosphorus load in treated wastewater thus reducing phosphorus pollution of the environment.

- **Peace and Justice (16):** By improving the phosphorus security of nations through a reduction in their dependency on others.

1.2 Document Setup

This thesis is setup in five chapters, following the chronological order of: 1) Introduction, 2) Background, 3) Methods and Materials, 4) Results, 5) Discussion, and 6) Conclusion. This core body is preceded by *Preface*, *Table of Contents*, *Abstract*, *Acknowledgements* and *List of Definitions* which serve as tools to aid the reader in understanding and navigating through the document. It is further succeeded by a *Bibliography* of references and the *Appendices*. Inspired by the text of (Ashley, Cordell, & Mavinic, 2011), the extensive *Background* section is an optional read with the purpose of informing the reader on the brief history of phosphorus in agriculture and in wastewater. This is presented next, in Chapter 2, after which the report continues with information particularly relevant to the research problem.

2 Background

Although beginning much earlier, the history of phosphorus takes us back to Europe of the Victorian Era. In an age characterized by the spurt of artistic (and industrial) development, the people of Victorian Europe were fascinated by poetic manner in which plants and animals were given life from dead and decaying matter (Ashley et al., 2011). Though this can be evidenced in the themes of literature of the time, it would have been the less-expressive farmers who must have had the greatest appreciation for this phenomenon. By these life-from-death principles their yorkshire grain was fed and their pockets filled. In order to satisfy growing demand for wheat as well as to simply make more profit, farmers would fertilize their fields to achieve higher yields. The resulting, high English demand for fertilizers would take a macabre form of international trade, one which entirely suits our imagination of the dark, Victorian era of heavy industrial pollution and Edgar Allen Poe. Ships from continental Europe would transverse the English Channel filled to the rim with bones - the effectiveness of skeletal remains in fostering greater harvests was an evidented truth.

Slightly less poetic, but almost equally ironic, are the life fostering properties of excrement. 'Night soil' is the romantic term given to define the human excrement that is collected as fertilizer. In ancient rural Asia, the journey of a farmer traveling from town to farm was only embarked upon after having collected a good bucket full of nightsoil (Mårald, 1998). Visiting homes, offering the service of removing waste material from the vicinity to spread it over his own fallow fields would all prove worth the effort with the coming of harvest season. Similar practices have been observed in agricultural societies around the globe. Despite the lack of knowledge regarding the biological processes, the empirical evidence for the benefit of fertilizing have allowed for these traditions to develop in early history and prevail through the hundreds of centuries to come. Only in 1840 was the first scientific research on fertilizers published. At this time a German

Image 1. *Calling card of 18th century nightsoil man, John Hunt - London.*

scientist by the name of Justus von Liebig presented his 'mineral theory'. Von Liebig corrected the Victorians with his research in showing that plant growth was promoted by the inorganic salts of phosphorus and nitrogen, not just simply by mere organic matter (Liebig, 1840). Although his formulations may take away some of the poetisism of the life-from-death romantics, his findings introduced science to the new field of organic chemistry and provided the first science based argument for fertilization.
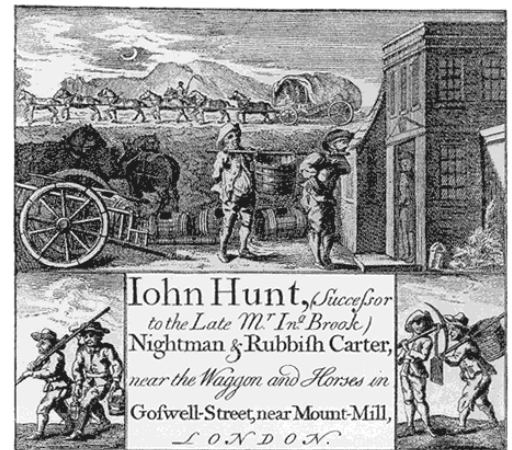
2.1 Sanitary Revolution

Yet, somewhere in history we lost this ancient, agricultural tradition of nutrient recycling. Although it is hard to indicate a precise tipping point - as with many changes throughout history the process has been predominantly gradual - there are a few moments that can be said to have had to accelerated the decline. One such culprit is the European Sanitary Revolution of the 19th century. The sanitary awakening in England marked the transition from a predominantly *land-based*- to *water-based* disposal system - ultimately changing civilization from a phosphorus recycling to a phosphorus through-put society (Ashley et al., 2011). Naturally, the intent was far from malevolent and there existed good justification for this transformation. The introduction of the flush toilet was a response to one of many critical issues London was facing. Like many European capitals at the time, old London was characterized by the foul smell of

decomposing matter (Johnson, 2006). Although the odours would be irritant, the wastes themselves had also come to pose a serious threat to the human wellbeing as urban mortality rates soared high (Snow, 2002). 19th century doctors had one explanation for the persistent disease outbreaks, namely the miasma theory. This theory attributed the continual pestilence directly to those foul odours. This day and age, we know these theories were wrong, yet, indirectly, they were right. Bacterium *vibrio cholerae* is waterborne, so although we now know that the smells themselves do not transmit diseases, we do know that these smells are a warning indicator for the presence of the substances that very possibly might.

The new phenomena of densely populated, urban cities posed society with two, new, unaddressed challenges both stemming from an issue of quantity. Firstly, the quantities of waste produced in cities as well as the distances that would have had to be traversed from city to countryside, far exceeded the capacity and means of the average nightsoil farmer (Vandenbroucke, Rooda, & Beukers, 1991). In their incapability and absence of servicing the city, the bacterial cesspools of waste would be left to decompose naturally in the backyards and basements of households. This, together with the second issue of quantity, namely that of people living in such high density, guaranteed further contagion and transmission of bacteria spawning in cesspools. Without a sewerage system, contact with bacterial

Image 2. *1858 – Death comes to claim those that don't contribute in cleaning up the Thames.*

breeding pools in a city so densely populated was certain and thus city-life was frequented by returning epidemics. The 1854 cholera epidemic famously known as the 'Broadstreet Pump' incident would result in the death of another 606 people on top of the 10,738 of the year before. The famous history of Broadstreet pump tells us how Dr. John Snow and Reverend Henry Whitehead had traced the source of a cholera epidemic to the Broadstreet pump, whose handle was subsequently removed. Their findings laid the foundation of public epidemiology and indirectly to those of modern urban drainage, as in the same year of the incident, the great stink drew parliament to action. By design of Sir Joseph Bazalgette and in assignment of the city parliament, London would complete 720 km of main sewer line with 120 km of interceptor sewers ten years later in 1865. Later still, the practice of rapid sand filtration was popularized and in 1880 Pasteur convincingly disproved the Miasma theory. Finally, by 1904, the chlorination of water had become common practice (Sawyer & McCarty, 1978). After the completion of the London Sewer, the streets would have slowly cleared of cesspools and immediate health hazards overcome, at the same time the Thames would grow thick, green and dark as it was effectively transformed into a main, open sewerage channel discharging to sea.
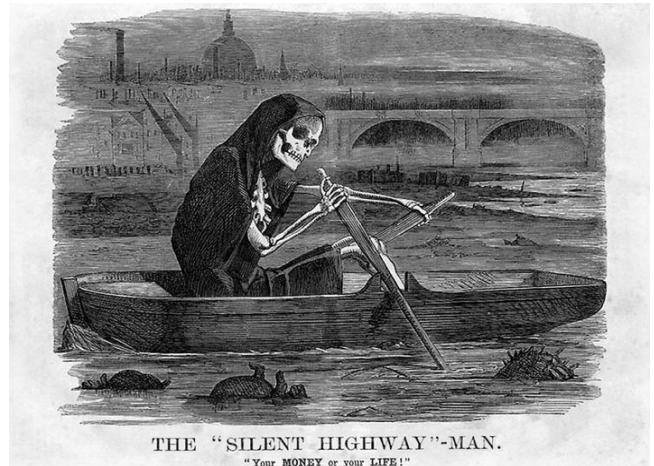
2.2 Night Soil Replacements

Urbanization had disturbed the sustainable cycle of returning organic waste to land and transformed it into a form more convenient in handling the quantities of waste urban areas produce. The new water-based waste system ingeniously applied principles of transportation through fluidization. The viscosity of the waste is lowered by mixing it with a less viscous fluid i.e. water. The resultant thin slurry can easily be transported by gravitation or pumping through pipes that isolate it from outside contact. The sewerage pipes would initially drain to small, covered streams, which in turn would drain to larger rivers - with all implications for water as both the sink and the medium as result. Extensive eutrophication was the disastrous consequence. The high biological oxygen demand of the untreated slurry entering open surface waters would effectively suffocate the underwater ecosystem. Apart from the ecological impact, the health hazard that polluted water

poses to the water users downstream would result in the introduction of new treatment procedures before discharge. With this new water-based system of waste removal, foul smells and cholera epidemics are no longer a direct threat for city dweller, but the farmer is deprived of his cheap fertilizer and the rural community is more exposed to the threat of waterborne diseases. Fortunately, with the discovery of concentrated phosphorus in the bird droppings on small, coastal nesting islands in mid 19th century, the farmer would be provided a superior alternative to recycling the human waste. This 'guano' was found to be a most effective night-soil substitute and therefore became a valuable commodity (Image 3). An even bigger shift in fertilizer history came when around the same time phosphorite formations were discovered in the United States (Brink, 1977). This 'phosphate rock' would come to replace organic phosphates nearly all together, and thereby breaking entire guano exporting economies.
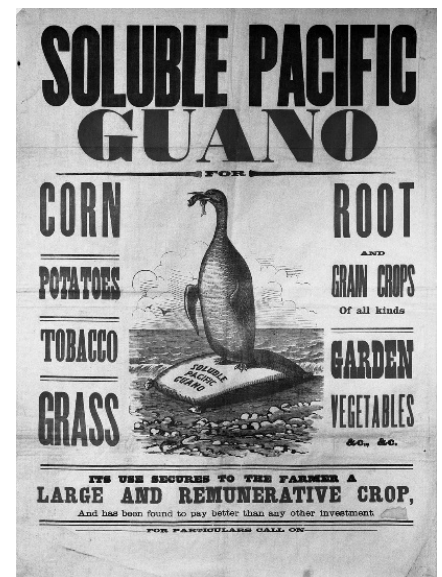
2.3 The Green Revolution

In the more recent history, a few decades later still, the global P mobilization would almost spontaneously be increased by roughly fourfold (Falkowski et al., 2000). In the 1930's to 1960's, a series of

Image 3. *1857-83. Courtesy of Mystic Seaport, Mystic, Conn.*

studies and reports had triggered the green revolution, which resulted in a tremendous boost in agricultural production. Nitrogen, Potassium and Phosphorus fertilizer use were popularized and thus contributed significantly to its effects (Elser & Bennett, 2011). In addition to this, high-yielding hybrid species, chemical pesticides and large irrigation projects, are all credited to have avoided widespread famine by feeding billions of people (FAO, 2011). The Green revolution ultimately enabled a population growth from 3 billion in 1960 to over 7 billion today (U.S. Census Bureau, 2016). However, with ever more mouths to feed the exploitation of phosphorus deposits intensifies proportionally. While nitrogen can be fixated from the atmosphere, phosphorus is only present in strong dilution in the ocean and in the form of natural geological reserves. Unfortunately, similar to many geological exploitations, phosphorus ore is non-renewable and its remaining reserve estimates come with high uncertainties (Edixhoven et al., 2013) (see *Appendix I* for more information on phosphorus reserves*).

2.4 Rock Phosphate

Rock phosphate (RP) is the most widely exploited source of phosphorus. It is commonly extracted from igneous, sedimentary or island deposits that contain various degrees of apatite minerals[1]. Open cast mines with large bucket wheel excavators typify most phosphate rock extraction operations (van Kauwenbergh, 2010). Rock phosphate comes in various grades or purities. RP of a higher purity will produce less waste and more phosphoric acid resulting in a higher profitability. Poor quality rock will instead have a higher waste to phosphoric content ratio, resulting in more processing problems, higher processing costs and a lower profitability (van Kauwenbergh, 2010). The amount of waste, phosphorus, and thus profit per tonne of rock varies depending on the ore grade, which can be categorized as follows(UNIDO & IFDC, 1998):

Low	29% P_2O_5	3.67 rock/P_2O_5 [t/t]
Median	33% P_2O_5	3.22 rock/P_2O_5 [t/t]
High	38% P_2O_5	2.8 rock/P_2O_5 [t/t]

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[1] Apatite is the geological name for a larger group of more than 200 phosphate based minerals. Of these Hydroxylapatite, fluorapatite and chlorapatite are the most common and well known.

Sedimentary deposits are the most widely exploited rock phosphate formations but vary highly in ore grade. These sedimentary deposits develop over geological time as dissolved phosphorus in the ocean gradually precipitates under specific physical and chemical conditions and/or as the bones of fish and marine mammals that settle to the ocean floor are covered and preserved. These deposits are eventually uplifted to the surface, where they return to the soil through natural weathering and erosion process, or are mined for industrial purposes. The rate at which we currently exploit these formations is far out of proportion to the rate at which they form or would erode at. Uncertain estimates on the quantities left in these natural reserves, as well as the increasing demand trends therefore show many parallels to fossil fuels.

2.4.1 The Reserve Estimates

There are two well-referenced organizations that present estimates of the global phosphate reserves: The United States Geological Survey (USGS) through their *Mineral Commodity Summaries*, and the International Fertilizer Development Centre (IFDC). The two organizations function independently from each other but are not unaware of each other' findings. The 2010 IFDC approximation of Moroccan reserves amount to 51,000 [Mt] PR (van Kauwenbergh, 2010), as opposed to the USGS reported 5,700 [Mt] PR (USGS, 2010). This discrepancy has led to a fourfold increase in USGS estimates for Morocco to 67,000 [Mt PR] over the successive years to 2014 (Edixhoven et al., 2013), exemplifying both the uncertainty and discrepancy in results reported by the institutes. Despite this, the USGS has provided global reserve estimates consecutively since 1994 and is therefore most often referenced. The reserve estimates by both groups, however, come with high uncertainty and are thus intensely debated (Edixhoven et al., 2013; Sutton et al., 2011; van Vuuren et al., 2010). Nevertheless, they are used in studies to determine approximately how much longer these reserves will last us (Table 2).

Study	Peak Year	Full Depletion	Size of Reserves	Mode Type	Assumptions and methods
Herring, Fantel, R. Herring, & J. Fantel, 1993		40-169	12.6-37.8		Linear growth or exponential production growth at a rate of 1.04–3%. Stable demand after 2025, 2050 or 2100 in the most optimistic scenarios.
Steen, 1998		60-130	10-22.4	Dynamic R/P	Annual production growth of 2–3%, but most likely lower.
Smil, 2000		80	10.5-24.5	Static R/P	Continued constant production.
Rosmarin, 2004		130	18	Dynamic R/P	Annual production growth rate of 3%.
Déry & Anderson, 2007	1989		2	Curve fitting	Aggregated world production data. URR is found with Hubbert linearization.
Fixen, 2009		93	15	Static R/P	Constant 2007–2008 production rate.
Vaccari, 2009		90	15	Static R/P	Continued constant production.
De Haes, Jansen, Van Der Weijden, & Smit, 2009		75	16.8	Dynamic R/P	Annual production growth rate of 0.7%.
Cordell, Schmid-Neset, White, & Jan-Olof, 2009	2033		16.5	Curve fitting	Aggregated world production data. URR is found by adding cumulative production and reserve data.
Smit et al., 2009		69-100	18	Dynamic R/P	Annual production growth rate of 0.7–2% until 2050 and 0% increase after that.
van Kauwenbergh, 2010		300-400	60	Static R/P	Continued constant production.
Van Vuuren et al., 2010		50-90% of resource base remaining in 2100	13-72.6	System dynamics	Four different scenarios for demand. Three different resource estimations; low, medium and high.
Mórrígan, 2010	1989-2033		2.5-17	Curve fitting	Using aggregated world data. URR is found with Hubbert linearization.
Sverdrup &	~2050	30-330	18/25	System	Demand–supply model, using price and recovery

Ragnarsdottir, 2011				dynamics	feedbacks to supply scarcity.
Cooper et al., 2011		370	65	Static R/P	Continued constant production.
van Enk et al., 2011		31-87/61-200	15/47	Dynamic R/P	Four different scenarios for the demand of food and biofuels.
Cordell, Rosemarin, Schröder, & Smit, 2011	2051-2092		60	Curve fitting	Aggregated world production data. URR is found by adding cumulative production and reserve data.
Mohr & Evans, 2013	2020-2136		6.7-57	Curve fitting and system dynamics	Demand-production interaction model based on URR for regions. Three scenarios are used for different size of the URR.
Koppelaar & Weikard, 2013	~2050-2100	100-200	15.7-53.9	System dynamics	Demand–supply model, using price feedbacks and global flow analysis. Recycling postpone depletion.

Table 2. P*revious studies on phosphate rock depletion, summarized by* Walan, Davidsson, Johansson, & Hook (2014)

Although the studies show significant discrepancies between the estimated reserves left, the vast majority of them conclude with the same striking message that our current consumption is unsustainable and that we will sooner (2040) or later (2400) have depleted the natural stock.

There also exists uncertainty on the rates of production. China is assumed to possess over many high-quality reserves, but does not export them (Vaccari, 2009). The Chinese National Bureau of Statistics only reports data for its largest mines thus the contribution and capacity of the countless, smaller mines is unknown.

With the uncertainty on the estimates addressed, it is important to define terminology in treating the matter of phosphorus reserves. What persists to convolute the debate is the indistinct use of the terms 'reserves' and 'resources' by the USGS and the improperly distinguishing of phosphate rock/ore and phosphate concentrate in literature, leading to miscommunication through incorrect summary figures (Edixhoven et al., 2013; Scholz & Wellmer, 2015). While phosphorus is in the eleventh most abundant elements on Earth (Tobergte & Curtis, 2013), the reserves are fairly limited. *Reserves* is defined as that proportion of resources that is economically exploitable. Since the economic extractability varies, among others, with the valuation of the resources, the cost of technology, the discovery of new deposits, as well as the accessibility of the ore, so do the reserve estimates. Most commonly, reserves are specified in tonnes of phosphate rock. The phosphorus equivalent is difficult to assess as the reported rock quantity is indistinctive of the highly variable rock quality. Also, in some cases, these rock quantities are assumed to be identical to the recoverable amount of phosphate rock *concentrate* even if in actuality the rock quantity figures or reserves estimates would still need to undergo a beneficiation[2] process before being sold, which normally requires a P_2O_5 content of 30% (Edixhoven et al., 2013; Walan et al., 2014). Nevertheless, the IFDC estimates 290 [Mt] of phosphate rock resources and 60 [Mt] reserves for 2010. The latest USGS estimate on global resources is 300 [Mt] of phosphate rock of which 68 [Mt] are approximated as the currently recoverable reserves (USGS, 2017).

The idea of diminishing, limited reserves may cause for alarm. Fortunately, by the laws of mass conservation, this exploited phosphorus cannot simply disappear. Question then remains as to how we can recover our utilized phosphorus in order to prolong our use of the natural reserves and so maintain our current agricultural practices in order to meet the global food demand. This concept at national scale defines the theme of *phosphorus security* (see appendix I)

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[2] "In the mining industry beneficiation or benefication in extractive metallurgy, is any process that improves (benefits) the economic value of the ore by removing the gangue minerals, which results in a higher grade product (concentrate) and a waste stream (tailings)." *Source: Beneficiation - https://en.wikipedia.org*

2.5 Phosphorus Demand

Phosphorus is a macronutrient and is therefore required for plant growth. Like other macronutrients such as Nitrogen and Potassium, natural levels of soil phosphorus are artificially supplemented through the application of fertilizers. Phosphorus is unique from the other nutrients in that it is also limiting. When all other conditions are met, and other nutrients are available in plenty, the growth of crops is often only stunted by the limited availability of plant available phosphorus.

2.5.1 Crop Nutrient Requirements

Crop nutrient requirements vary per crop type, yield, and growth stage. Phosphorus is most essential in the early developmental phases. A plant may have attained 75% of its total phosphorus requirement by the time it has only acquired 25% of its total dry weight (Mckenzie & Middleton, 2013). Insufficient phosphorus in the early growth stages may cause stunting and abnormal discoloration. A prolonged deficiency will slow crop maturity and seed development. High yielding species typically require more phosphorus. The phosphorus recovery efficiencies of crops commonly varies between 50–60%, but some agroecosystems use the applied P with recovery efficiencies as high 70–90%, depending on the crop and soil characteristics (Frissel & Kolenbrander, 1977; Isermann, 1990; Johnston, 1988). Considering also intense variation in species and associated optimal yields, a global phosphorus requirement per crop is difficult to define. With an indefinitive crop phosphorus requirement and provided also the complex soil-phosphorus dynamics (*Appendix I*), a precise phosphorus fertilizer application rate becomes difficult to define. Nevertheless, the IFA and FAO have published a pocket guide for extension officers in which they provide fertilizer guidelines for an extensive selection of crops (FAO & IFA, 2000). The description suggests that these values reflect the crop's needs. Whether these are minimal needs for development, or the needs for optimal yield remains unclear. Nevertheless, it is one of the few sources that has published freely available recommendations for many crops with regards to their phosphorus requirements. Table 4 summarizes the phosphorus requirement and optimal yield as reported by FAO and other sources.

Crop	**FAO & IFA** P_2O_5 [kg/ha]	**FAO** Optimal Yield [t/ha]	
Maize	36-50	17	
Wheat	27-60	10	
Rice	26-50	12	(Fageria, 2009)
Soybean	35	12	
Sorghum	20-60	5	
Potato	39-80	50	

Table 4. Crop specific phosphorus requriements and optimal yields
(FAO & IFA, 2000; Steduto, Hsiao C., Fereres, & Raes, 2012)

For a variety of reasons, the crop P demand is not always met, which has implications for the yield as a result. Sub-optimal yields are not merely undesirable but can also pose a severe threat to human wellbeing in areas that are already coping with food shortages. Studies have revealed that 'soil-fertility depletion in smallholder farms is the fundamental biophysical root cause of declining per capita food production in Africa […]' (Sanchez et al., 1997). Soil P deficiency can then, together with droughts and floods, be regarded as important variable negatively affecting agriculture in Africa, ultimately contributing to the continent's undernourishment. Soil deficiencies, however, are not unique to Africa as it is limiting crop production in agricultural soils worldwide (Arcand & Schneider, 2006). It is estimated that in total 30% of the soils globally suffer from a phosphorus deficiency (MacDonald et al., 2011), while soils in many industrialised countries

are completely saturated with P due to excessive fertilizer application in the past (Smil, 2000) . Soil fertility replenishment should be a priority to close the crop yield gap especially in areas of low food security. For this reason it is important to ensure farmer awareness on crop nutrition management and to provide even remote areas with access to the fertiliser market. An equal usage of fertilisers should be prioritized for many reasons but especially considering the limited reserves (Syers, Johnston, & Curtin, 2008; van der Eijk, Janssen, & Oenema, 2006).

As with the reserve and production estimates, the fertilizer consumption rates are also uncertain. Both the FAO, as well as IFAD show differences in up to 36% in their fertilizer consumption estimates (van Enk et al., 2011). This data reflects only the application of conventional P fertilisers, and does not include other sources of phosphate (i.e. manure, sewerage sludge ash, use of wastewater for irrigation, etc) due to a lack of data availability. An exception is the data for the Netherlands, which is adapted to include the spreading of manure. Furthermore, the current demands represent the market demand, and therefore excludes up to a billion of the world's farmers who currently don't have sufficient purchasing power to access fertilizer markets (Cordell & White, 2013). Many of those farmers practice subsistence farming in low food security areas in Sub-Saharan Africa, South East Asia and Latin America, on soils that are phosphorus-deficient or have a high phosphorus-retention potential (Kochian, 2012; Smaling, Moctar, & de Ridder, 2006). More remarkable than the national consumption rates is the spatial heterogeneity in the changes of those rates. The FAO predicts that the fertilizer demand from Asia will increase by more than 55% in 4 years, while that of Africa will increase by only 4.1% (Figure 5).
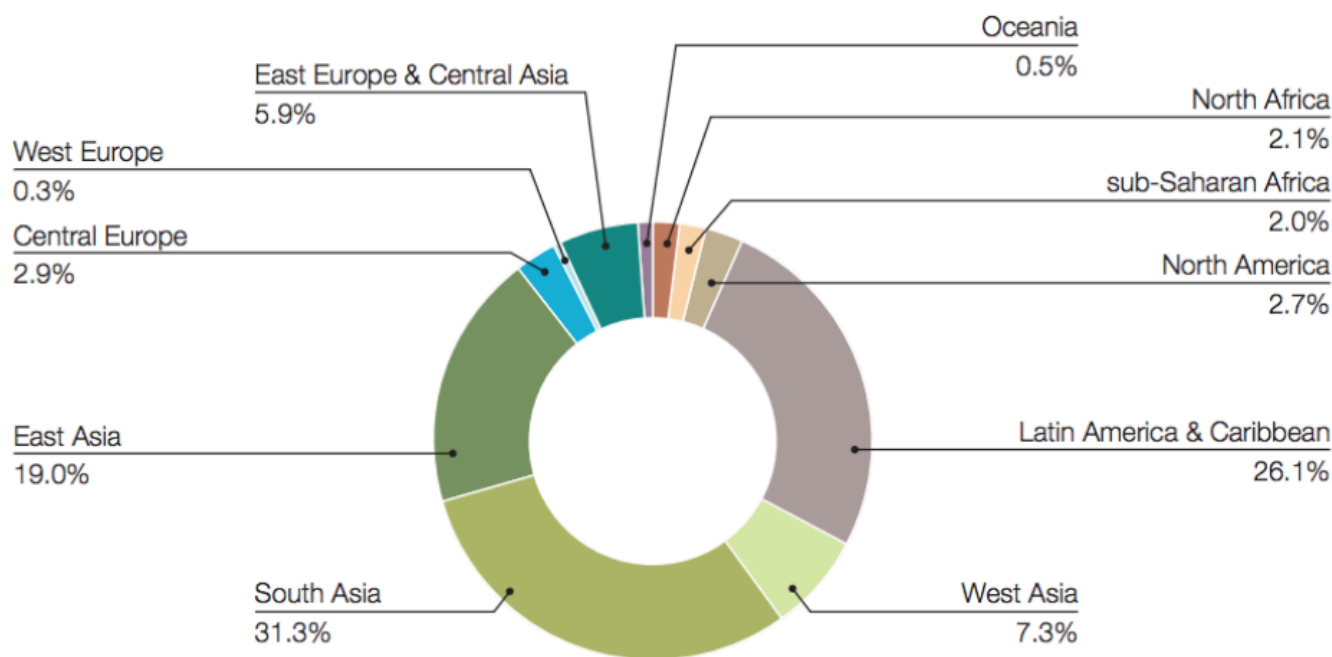

**Figure 5.** *Share of the world increase in fertilizer consumption 2014-2018 (FAO, 2015).*

2.6 Sustainable Phosphorus Production

Mass balance laws teach us that all the mined, processed and plant-consumed phosphorus does not simply disappear after a crop is harvested. The phosphorus cycle continues with the consumers of those crops that now store phosphorus in their biomass or temporarily in their stomachs. Absorption of the nutrients in the consumed biomass through metabolic processes allows the livestock and/or human body to grow and replace old cells. As metabolism is not 100% efficient, and given the relative overconsumption of phosphorus, the vast majority of the consumed nutrients are excreted through urine and faeces - which

accumulate in wastewater flows. The recovery of these nutrients from wastewater offers a sustainable source of phosphorus 'production'. The rates and nutrient loadings of urine and faeces excretion varies per diet and age. In a Swedish diet, 88% of the excreted nitrogen and 67% of the excreted P are present in urine (Jönsson et al., 2005). Urine under a Chinese diet accounts for approximately 70% of the excreted nitrogen and 25–60% of the excreted phosphorus (Gao et al., 2002). The remainder is discharged with faeces (Mihelcic, Fry, & Shaw, 2011). The potential production of phosphorus from *urine* in Europe has been estimated as 0.3 [kg] phosphorus per person per year (Lienert, Haller, Berner, Stauffacher, & Larsen, 2003). The approximate, *total* anthropogenic phosphorous loading in wastewater is 0.77 [kg h^{-1} a^{-1}] (Gilmour, Blackwood, Comber, & Thornell, 2008). Although urine is highly concentrated in phosphorus, the contributions of other human phosphorus wastes are thus observed to be significant also. The 0.77 [kg h^{-1} a^{-1}] then includes the flushed food wastes, detergents and washing products, on top of urine and faeces combined. The actual, global recovery potential of phosphorus cannot be simply approximated as the human population multiplied by a phosphorus excretion rate, not only because of different diets, but also because of lacking sanitary facilities. Approximately 2.6 billion people, 72% who live in Asia, still do not have access to improved sanitation facilities (WHO & UNICEF, 2012). Once the sanitary facilities are in place, they may be equipped with a number of different phosphorus recovery technologies. A few of the most common are summarized in *Appendix I*.

2.6.1 Struvite Precipitation

The most common form of P-recovery currently takes place as struvite precipitation. Struvite (Magnesium Ammonium Phosphate, MgNH$_4$PO$_4$) is a crystalline phosphate mineral that is precipitated in solution when concentrations of magnesium (Mg^{2+}), ammonium (NH^{4+}) and phosphate (PO$_3^{-4}$) exceed solubility levels (eq. 1)(Bergmans, Veltman, van Loosdrecht, van Lier, & Rietveld, 2014). Struvite precipitation has a high P recovery of 57-97%, is dense in P (13-14%), and is also odourless, compact and efficient to transport (Bergmans et al., 2014). Together with the technology of direct application of manure and urine, struvite precipitation is a relatively cheap, low technology form of phosphorous recovery, which makes it appealing for urban areas of both low and high capital. The economic feasibility of recovery, however, strongly depends on price of magnesium source (Tilley, Gantenbein, Khadka, Zurbrügg, & Udert, 2009).
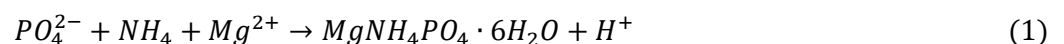
$$PO_4^{2-} + NH_4 + Mg^{2+} \rightarrow MgNH_4PO_4 \cdot 6H_2O + H^+ \tag{1}$$

Phosphorus recovery beneficially influences the finances of wastewater treatment facilities in multiple ways. Recovery reduces operating costs by reducing downtime for cleaning struvite precipitants, reduces sludge disposal costs, and offers profits from a marketable fertiliser product. A brief assessment of the cost-savings of struvite precipitation is presented in *Appendix I*.

2.6.2 Struvite as a Fertilizer

Recovering struvite granules reduces plant effluent P concentrations and creates a product that can be marketed as a *slow release fertiliser* (Schauer, Baur, Bernard, & Britton, 2011). Commercial fertilisers are developed to be readily soluble, releasing high P concentrations when in contact with water, and applied directly together with the planting of the seed, given that phosphorus is critical in high amounts for crops in the early stages of development. Other fertilizers release their nutrients more slowly, and therefore a distinction is made between fast- and slow release fertilizers. Struvite is deemed a 'slow release fertiliser' as it is only slightly soluble in water, 1–5 % (Achat, Daumer, Sperandio, Santellani, & Morel, 2014; Cabeza, Steingrobe, Romer, & Claassen, 2011). Although 'slow' comes with a negative connotation, slow-release fertilizers actually have numerous benefits over fast-release fertilizers.

Fast-release fertilizers release high concentration of nutrients rapidly when in contact with water. Often these are subsequently traced in land runoff when rain falls shortly after fertiliser application (Hart, Quin, & Nguyen, 2004). Furthermore, this P quickly becomes adsorbed and immobilised onto soil particle surfaces, reducing the quantity available for plants in later stages of development. (Barrow & Debnath, 2014; Chang & Chu, 1961; Holford & Mattingly, 1975; Veneklaas et al., 2012). Laboratory studies conclude that struvite as a source of phosphorus for plants is as effective as highly soluble mineral P fertiliser (Achat et al., 2014; Antonini, 2013; Bonvin et al., 2015; Cabeza et al., 2011; Johnston & Richards, 2003; Massey, Davis, Ippolito, & Sheffield, 2009; Talboys et al., 2016). The less soluble nature of struvite can supply phosphorus at longer terms than readily soluble forms of P, thus more closely matching the plant's demand for P later in the growing season and increasing its efficiency of use (Withers, Sylvester-bradley, Jones, Healey, & Talboys, 2014). The slower dissolution of struvite could also reduce the amount of fertiliser P that becomes adsorbed on to soil particles or that is lost as runoff (Talboys et al., 2016). Although struvite alone supplies lower rates of phosphorus uptake early in plant development (39% less), it comes with no significant implications for the final yield (Talboys et al., 2016). Over the course of the growing period, plant recovery of P from the dissolved component of the incompletely dissolved struvite was 38 %, which is 175 % greater than from conventional Triple Super Phosphate (13 %). Talboys et al. (2016) concludes that mixing struvite with a more soluble fertiliser P source achieves maximum benefit, as it takes advantage of the qualities of both slow and fast release fertilizers. This would already imply that a post-phopshate rock depletion market of only struvite fertilisers will result in sub-optimal agriculture, regardless of whether the crop phosphorus budgets are met or not.

A number of the mentioned P recovery processes (*Appendix I*) that are now commercially available or in advanced research or pilot plant stages, were developed first in the Netherlands during the late-1970s (British Sulphur Corporation, n.d.; Imperial College of Science, 1997). Struvite precipitation is one of these processes, and was simultaneously developed at Delft University of Technology in cooperation with Geochem Research, as well as at the Japanese Unitika (Smil, 2000). This technology would later be widely adopted, adapted and commercialised by the private sector. The current leading, global, wastewater phosphorus recovery company is Ostara (est. 2005) with the patented Pearl® reactor. There are 14 Pearl® installations globally, the majority in the United States and three in Europe. Other struvite precipitation installations can be found worldwide, most notably in Japan.

Struvite precipitation from **livestock manure** follows the same principles as for wastewater treatment. The high organic matter content, however, troubles the precipitation and crystallization process (Cerrillo, Palatsi, Comas, Vicens, & Bonmatí, 2015; Liu, Xu, Wang, & Jin, 2012; Tilley et al., 2009; Tao Zhang, Fang, Li, & Jiang, 2014). Nevertheless, different types of manure or liquid manure (fractions) result in high P recovery rates of (50–90 %). Calf manure (Schuiling & Andrade, 1999; Siciliano & Rosa, 2014), dairy slurry (Huchzermeier & Tao, 2012; QURESHI et al., 2006; Qureshi, Lo, & Liao, 2008; Rico, García, & Rico, 2011; Uludag-Demirer, Demirer, & Chen, 2005; Uysal & Kuru, 2013; Tianxi Zhang, Bowers, Harrison, & Chen, 2010), pig slurry (Capdevielle, Sýkorová, Biscans, Béline, & Daumer, 2013; Jordaan, Ackerman, & Cicek, 2010; Nelson, Mikkelsen, & Hesterberg, 2000; O F Schoumans, Nelemans, Tintelen, Rulkens, & Oenema, 2014; Shepherd, Burns, Raman, Moody, & Stalder, 2009; Suzuki et al., 2006) and even poultry manure (Yetilmezsoy, Turkdogan, Gunay, Yilmaz, & Kaleli, 2013; Yilmazel & Demirer, 2013; W. Zhang & Lau, 2007), have all proven to be appropriate media for phosphorus recovery (Oscar F. Schoumans, Bouraoui, Kabbe, Oenema, & van Dijk, 2015).

While recovery of phosphorus poses some complications, the marketing of the products proves yet another difficulty. This introduced the aspects of *phosphorus trade* to the subject.

2.7 Phosphorus Trade

The global disproportionality in regional surpluses and deficits in organic phosphorus balances offer the opportunity for interregional trade. Phosphorus recovery from those areas where phosphorus in wastewater poses a threat to the environment (I.e.: growing urban areas), could then supply other sectors where there exists a demand. At smaller scales, such win-win scenarios can already be observed to occur in practice. Tilley et al., (2009) have investigated the potential for community-scale struvite processing in Siddhipur, Nepal. The farming town is not connected to the sewage treatment facility of Kathmandu proper and so urine-diverting dry toilets have been installed for a struvite recovery experiment. The study concludes that the recovery of phosphorus through struvite is socially and economically feasible, as the sale prices of 240 – 410 [$/tonne] of struvite are in price range of the locally available DAP fertiliser. Other cases where phosphorus recovery partakes in the phosphorus fertilizer market can be identified in Japan, as well as with the aforementioned 14 Pearl® reactors worldwide.

A more widespread and traditional form of phosphorus 'trade' is by manure. With rising costs of commercial fertilizers and the increased emphasis on sound manure management to protect water quality, a renewed interest has arisen on maximizing the fertilizer returns of organic manures (Barker, Hodges, & Walls, 2001). The disadvantage of manure lies, however, in its low phosphorus density given the high water content. For swine, a livestock that has amongst the highest phosphorus content in its waste, this amounts to 0.2 [%] P in raw manure (Barker et al., 2001). Once dehydrated, the highest phosphorus density by dry weight increases 15 fold, to 3.2 [%] P (Li, Li, Leffelaar, Shen, & Zhang, 2014). The high volume and thus relatively low P-density of manure makes it that the transport costs per tonne P is too high such that cannot compete with the transport costs of alternative phosphorus sources (i.e. Diammonium Phosphate: 20% P, or Struvite 14% P). This limits phosphorus trade by manure to the immediate neighbours and inhibits development of trade on global, or even, regional scale. Struvite precipitation of this manure has the potential to substantially reduce transportation costs compared to manure (Burns & Moody, 2002) by increasing the phosphorus density approximately by 70 times. However, while investigators have examined struvite precipitation from livestock (*Appendix I*), little work has been done to develop this process for field scale application (Nelson et al., 2000). Prices, as determined by both the production and transportation components, are therefore decisive for the marketability of recovered products. Fortunately, the future of recovered products looks favourable given current price trends.

2.7.1 Price Volatility

There are various price trends for phosphorus, as there are various phosphorus products. Numerous kinds of P-fertilizers have been developed since the beginning of the green revolution. They often take the form of pellets or powder that can be distributed directly over the fields or shortly after their dissolution in a solvent. The most widely commercialised fertilizers are summarized below:

Name	Abbrev.	Formula	P content
Monoammonium Phosphate	MAP	$NH_4H_2PO_4$	21-27%
Diammonium Phosphate	DAP	$(NH_4)_2HPO_4$	20-23%
Triple Super Phosphate	TSP	$Ca(H_2PO_4)_2$	20%
Single Super Phosphate	SSP	$Ca(H_2OP4)_2$	7-9%
Dicalcium Phosphate	DCP	$CaHPO_4$	17%
Monopotassium Phosphate	MKP	KH_2PO_4	17%

Table 4. Conventional phosphorus fertilizers and chemical formula's.

Diammonium phosphate (DAP) is the world's most widely used fertilizer and will be taken as a proxy for all conventional fertilisers in this investigation. Over the past 15 years, DAP price have increased from 665 [$ t^{-1}] to 1,552 [$/tP], reaching values as high as 5,217 [$ t^{-1}] in 2008 and as low as 656 [$ t^{-1}] 2002. The rock phosphate prices show similar trends, and their interrelation is clearly evidenced in Figure 6. The DAP price can be approximated as $\frac{1}{3}$ of the rock phosphate price.
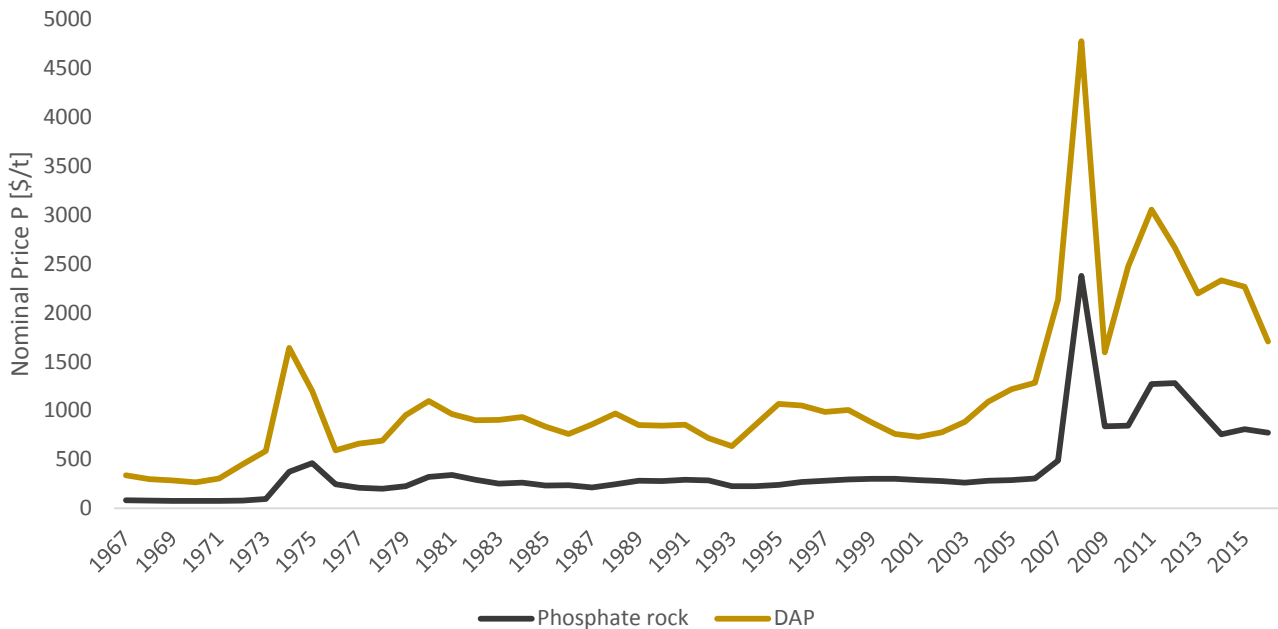

Figure 6. *Historical phosphate rock and DAP price trend* (IndexMundi, 2017)

While the costs of phosphorus mine exploitation are still extremely low, as evidenced by the rock phosphate prices of 772 [$ t^{-1}], prices have risen by 130% over the past 15 years. Such a positive trend is expected to continue as the most easily accessible, high quality RP reserves are depleted, and lower quality, less accessible reserves are explored. Another variable working against rock phosphate mines is the geographic concentration of mine sources (Figure 1 and Appendix I) which leads to high transportation costs in supplying especially agricultural demand sites situated far away. As humans and livestock will continue to produce wastewater at steady or increasing rates, sustainable phosphorus recovery from wastewater can be concluded to have two major economic advantages over mines. Not only are major urban and livestock phosphorus recovery sites far more geographically widespread than mines, they are also able to supply phosphorus at a much more reliable rate and price than the mines are able to. These two advantages may in some cases outweigh the high initial investment costs of equipping wastewater treatment plants with phosphorus recovery technologies and the costs associated with magnesium dosing for struvite precipitation. This study hopes to reveal where these sites are, under what price conditions they are competitive and what the resulting trade network may come to look like.

3 Materials and Methods

The anthropogenic component of the phosphorus cycle is delineated by combination of both *social* and *physical* attributes. As such, the study demands not a classic hydrological but a socio-hydrological approach, where both these attributes are expressively and emphatically accounted for. The social component, however, of this human-phosphorus relationship is confined to the characteristics of a distinct economic nature. The materials and methods employed in answering the research question are therefore selected from not only the subject span within hydrology, but are extended to the field of economics as well.

Several methodological phases can be identified in addressing the objectives. Firstly, a geospatial data processing phase is required to identify phosphorus production and consumption areas that are necessary to create supply and demand nodes. Through population density maps and phosphorus throughput figures, a simple determination of global *phosphorus production concentrations* is established. In assessing *phosphorus demand concentration*s, crop harvested area, together with optimal fertilizer application rates and estimates on optimal yield ratio by water stress are used. Figure 7 illustrates the simplified steps of this process chain. The details of this initial phase in the methodology, are treated in section 3.1 for *Phosphorus Production*, and 3.2 for *Phosphorus Demand* sites.
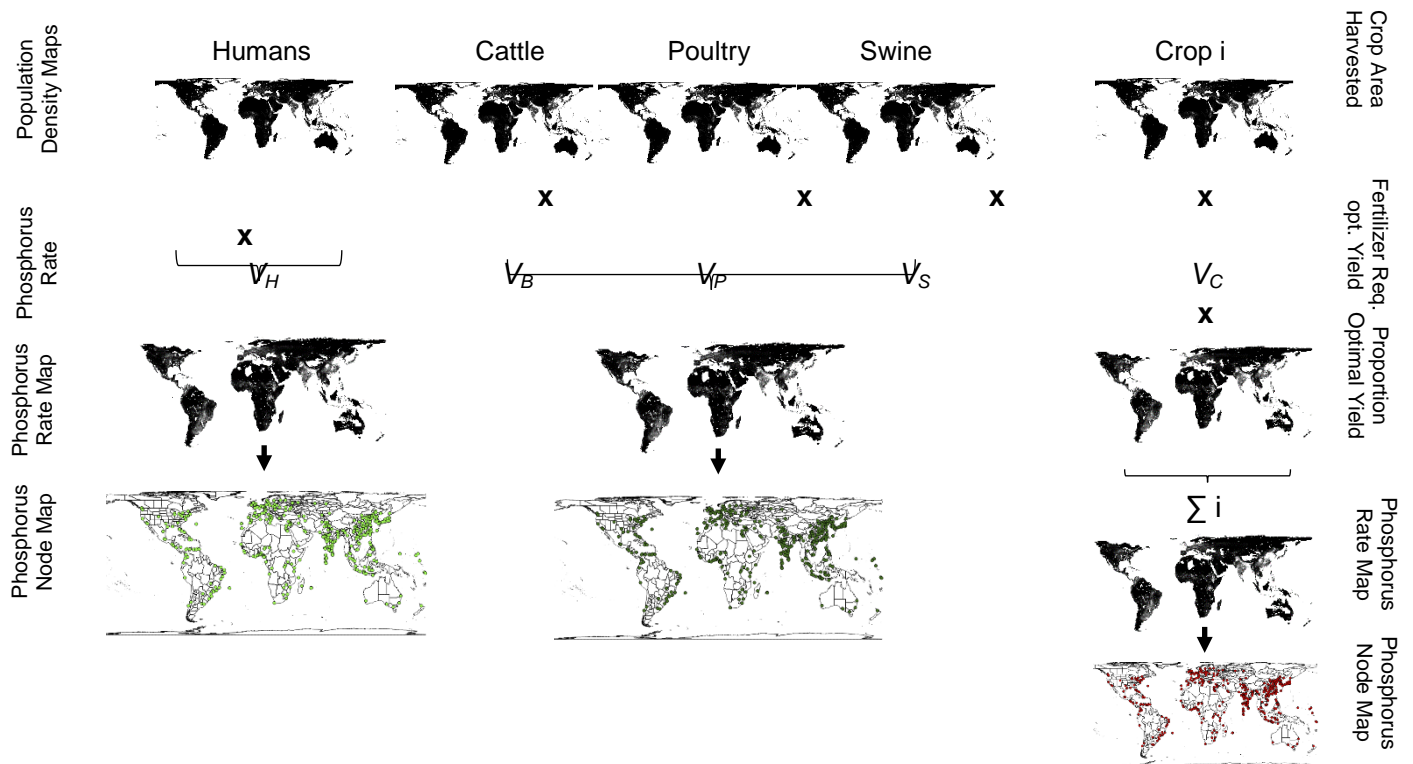

Figure 7. *Visualization of map creation process. Variables V_H, V_B, V_P, and V_S indicate the phosphorus excretion rate per head for humans, bovine, poultry, and swine, while V_C for crops represents the phosphorus requirement per hectare for that crop.*

In the second phase, a model framework is developed that can assess the progression of phosphorus trade for different scenario's, at different prices. The purpose of this model is twofold. Firstly, the model will determine the optimal price for international phosphorus trade. Secondly, the model will produce a trade network that shows which nodes are involved in trade, with what amounts, and for which prices. These two products are determined for three market supply scenarios:

- **Current Scenario:**   Mine supplied phosphorus only
- **Future Scenario:**   Mine and sustainably supplied phosphorus

- **Far-Future Scenario:** Only sustainably supplied phosphorus

In determining the price and quantities of international phosphorus trade, the model will have a supply meets demand micro-economic foundation. The supply 'meets' demand equilibrium states that the price of a good will be the level where the quantity demanded equals the quantity supplied (i.e. the market for P is cleared). This can be visualized in a graph as the point where a *demand function* intercepts a *supply function* (Figure 8).
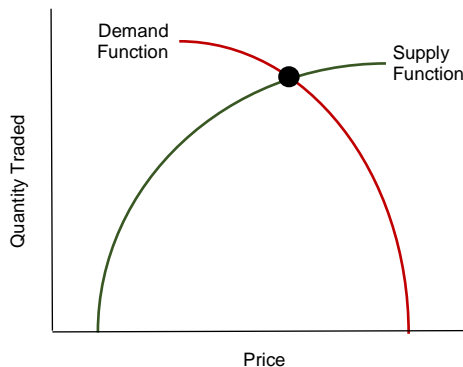

Figure 8. *Conceptualization of supply-demand curves.*

The demand function shows the maximum prices at which demand nodes are willing/able to purchase phosphorus. As prices increase, the demand falls as demand nodes are slowly forced out of the market. The supply function shows the opposite, namely the minimum prices at which supply nodes can sell certain amounts of phosphorus. More supply nodes can enter the market to sell their phosphorus as prices increase. The highest point at which the supply and demand curves intersect marks the equilibrium price and quantity such that the demand and supply nodes are both happy with price as well as the amounts.

This study on phosphorus deviates slightly from this method of price-quantity assessment. Good nutrient management would lead to farmers not purchasing more phosphorus than the optimal amount required for their crops. As such, farmers will not overfertilize (buy more fertilizers than they need) when fertilizer prices are extremely low. By the premise that there is abundant supply phosphorus, the phosphorus trade will be limited by maximum global demand (Q_m) for P. As illustrated in Figure 9, this maximum possible trade, Q_m, will then occur at a price P no larger than the minimum willingness to pay $\overline{P}$ across all potential consumers.
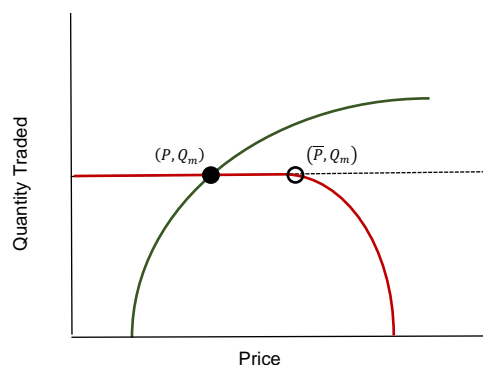

Figure 9. *Conceptual Illustration of supply (green) and demand (red) curves with maximum limit on demand.*

In creating the supply and demand curves for a set of nodes, consider the following six node example. Three production ● nodes (   ) with minimum per unit production costs ($P_1 < P_2 < P_3$) and with quantities ($Q_1, Q_2,$ and Q_3) to sell, as well as ● three demand nodes ( ) with maximum willingness to pay prices ($P_4 < P_5 = P_6$) for their quantities ($Q_4, Q_5,$ and Q_6) to buy, define a hypothetical network (Figure 10). The supply and demand curves can be reconstructed using the information above (Figure 11).
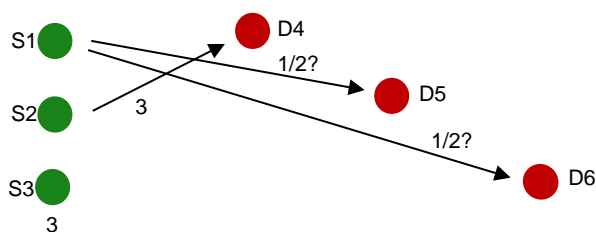

Figure 10. *Network of demand and supply nodes. Arrows with numbers indicate trade order. Green are supply nodes, red are demand nodes.*
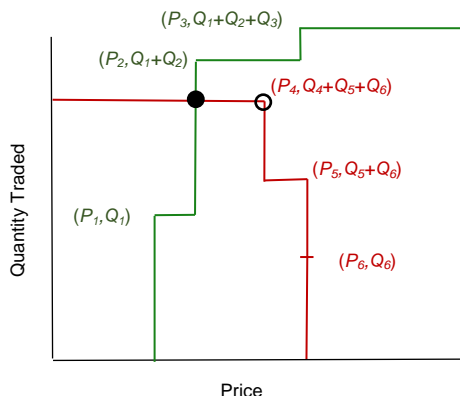

Figure 11. *Adapted supply (green) and demand (red) curve, for six node network illustrated in Figure 10.*

25

Supply node *i* enters the market at market prices equal to P_i and supplying quantity Q_i, while demand node *n* enters the market willing to buy quantity Q_n at price P_n. Based on the constructed demand and supply curves, no demand node needs to pay the high prices of P_3 as the total demand can be satisfied by the other two, cheaper supply nodes. The trade occurs at prices between P_4 and P_2, where then not all the supply is exhausted but the total demand is met.

While Figure 11 provides an estimation of total *quantity* and *prices* of trade, however, several possible *ways of trading* may exist. One possible order of trading is illustrated in Figure 10 by the numbered arrows. The biggest difference between selling price and willingness to pay (buying price) allows for most room for negotiation between the pair (seller-buyer), and is thus assumed to be the first trade pair. The negotiation room gives the demand node the power to outbid competing demand nodes that do not have as high negotiation range, while the same holds for the cheapest supply nodes. In this example, the biggest difference in prices is between supply node S1 and demand node D5. D5 would be the first traded with as it is situated closer to S1, which would result in lower transportation costs. However, transportation cost is not included in the above definition for P_1. Since the transportation cost varies with the distance between each unique node pair, the actual, transportation-inclusive P_1 will be different for each demand node. It is therefore impossible to recreate the above curves for a network when including transportation costs.

To execute an accurate analysis that does include transportation cost, the above curves are recreated through an adapted methodology. Instead of plotting the prices and supply/demand quantities of each unique node (irrespective of their ability to trade), the actual amount potentially traded in the network is assessed and plotted with the traded at prices.

Consider again the six node example (Figure 12). The supply and demand prices ($P_1 < P_2 < P_3$, $P_4 < P_5 = P_6$) as well as quantities (Q_1, Q_2, Q_3, Q_4, Q_5, and Q_6) remain the same. The transportation costs ($T_{(i,n)}$) are lowest to demand node D4, highest to D6 and intermediate to D5 ($T_{(i,4)} < T_{(i,5)} < T_{(i,6)}$). This results in the cheapest, and therefore first, trade occurring between S2 and D4, as: $P_2 + T_{(2,4)} << P_i + T_{(i,n)}$ (line 1, Figure X). Quantity Q_4 is smaller than Q_2 and therefore the amount traded is equal to the node's entire demand, Q_4. Executing this procedure successively for all nodes and plotting the prices inclusive of transportation cost with the networks cumulative quantity traded while progressing on the price ladder, a figure similar to the supply-demand curves illustrated above can be created (Figure 13). In this figure, the supply function now solely includes those supply nodes that are active in the network, now also limiting the maximum quantity supplied to the market to the quantity of demand that can be met.

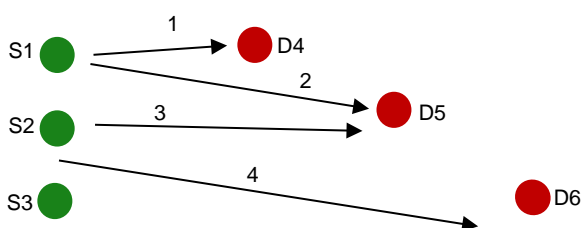**Figure 12.** *Network of demand and supply nodes. Arrows with numbers indicate trade order, including transportation costs.*
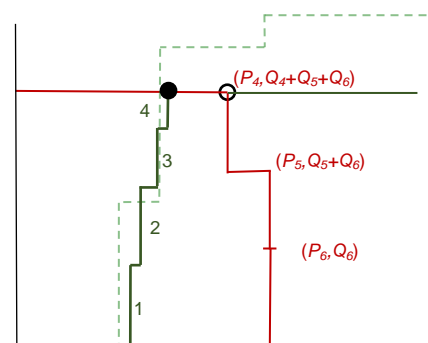

Figure 13. *Adapted supply (green) and demand (red) curve, for six node network illustrated in Figure 12, including transportation cost component in price*

A summary of the order of trade for different pairs and the prices and quantities traded between them, is presented in Table 5.

Trade Order	Node Pair (i,n)	Best 'hypothetical' Prices	Quantity Traded	Cumulative Quantity Traded
1	(1,4)	$P_1+T_{(1,4)}$	Q_4	Q_4
2	(1,5)	$P_1+T_{(1,5)}$	$Q_1- Q_5$	$Q_4 + Q_1 - Q_5$
3	(2,5)	$P_2+T_{(2,5)}$	$Q_2- (Q_1- Q_5)$	$Q_2 + Q_4 + Q_5$
4	(2,6)	$P_2+T_{(2,6)}$	Q_6	$Q_3 + Q_4 + Q_5$

Table 5. *Trade order, prices and quantities for node pairs for supply curve.*

At lower prices, the market is defined by the supply function while at higher prices, it is defined by the demand function. Since the curves do not intercepts before the global demand is met (in the given example), the optimal price for this theoretical network will lie between $P_2+T_{(2,6)}$ and P_6. Approximately in the middle of this range, the market shifts from prices that maximize consumer surplus (minimum production cost + transportation ($P_i+T_{(i,n)}$) prices) to prices that maximize producer surplus (maximum paying price – transportation cost $P_n-T_{(i,n)}$).

The optimal price is further differentiated from this (potentially large) range. Depending on the proportion of global phosphorus supply to demand, it is possible to determine whether the optimum price will lie in the upper or lower half of this range. Then, this second range can then be further refined by making use of the exact proportion that the supply is greater or less than demand and scaling the distance of our best price approximation from the middle of the range, proportionally. The limits of the different ranges, as well as the best approximation of the optimum price, all together allows for a box-whisker-plot-like presentation of the modeled price data. The benefit of describing the price in such a manner is that it allows for better comparison with observed price data, which fluctuate significantly within each year. This data can be represented statistically though box-whisker plots, showing the range, quartiles and median for the price data of each year. The price range and values determined by the model can be represented in a similar box-whisker-plot-like fashion, thereby making comparison with observed data more convenient. It is important to note that the box-whisker-like plots of the modeled data, however, do not have a statistical foundation (range, quartiles and medians). Its parameters are instead determined through the procedures described in Appendix II: Presentation of Optimum Price Approximation.

The conceptualizations in this section have briefly introduced the simple premises by which the model works. Before being able to execute the model, however, a series of functions are required to define the maximum and minimum prices for each node. These are expounded upon in section 3.3 *Costs and Prices*. Further detailing of the model's essentials are covered in section 3.4 *The Model.* Before delving into model design any further, it is important that the locations, production/demand capacities, and nature of their production (mines/recovered) or consumption (corn/wheat/rice/sorghum/soybean/potato), are established. This will be done in the next following sections: section 3.1 for *Phosphorus Production* and 3.2 for *Phosphorus Demand*.

3.1 Phosphorus Production

Phosphorus production sources considered in this investigation are potential phosphorus recovery nodes from major urban and livestock wastewater streams (3.1.1) and rock phosphate mines (3.1.2).

3.1.1 Phosphorus Production from Organic Sources

Both human excreta as well as livestock waste are considered as organic sources of phosphorus. Some indication of the global production potential of these organic sources, and how the production varies

spatially, is assessed using the results of studies on the individual phosphorus[3] throughput rates of livestock and humans; population density maps; and some correctional approximations for the recovery feasibility. Quantitatively, the approach in estimating the maximum P production potential from organic sources can be summarized in the following equation (Eq. 2):

$$S_{PT} = (H * H_{PP}) * E_{rH} + \left(B * B_{PP} * \frac{d_s}{365} + P * P_{PP} + S * S_{PP} \right) * E_{rL} \qquad (2)$$

Where S_{PT} is the total organic phosphorus supply rate [kg km^{-2} a^{-1}]; H is the human population density [h km^{-2}]; B is the bovine density [h km^{-2}]; d_s is the approximate amount of days bovine are stabled per year [d]; P is the poultry density [h km^{-2}]; S is the swine density [h km^{-2}]; E_r are the estimated recovery efficiencies [-]; subscript pp is the respective phosphorus throughput of each class [kg h^{-1}a^{-1}].

There are numerous studies that have assessed P throughput rates for humans and different livestock. Only a few studies were selected for comparison provided their systematic assessment of multiple kinds of livestock. Table 5 summarizes the phosphorus throughput values of humans and livestock as determined in a few of these studies. Genetic variation within a species and variation of diets can cause for large differences in phosphorus yearly throughputs, which explains variation among the results.

Livestock	Throughput		Site	Author
Bovine (Dairy)	25	kg P	US	Barker et al., 2001
	17.16	kg P	NL	Blokland, Luesink, & Jongeneel, 2015
	17.9	kg P	NL	CBS, 2014
	20.8	kg P	US	Weiss & Wyatt, 2004
	9.6	kg P (stabled period)	NL	CBS, 2014
Bovine (Beef)	11.7	kg P	NL	CBS, 2014
	13.3	kg P	US	Barker et al., 2001
	5.4	kg P (stabled period)	NL	CBS, 2014
Poultry (layer)	1.2	kg P	US	Barker et al., 2001
	0.17	kg P	NL	CBS, 2014
Poultry (broiler)	0.6	kg P	US	Barker et al., 2001
	0.08	kg P	NL	CBS, 2014
Swine	4.1	kg P	US	Barker et al., 2001
	2.1	kg P	NL	CBS, 2014
Swine (sow)	6.4	kg P	NL	CBS, 2014
Human	0.77	kg P	UK	Gilmour et al., 2008
	0.2-0.7	kg P	Global	Mihelcic et al., 2011
	0.78	kg P	-	CRC, 2005
	0.7	kg P	US	Smil, 2000

Table 5. *Annual phosphorus excretion rate by species, per head.*

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[3] *All phosphorus quantities are expressed in the form of elemental phosphorus unless stated otherwise. Literature, and the phosphorus debate in general is convoluted by inconsistent use of units. Data from different sources frequently had to be converted. Phosphorus in other sources can be expressed as: 'phosphate rock, which varies in P$_2$O$_5$ content from 25-40%; Phosphoric acid, which can vary in P$_2$O$_5$ content from around 20-60%; and as phosphate (P$_2$O$_5$), which is approximately 44% P.*

Approximately average rates from the different sources are adopted in this investigation. For the purpose of analysing the *potentials*, the recovery efficiencies are based on maximum efficiency of struvite precipitation (90%) and a small loss in collecting the waste (5%). An additional loss for poultry is considered as the poultry litter (feathers and fluff) complicates waste gathering and the struvite precipitation process. Table 6 summarizes the phosphorus throughput values and recovery efficiencies used in the study.

	P		**Recovery Efficiency**
Cattle Dairy	20	[kg a^{-1}]	85 %
Cattle Beef	12	[kg a^{-1}]	85 %
Poultry	0.6	[kg a^{-1}]	75 %
Swine	4	[kg a^{-1}]	85 %
Human	0.77	[kg a^{-1}]	85 %

Table 6. *Approximated phosphorus production per head, per annum.*

It is unclear what causes the significant difference between the CBS and Barker (2002) values for poultry. These values have systematically been converted to elemental phosphorus to achieve the final values in Table 6. The less conservative value by Barker has been selected for the study with the assumption that the extra contribution of phosphorus in poultry litter (fluff) will partially compensate the possible overestimation. Also, the bovine production has been corrected for differences in dairy- and beef bovine populations proportionally. With approximately 45% cattle kept in dairy and 55% in beef industries, the *average* phosphorus throughput per 'generic' cow can be approximated as follows in equation 3:

$$20 \; [\text{kgPa}^{-1}] * 0.45 \; \left[\frac{\text{dairy}}{\text{Total}}\text{pop.}\right] \; + \; 12 \; [\text{kgPa}^{-1}] * 0.55 \; \left[\frac{\text{beef}}{\text{Total}}\text{pop.}\right] = 15.6 \; [\text{kgPa}^{-1}] \qquad (3)$$

Furthermore, the collectable waste of cattle is limited to that excreted while stabled. The other proportion is returned to pastureland from which it cannot be recovered. It is assumed that the high-density livestock nodes represent intensive livestock farming, and that cattle are thus stabled for 180 days of the year. Substituting d_s in Eq. 1 with 180 [d] will reduce the recoverable livestock phosphorus by approximately half, where 180/365 = 0.49 [-].

Although acknowledging the disregard for many other influential variables, the above methodology will allow for very general assessment of potential, global, organic phosphorus production. However, sustainable, organic phosphorus production is just a small portion of a market that is dominated by phosphate mines. Fortunately, the USGS has published a spatial dataset on phosphate mines that makes it possible to include these mines in this investigation.

3.1.2 Phosphorus Production from Mines

The largest uncertainties in the model arise because of the uncertainties associated with the mine production. In 2002, the USGS created an inventory of the global, known phosphate mines and their locations (USGS, 2002). The data set shows accurate coordinates, but is incomplete and inconsistent, and therefore requires extensive, correctional processing. Firstly, the mines reporting to be inactive, terminated, past producers, or occurrence mining, as well as mines of no or extremely little information (assumed to be of insignificant production) were removed. Furthermore, where the average ore grade was not provided, a medium grade of 33% phosphatic content was applied. After homogenizing the data to standard units of production [kt a^{-1}] of elemental phosphorus (44% P in P_2O_5), the remaining mines with missing data were manually attributed a production value so as to match the USGS reported 2005 phosphorus production estimates. Finally, the Fertilizer Manual (1998) reports an efficiency of 94% at very best for the conversion

of phosphate rock, so the final data corrected for by an optimistic 90% recover factor to account for losses in the production chain (See *Appendix 1: Environmental implication of phosphate mining*). In converting rock phosphate to phosphate (eq. 4) the following calculation is made:

$$M_{RP} * R_{grade} = M_{P_2O_5} \tag{4}$$

Where M_{RP} is the mass of rock phosphate [M]; R_{grade} is the rock grade in decimal percent [-]; and $M_{P_2O_5}$ is the equivalent mass in phosphate [M]. When the ore grade is not provided in the data, it assumed that the ore is of medium quality, at 33% phosphate. This phosphate is converted to elemental phosphorus. The Molar Mass (MM) of Phosphorus is 30.9 [g mol^{-1}], of oxygen is 15.9 [g mol^{-1}], and as such the molar mass of phosphate (P_2O_5) is 142 [g mol^{-1}] as demonstrated below in equation 5:

$$\frac{1}{142} \frac{[mol_{P_2O_5}]}{[g_{P_2O_5}]} * 2 \frac{[mol_P]}{[mol_{P_2O_5}]} * 31 \frac{[g_P]}{[mol_P]} \approx 0.44 \frac{g_P}{g_{P_2O_5}} \tag{5}$$

The final, adapted 2002 mine data that is used in the model is compared to the reported USGS rock phosphate data of 2005/6 in table 7.

Country	Mines [#]	Mapped Total Production [Kt P$_2$O$_5$]	[Kt P]	Reported Production Production (2005/6)(USGS, 2007) [Kt Rock]	[Kt P$_2$O$_5$]	[Kt P]	Difference [%]
Afghanistan	1	100	44				
Algeria	1	10	4				
Australia	2	400	176	2000	540	238	-25.9
Brazil	12	1751	770	6400	1728	760	1.3
Canada	2	270	119	1000	270	119	0.0
China	43	7020	3089	26000	7020	3089	0.0
Colombia	1	200	88				
Egypt	8	600	264	2200	594	261	1.0
India	4	330	145	1200	324	143	1.9
Iraq	1	400	176				
Israel	4	850	374	3200	864	380	-1.6
Jordan	8	1900	836	7000	1890	832	0.5
Kazakhstan	2	350	154				
Mexico	1	200	88				
Morocco	10	7640	3362	28000	7560	3326	1.1
Russia	11	2930	1289	11000	2970	1307	-1.3
Saudi Arabia	1	200	88				
Senegal	2	490	216	1800	486	214	0.8
South Africa	4	500	220	2000	540	238	-7.4
Syria	3	750	330	3000	810	356	-7.4
Tanzania	1	50	22				
Togo	1	300	132	1100	297	131	1.0
Tunisia	6	2200	968	8000	2160	950	1.9
United States	18	10000	4400	38300	10341	4550	-3.3
Zimbabwe	1	100	44				
Sum of others	10	1610	0	4900	1323	582	21.7
Grand Total	**148**	**39541**	**17398**	**147100**	**39717**	**17475**	**-0.4**

Table 7. *Mapped and reported phosphorus mine outputs.*

By these numbers, Australia will have less phosphorus output in the model than is reported because of significant inconsistencies between the 2002 spatial dataset and 2005/6 reported data. A diversity of other nations will have a greater output than in the USGS reported figures. After this calibration, the net global mine production is approximately equal to the reported figures, tolerating a difference of 0.4%.

A global study on phosphorus recovery and mining is interesting largely because of the vital role of phosphorus in agriculture. The next section will present the materials and methods employed in approximating the global distribution of phosphorus demand for six major crops.

3.2 Phosphorus Demand

Section 2.5 of the *Background* chapter introduced, and Appendix I elaborates on, the complexities of soil-plant-phosphorus dynamics. To simplify the matter, the phosphorus demand in this investigation is assumed to vary only with crop type and its water-constrained yield. This is assessed for six major crops: maize, wheat, rice, sorghum, soybean, potato, that constitute approximately 56% of the global fertilizer demand (Heffer, 2009). This demand is then scaled to represent the total agricultural demand by dividing the demand value of each node by 0.56. Although the spatial distribution may not be entirely accurate to what would be observed if all crops were included, at least the phosphorus supply and demand ratio's would be in proportion to what is observed in the actual phosphorus market.

A crop's phosphorus demand is proportionally scaled to the maximum achievable yield that is limited by the availability of water. This yield is determined through the evaporation-transpiration deficit (ED) approach (eq. 6) (Steduto et al., 2012). As the focus of this study is not on creating a precise crop yield map, and given that growing seasons vary globally and per crop species and sub-species, an approximation per crop is made by taking yearly values corrected for by the duration of the growing season.

$$1 - \frac{Y_a}{Y_m} = K_y \left(1 - \frac{E_a}{E_m} \right) \tag{6}$$

Y_a is the actual yield [kg km^{-2} a^1]; Y_m is the optimal yield [kg km^{-2} a^{-1}]; K_y is the Crop coefficient [-]; E_a is the actual evaporation-transpiration [mm a^{-1} Area^{-1}]; E_m is the evaporation-transpiration for optimal yield [mm a^{-1} km^{-2}]. E_m is substituted by W_r, the crop water requirement for optimal yield, as summarized in the crop data in table 8.

Crop	Ky [-]	Water req. [mm/harvest]	Growing Period [days]	P$_2$O$_5$ [kg/ha]	P$_2$O$_5$ [kg/ha]	P [kg/ha]
Maize	1.30	500-800	80-180	36-50	50	22
Wheat	0.55	450-650	120-150	27-60	40	15
Rice[4]	1.00	450-700	90-150	26-50	35	15
Soybean	0.90	450-700	135-150	35	35	15
Sorghum	0.90	450-650	120-130	20-40, 40-60	40	15
Potato	0.90	500-700	105-145	39-80	80	35

Table 8. *Crop Data* (FAO, n.d.; UNIDO & IFDC, 1998)

The actual, yearly accumulated evaporation and transpiration from the geospatial data set is not representative of solely the crops evaporation and transpiration. Crops not only grow for only a small part of the year (varying with the local climate and season), but also the entire area (pixel) does not have to be planted with this specific crop. E_a is thereore substituted by E_c, which marks the approximated crops contribution to the actual evaporation-transpiration in the area. E_c is then approximated as (eq. 7):

$$E_c = E_a * \frac{T_g}{365} * A_H * C \tag{7}$$

E_c is the approximated crop transpiration [mm a^{-1} Area^{-1}]; T_g is the crop growing period [d]; A_H is the fractional area harvested [-]; and C [-] is a correctional value that accounts for the induced error by the

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[4] Fageria, N.K. The Use of Nutrients in Crop Plants. Google books

'annual approach' to the evapotranspiration-Deficit equation by scaling the maximum yield globally to be no greater than 1.

To simplify the model, the phosphorus input – yield relationship is simplified. $\frac{E_a}{E_m}$, the proportion of actual evaporation-transpiration to maximum evaporation-transpiration of a crop is approximated as $\frac{E_c}{W_r}$, where W_r is the crops water requirement for over the entire growing period (eq. 8).

$$1 - \frac{Y_a}{Y_m} = K_y \left(1 - \frac{E_c}{W_r}\right) \tag{8}$$

With an approximation of crop yield, a relationship still needs to be defined with the crops phosphorus requirement. The theoretical phosphorus-yield relationship (black), the linearized relationship applied in the model (brown) and commonly observed relationship (green) (Syers et al., 2008), are plotted in Figure 13 for comparison. The impact of a less than optimum, water constrained yield on the actual phosphorus demand, through the linearized phosphorus input-yield relationship, is demonstrated in Figure 14.
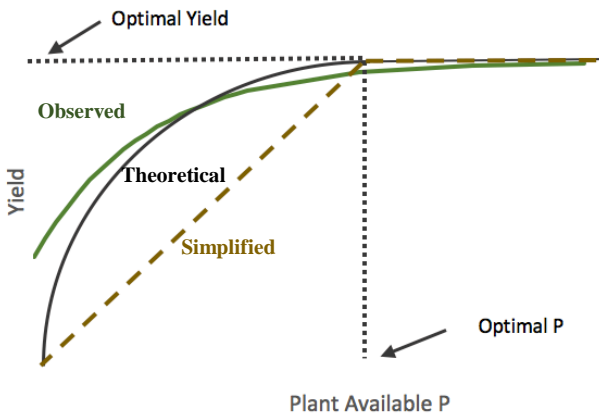

Figure 13. *Different phosphorus-yield relationships: observed (green), theoretical (black) and simplified (brown). Optimal phosphorus application for optimal yield indicated by dotted line.*
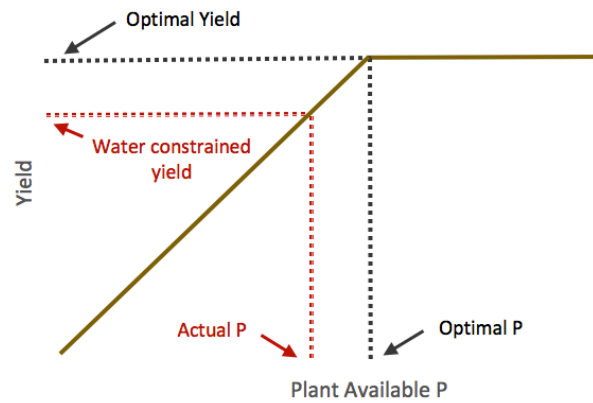
Figure 14. *Simplified, linear phosphorus-yield relationship. Reduction in phosphorus requirement for water constrained crops illustrated in red.*

The linearization simplification implies that the model overestimates the actual fertilizer requirement for those crops whose optimal yield is inhibited by water constraints. The induced error by this simplification is expected to be negligible considering the more significant errors associated with the crude yield determination. The simplification is further justified considering the unpredictability of water constraints. Farmers should fertilize slightly more than optimum for water constrained crops so that when there is enough water, the crops are not stunted in growth by a shortage of nutrients.

Knowing also the crop harvested area, the actual phosphorus demand of the crops can be determined through eq. 9:

$$D_{PT} = \frac{Y_a}{Y_m} * P_{opt}^n * A_H \tag{9}$$

Where D_{PT} is the total P-demand [t ha^{-1}a^{-1}]; P_{opt}^n is the crop specific P-demand for optimal yield [t ha^{-1}]; and A_H is the crop harvested area [ha^{-1}].

As hinted upon, the total water deficit that a crop will endure is unknown at the beginning of the growing season. A farmer therefore cannot accurately dose fertilizers to match the water-inhibited yield. To accommodate for this uncertainty, it is assumed that farmers will adjust their phosphorus input to yield

proportionate amounts only when the yield ratio is lower than 80%. If the yield reduction by water is less than 20% (>80% optimal yield), the farmer will be optimistic and fertilize proportionally to the optimum yield. Including these conditions, the phosphorus demand calculation can be summarized as followed (eq. 10):

$$D_{PT} = \begin{cases} P_{opt}^n * A_H & if \frac{Y_a}{Y_m} > 0.8; \\ \frac{Y_a}{Y_m} * f_{opt}^n * A_H & if \frac{Y_a}{Y_m} < 0.8; \end{cases} \tag{10}$$

The above procedures allow for the determination of approximate amounts and spatial distributions of phosphorus production and consumption rates. This allows for assessment of the first two objectives of this study: 1) Geographical identification of high phosphorus production and demand areas; and 2) Approximation of the potential contribution of recovered phosphorus to global phosphorus demand. The products created are also essential input components to the model that is built to address the other three objectives: 3) Determination of areas where there is an economic feasibility for phosphorus recovery; 4) Evaluation of the emissions that come with the transportation of recovered vs. mined phosphorus; and 5) Evaluation of the effects of different financial and policy measures on the created network. Much more information is required, however, before any model is to enable such assessment. The next most important information that the model now requires are the economic formulations on costs and prices.

3.3 Costs and Prices

The phosphorus quantities and characteristics, as determined in the previous section, are aggregated into individual nodes. Each area is then represented by a single, community actor that interacts uniformly with other nodes on behalf of that represented area. The geospatial position of the nodes will be in the approximate centre of the potential areas. In reality, the centres of high potential areas are also likely to be most suitable for the construction of distribution warehouses or processing facilities, thereby partially justifying the assumption. Each node has the following properties: source/class (i.e. Livestock, Mines, Maize, etc.), coordinate position, production/demand quantity, and a price boundary. The first three properties are either self-defined or have been determined in the previous section, leaving only the last property, each node's individual price boundary, to yet be determined.

A node's price boundary is a value that determines whether or not that node can partake in international trade at a given market price. These need to be determined for each node so that the model can accurately recreate the demand and supply functions for the phosphorus market. For demand nodes, this value describes an upper limit, a price beyond which it will not purchase phosphorus as the investment is no longer profitable. For supply nodes, it describes a lower limit, a price below which it will not produce because, similarly, production is no longer profitable. If the market price falls between these ranges, then trade between the nodes is negotiable (neglecting transportation costs for now). This concept is illustrated in Figure 15.

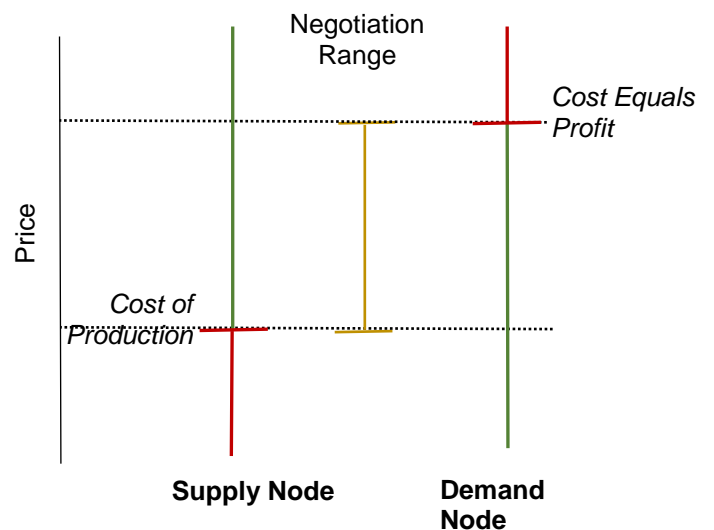The *cost of production* essentially defines a

Figure 15. *illustration of cost boundaries of two nodes. Green ranges showing prices at which the node can participate in trade, red at which they cant. Yellow shows the range where the green ranges overlap indicating the prices at which trade is possible.*

minimum market price necessary for the participation of a production node in the global network. Similarly, the Phosphorus price where the *costs* (of buying P) *equals revenue* that is generated by using the input marks the maximum price by which a demand node will still participate. In the following sections, these minimum and maximum prices will be further defined and explained.

3.3.1 Price Upper Limit

Exceedance of a demand node's upper limit results in the node's inability to partake in trade. This upper limit is defined as the price at which the node can no longer make a profit from selling their crops because of the high fertiliser cost. The marginal value of phosphorus that defines this limit, depends on: yield, the crop market value, the phosphorus requirement and an approximated value that corrects for farm operational costs. These variables can be summarized in equation 11.

$$f_{max}^n = \frac{Y_{opt}^n * C_a^n}{P_{opt}^n} *\ R^n \tag{11}$$

Where f_{max}^n is the max price for phosphorus [$ t^{-1}]; Y_{opt}^n is the optimal yield [t ha^{-1}]; C_a^n is the crop price in year a [$ t^{-1}]; P_{opt} is the optimum fertilizer dosage rate (equal to P-demand for optimal yield) [t ha^{-1}]; and R^n is the ratio of fertilizer cost to total costs [-], for crop *n.* The fertilizer cost ratio is introduced to account for other expenses in industrial agriculture. It is defined as the proportion of total expenses that are typically spent on P-fertilizers. The equation therefore implies that the maximum price equals the point where the farmer no longer makes a profit and thus the fertilizer cost equals the proportion of the revenue generated by the fertilizer.

The input data for determination of this maximum price, is summarized below in Table 9.

	Cost Ratio (total) (MAFRD, 2016) [-]	2005 Crop Price (IndexMundi, 2017) [$/t^{-1}]	Opt. yield (Steduto et al., 2012) [t ha^{-1}]	Opt. Fert. (FAO & IFA, 2000) [kg ha^{-1}]
Maize	0.2	97	17	22
Wheat	0.17	141	10	15
Rice	0.07 (KOSTAT, 2015)	288	8	15
Sorghum	0.17	97	12	15
Soybean	0.12 (Purdue University, 2017)	250	5	35
Potato	0.09 (UNIDO & IFDC, 1998)	100	50	35

Table 9. *Data for crop price determination.*

The cost ratio above is recorded as the total cost of all fertilizers. To reduce this further to only the P-fertilizer proportion, it is corrected through a division by three, where the three fertilizers, Nitrogen, Potassium, and Phosphorus, all share an equal portion of the cost.

3.3.2 Price Lower Limit

Inversely to the demand node's upper price limit, the production nodes have a lower limit. The lower limit defines the price below which the production node cannot produce phosphorus profitably. It is the minimum price that a production node needs in order for its revenue from potential selling of the product breaks even with the costs of production. Any price above this lower limit allows for trade, with higher values resulting in more profit for the supply node. The production cost that defines this limit depends on the annual base cost

for operation and the material-operational costs per unit of phosphorus produced. A node's lower price limit is determined by the following equation (eq. 12):

$$f_{min}^i = \frac{M_c^i + B^s}{S_{PT}} - S_s \tag{12}$$

Where f_{min}^i is the minimum price for phosphorus [$ t^{-1}]; M_c^i is the cost of mining or magnesium dosing [$]; B^i is base cost of operation [$]; S_{PT} is the phosphorus production potential [t]; and S_s is the minimum scaling cost savings from struvite precipitation for urban wastewater treatment plants, 620 [$ t^{-1}] (Shu, Schneider, Jegatheesan, & Johnson, 2006).

One of the components in the equation is M_c^i, the cost of mining or magnesium dosing for sustainable supply nodes. For the latter, the total cost for the production of a tonne of struvite is reduced to its resource costs, namely that of Magnesium. These costs are determined through the following equation (eq. 13):

$$M_c^i = P_m * R_{mp} * C \tag{13}$$

Where M_c^i is the magnesium cost per ton of phosphorus for node i [$ t^{-1}]; P_m is the price of magnesium [$ t^{-1}]; R_{mp} is the ratio of magnesium required per ton of phosphorus; and C is a correctional value for potential magnesium already present in the wastewater, for this study approximated as 1 (none).

R_{mp} is equal to 0.77 as for every tonne of phosphorus in struvite, one needs 0.77 tonnes of Mg[5]. Magnesium is most commonly dosed in the form of Magnesium Hydroxide ($Mg(OH)_2$) or Magnesium Chloride ($MgCl_2$)[6]. Ostara can supply magnesium chloride at 250 [$ t^{-1}] (Seymour, 2009). Mg has a 1:1 molar ratio of Mg to $MgCl_2$ and the molar mass of $MgCl_2$ is 24 [g mol^{-1}] Mg + 70 [g mol^{-1}] Cl_2 = 94 [g mol^{-1}]. As such, there is one tonne of Magnesium in every 3.9 tonnes of $MgCl_2$. The price of magnesium, P_m, thus becomes $975,- [$ t^{-1}]. Together with the determined R_{mp}, of 0.77, equation 13 results in a price of magnesium per tonne of phosphorus, M_c^i, of approximately $751,- [$ t^{-1}].

The annual base cost of operation for struvite precipitation varies depending with the required capacity of the WWTP, which in turn depends on the amount of wastewater that needs to be treated. As the model is designed around maximum potentials, the treatment facilities considered in the model will be large, 500,000 Person Equivalent (PE) Ostara Pearl Reactors® as opposed to the smaller 100,000 PE reactors. The number of required reactors for urban nodes is determined depending on the amount of connected people: 1 reactor per every 500,000 individuals (PE). A 'person' equivalent does not hold for livestock however. Livestock waste flows are potentially of much greater magnitude per head (depending on the livestock) with higher phosphorus concentrations than that of human waste flows. The amount of large Ostara Pearl Reactors® required for livestock waste flows, is taken to be equal to the phosphorus production rate divided by 500,000. Thus, instead of 0.77 kilograms of P defining one PE, 1 kilogram defines 1 'livestock' PE. The annual base costs of a single Ostara Pear Reactor® is directly taken from a dissertation by L. Egle (2016). In the dissertation, a summary of investment costs, capital costs and detailed breakdown of the operating costs by resources, personnel, energy, maintenance and disposal for struvite precipitation and other commercial recovery technologies are presented. The *resource costs* reported by Egle is subtracted from the annual cost, as this is determined more precisely, and per node, above through equation 13. The yearly base fee of production per recovery reactor is then $ 176,000 [$].

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[5] Struvite ($NH_4MgPO_4 \cdot 6H_2O$) has a molar ratio of 1:1 Mg:P. The molar mass of Mg is 24 [g mol-1], and of P is 31 [g mol-1].
[6] Although each compound behaves differently in solution, one does not appear to be better than the other concerning struvite production rates. $MgCl_2$ dissolves more rapidly, allowing for shorter reaction times, while $Mg(OH)_2$ is cheaper and assists in raising the pH (Jaffer et al., 2002; Münch & Barr, 2001).

The cost of *mine exploitation* is also defined through the two component costs summarized in equation 11. Because of the micro-economical complexity of each mine's business case, the production cost per tonne of phosphorus for all mines is assumed to be the market value of phosphate rock. Considering the close relation between rock phosphate and commercial DAP prices (Figure 6, page 21), the fertiliser manufacturing costs is assumed to be 3.3 times the rock phosphate market price. This value of 3.3 is the average price ratio of rock phosphate with DAP, with a standard deviation of 0.86. The average is calculated for a period of nearly 50 years. The 2005 price index for PR is 42 [$/tonne] (IndexMundi, 2017). Translating this price from RP to elemental phosphorus, the minimum production cost amounts to approximately 200 [$ t^{-1}] when assuming a high, 30% phosphorus content.

The yearly base costs of a phosphate mine is taken as an approximation of the required, yearly return on investment only, where other costs are assumed to be included in the 'per tonne' rock price above. Again, the investment costs are highly location and capacity dependant so an accurate approximation for the investment costs of each modelled mine is difficult to establish. To keep matters simple, all mines are deemed to require $31,000,000 return over a 10-year period (3,100,000 [$ a^{-1}]), a monetary figure taken from the World Bank finance phosphate mine project in Shidiya, Jordan (World Bank, 1994). With the upper and lower price limits now defined, there is one, last, fundamental cost of trade that remains unaddressed: the transportation cost of moving (mega) tonnes of phosphorus around the globe.

3.3.3 Transportation Cost

The transportation costs for phosphorus trade depends largely on distance between the nodes. If the transportation costs between two nodes exceeds the maximum price of the demand node, then the demand node cannot buy and the supply node cannot sell to that node. This influence of distance on the ability to trade was introduced in Figures 12 and 13 and Table 5. To further illustrate this influence, consider the hypothetical, three-node network below (Figure 16).The greater transportation cost, due to the greater distance from supply node *S1* to demand node *X*, results in prices too high for demand node *X* which is then limited to trade with S2 only (Figure 17).
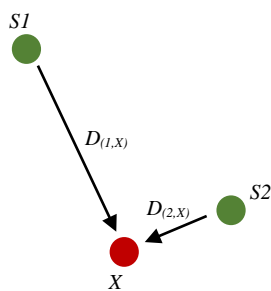

Figure 16. *Hypothetical, three node network of demand node X and supply nodes S1 and S2 situated at distance $D_{(1,X)}$ and $D_{(2,X)}$, respectively.*
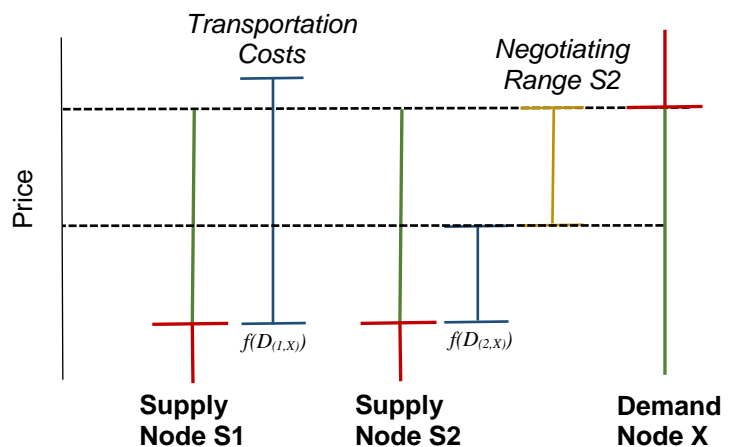
Figure 17. *Plot of price limits, revealing where trade is possible (similar to Figure 13). Transportation costs in blue and negotiating range in yellow.*

Although there are numerous modes of transportation that are more, or less, economically viable for different transportation distances and loads, the model calculates transport cost as if it were transported by either truck or cargo ship, only. The transportation of bulk goods over land is typically less cost efficient than over water transportation, especially for long distances. Over water transportation occurs therefore not only

on the seas and oceans but also takes place along major rivers and canals. Considering the financial appeal of over water transportation, it is estimated that 90% of global trade is carried by the international shipping industry (ICS, 2017) with more than 10 billion tonnes of goods and materials transported in 2015 (UNCTAD, 2016). The model cannot distinguish between the proportion of land or sea crossed in transporting phosphorus from one node to another. In differentiating between the two, a cumulative probability curve is employed that gives some approximation of the proportion of the total distance likely transversed over water (eq. 14) and over land (eq. 15) (Figure 18).
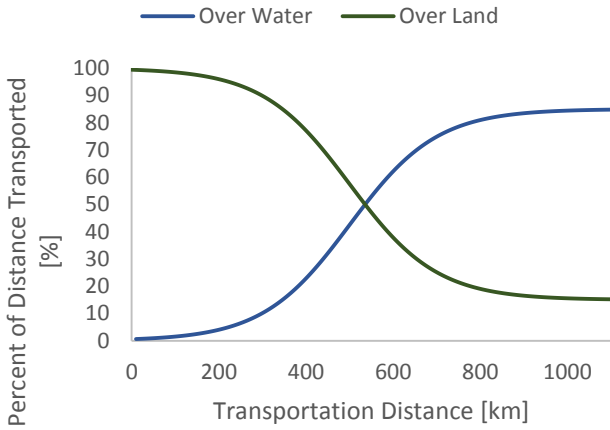

Figure 17. *Proportion of transportation over water (blue) vs transportation over land (green), by distance.*

$$F_W = \frac{85}{1 + e^{-\frac{D-\mu}{S}}} \tag{14}$$

$$F_L = \frac{85}{1 + e^{\frac{D-\mu}{S}}} + 15 \tag{15}$$

Where F_W and F_L represent the fraction [-] of total distance D [km] transversed over water and land respectively; and μ and S are function shape constants of 500 and 100 [-].

Some degree of over land transportation is usually inevitable as most phosphorus production and consumption sites are not always directly accessible from water. To account for this, a maximum of 85% of the total transportation distance can take place over water, with a minimum of 15% of the transportation distance always taking place over land. The maximum water transport occurs at any distance greater than 1,000 kilometres, approximately the distance from Iceland to Norway, or traveling from the southern end of the UK, to the north. With proportion of land vs. sea transport distinguished, the total transportation cost can be expressed as the proportional costs of the two (eq. 16):

$$T_c^{i,n} = D^{i,n} \left[F_W * \frac{P_b * E_W + C_F}{W_W * \overline{V}_W} + F_L * \frac{P_d * E_L + \frac{L_c}{\overline{V}_L}}{W_L} \right] \tag{16}$$

$$\underbrace{\hspace{4cm}}_{\text{Water transport cost}} \quad \underbrace{\hspace{4cm}}_{\text{Land transport cost}}$$

Where $T_c^{i,n}$ is the transportation cost from node *i* to node *n* [$]; $D^{i,n}$ is the distance between node *i* and node *n* [km]; P_b is the bunker fuel price [$ t^{-1}]; P_d is the price of diesel [$ L^{-1}]; E_W is the fuel efficiency of a full *handysize* bulk carrier [t d^{-1}]; E_L is the fuel efficiency of 2x30 tonne trucks [L km^{-1}]; C_F is the fixed costs per ship [$ d^{-1}]; L_c is the labour wage [$ h^{-1}]; $\overline{V}_W$ is the average velocity of the carrier over water [km h^{-1}]; $\overline{V}_L$ is the average velocity of the truck over land [km h^{-1}]; W_W is the carrier load weight; W_W is the truck load weight [t]. The values of the constants are presented in Table 10.

Sea Transport Component Cost				**Land Transport Component Cost**			
Constant		Value	Source	Constant		Value	Source
P_b[7]	[\$ t^{-1}]	173	(World Scale, 2017)	P_d	[\$ L^{-1}]	1.9	(IndexMundi, 2017)
E_W	[t d^{-1}]	30	(Počuča, 2006)	E_L	[L km^{-1}]	0.53	(Nylund & Erkkilä, 2005)
W_W	[t]	28,909	(Počuča, 2006)	W_L	[t]	60	
$\bar{V}_W$	[km d^{-1}]	622	(Počuča, 2006)	$\bar{V}_L$	[km h^{-1}]	80	-
C_F	[\$ d^{-1}]	5,000	(Počuča, 2006)	L_c	[\$ h^{-1}]	17	-
C_b	[kg t^{-1}]	3,130	(IMO, 2009)	C_d	[kg L^{-1}]	2.7	(IEEP, Ecologic, & Dias Soares, n.d.)

Table 10. *Constants for transport cost determination equation (eq. 16)*

The transport distance will vary highly depending on whether a node is buying from geographically concentrated mines or widespread recovered phosphorus, and therefore the transport-associated CO_2 emissions will do so as well. The following simple formulation may then be used to approximate the CO_2 emissions that come paired with the transportation (eq. 17).

$$E_{CO2}^{i,n} = D^{i,n} \left[F_W * \frac{C_b * E_W}{W_W * \bar{V}_W} + F_L * \frac{C_d * E_L}{W_L} \right] \tag{17}$$

Where $E_{CO2}^{i,n}$ is the CO_2 emissions in transportation between node i to node n [kg]; C_{bf} is the CO_2 per tonne of bunker fuel [kg t^{-1}] ; and C_D is the CO_2 per litre of diesel [kg litre^{-1}]. The constants in the above two equations (13 and 14) are retrieved from various sources and summarized in Table 10 below.

With all costs now established, the model has all the information it needs to determine the price curve and network shape. The next section (3.4) will show how the model utilizes the above defined information so that the remaining study objectives may be answered.

3.4 The Model Algorithm

A brief introduction of the model fundamentals was provided at the beginning of this chapter. The model is run for different, predefined, market price intervals limited to the optimal price range (P_1, P_2, etc.), where for each price an assessment is made on the global quantity of phosphorus that could be traded at that price. Plotting the prices and quantities traded for these various iterations reveals how different amounts are traded for the different market prices, (Figure 19). For each price iteration, there are several steps that the model takes in order to creates its product. The first is the identification of all potential, feasible trade partners.
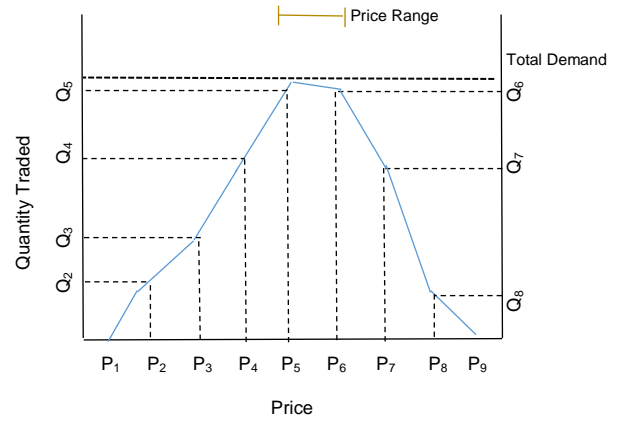

Figure 19. *Quantity traded vs. price plotted for different iterations.*

3.4.1 Identification of Trade Partners

From the many possible combinations of node pairs, the model needs to determine between which nodes trade is actually possible. In order to do so, all possible supply-demand node combinations pass through two filters. The first filter removes the pairs that can never trade with each other provided their combination of minimum production costs, maximum price boundaries and transportation costs. The second filter

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[7] Bunker defines any fuel that is stored and used aboard vessels. The Bunker Index (BI) is a price index for this group of fuels.

removes node which cannot trade with each other provided the new market price imposed for the respective iteration.

The first filter check can be summarized in one conditional statement: whether the sum of the minimum production cost of the supply node and the transportation cost are below the maximum price of the demand node (Figure 20). If the condition is satisfied, then trade between the node pairs is feasible and thus the pair is saved in in a list of feasible trade partners. This evaluation is conducted for every possible node pair resulting in an extensive list of all possible trade partners and their prices.
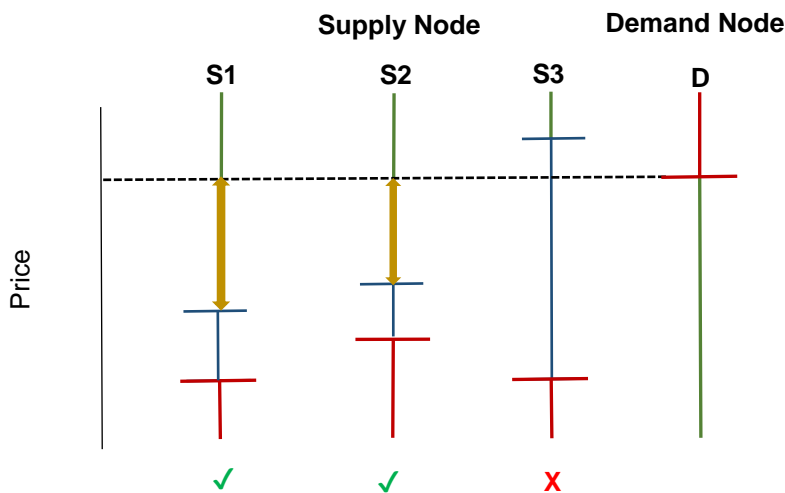

Figure 20. *Illustration of first filter. Price boundary (red), transportation costs (blue), negotiation range (yellow). If sum of lower price boundary and transport cost is greater than upper price boundary, then the nodes cannot trade.*

The list of nodes pairs is passed through a second filter. Instead of potentially trading at consumers best-deal prices (minimum production and transportation cost), all nodes trade at the same global market price. If this market price falls outside of the negotiation range defined in Figure 19, then the nodes pair is removed from the list. Figure 21 visualizes the node pairs with demand node D for three hypothetical supply nodes, where P_1, to P_4 are arbitrary market prices and P_{MD} is the maximum price for D.
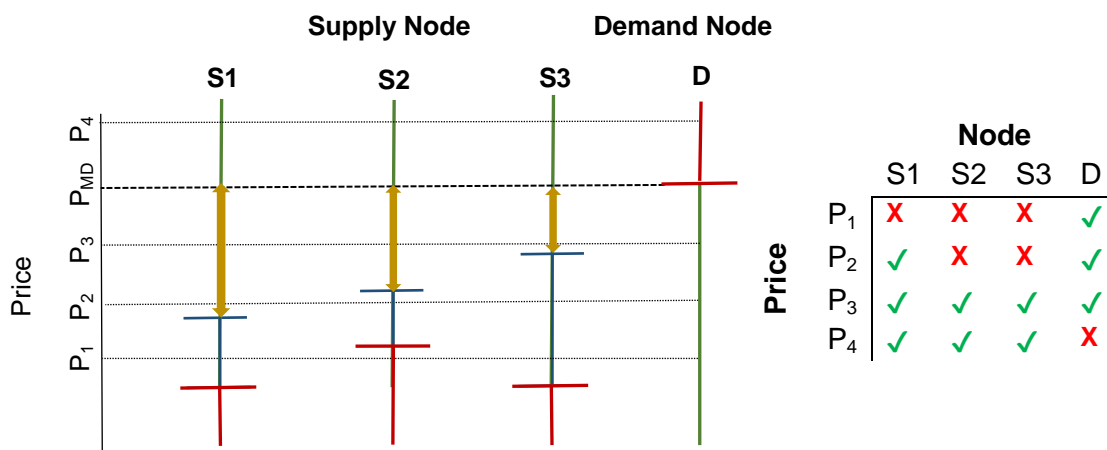

Figure 21. *Visual representation of second filter for demand node D, at four iterations with each their own market price (P_1, P_2, P_3, and P_4). Green shows prices at which nodes can trade, red at which they cannot. Transportation costs are in blue. Yellow shows the price negotiation range, where trade is possible. Table summarizes which nodes can trade at which prices.*

Only for the third market price, P$_3$, can *D* trade with all supply nodes. Should the market price be defined as P$_1$ or P$_4$ then no trade is possible. Having narrowed down the possible trade *options*, the model will begin evaluate how much phosphorus can be supplied and consumed at that market price.

3.4.2 Identification of Trade Flows

In the model, phosphorus consumers will look for the cheapest suppliers. The matter becomes obscure here as, in reality, there are no cheaper or more expensive suppliers when there is a single, set market price. However, supply nodes that *could* supply at prices far lower that the set market price have a competitive advantage over those that cannot. This results in them being traded with first (see discussion on Figures 12 and 13 and Table 5). These nodes have the luxury to undercut their (more expensive) competitors thereby safeguarding their favourable trading position. In the example of Figure 22, the first trade therefore occurs between S2 and *D*, followed by S1 and *D*. This is done for all the nodes in a network by sorting the list of trade partners from lowest to highest by corresponding best 'hypothetical' price (see

Figure 22. *Visual representation of trade choice. Green shows prices at which nodes can trade, red at which they cannot.*

Table 5), executing the trade, and updating the list in terms of quantities demanded by demand node *n*, D_{PT}^n , and supply available at supply node *i*, S_{PT}^i.
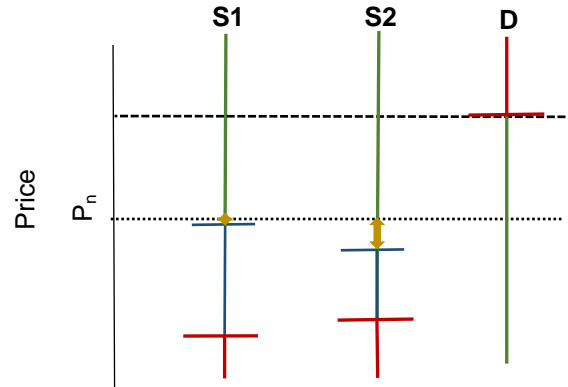
The amount traded between each node pair is taken to be equal to the minimum of possible supply and quantity demanded. The supply available and quantity demanded at each supply demand nodes are updated accordingly:

$$Amount\ Traded = \begin{cases} S_{PT}^i & if\ D_{PT}^n > S_{PT}^i; \\ D_{PT}^n & if\ S_{PT}^i > D_{PT}^n; \end{cases} \tag{17}$$

$$Updated\ quantities = \begin{cases} S_{PT}^i = 0, & D_{PT}^n = D_{PT}^n - S_{PT}^i & if\ D_{PT}^n > S_{PT}^i; \\ D_{PT}^n = 0, & S_{PT}^i = S_{PT}^i - D_{PT}^n & if\ S_{PT}^i > D_{PT}^n; \end{cases} \tag{18}$$

Where S_{PT} and D_{PT} denote the phosphorus supply and demand quantities for nodes *i* or *n,* respectively. By formulation (18), one of the nodes will have 0 capacity after each trade, and so all possible trade combinations with that node are removed from the items still saved in the list of possible trade partners. This process is continued until the list is empty and thus all feasible trade has been conducted. The total amount traded between every node defines the global amount traded. The price range determined from supply and demand curves, will mark the prices for which global trade in P is executed. By Arrow-Debrew market equilibrium principles, within this price range the 'excess demand' (the difference between the supply and demand curve) is zero and remaining supply is minimized (Arrow & Debreu, 1954).

3.4.2 Network creation

A series of network maps will be created that show the global phosphorus trade network at the different market prices within the 'equilibrium' price range. Doing this for all scenarios results in three series of maps that show trade flow at their own optimal market prices. In these maps the trading node pairs are connected through a line whose width is proportional to the amount traded. Similarly, the node sizes are proportional to

their demand/production capacity. The colour of the line will indicate what the nature of the source is (Mine, Urban or Livestock phosphorus). These maps will serve as a visual tool to address the third objective: Determination of areas where there is an economic feasibility for phosphorus recovery. The produced maps will show high and low densities of lines, indicating areas of intensive and less intensive trade, while colours will allow for quick assessment of what the dominant source is of the phosphorus being traded.

4 Results

The results section chronologically presents the findings that each address one of the aforementioned study objectives. The maps created in the first phase of the methodology are presented first. These maps allow for the identification of production and demand areas (4.1), and assessment of the potential contribution of recovered phosphorus to global demand (4.2). The second phase of the methods are presented next, which reveal variation in economic feasibility for recovery of phosphorus at different prices for the different scenarios (4.3). A brief assessment of the difference in transportation emissions is provided also (4.4), and concludes with an assessment of the influence of different financial and policy measures (4.5).

The nature of the question in identifying *areas* where phosphorus trade is possible, implies that a large component of the results is visually presented as maps. Although many maps have been created (one for every 10 [$] interval, for every scenario, for three simulation years), only those pertaining to the boundaries of the determined optimal price ranges, as well as the best approximation of the optimal price, are presented in this report.

4.1. Identification of Production and Demand Areas

4.1.1 Mapping Livestock Phosphorus Production Potential

The spatial distribution of global livestock phosphorus recovery potential [t km^{-2} a^{-1}] is presented in Map 2 at a resolution of 0.08 decimal degree in a WGS84 projection. Darker shades of green indicate higher potentials due to a higher population density of bovine, swine and/or poultry livestock in the area. India, China, Vietnam, Ireland, Denmark, The Netherlands, Belgium, Argentina, and parts of Germany are coloured a deep green therefore indicating a high national livestock phosphorus recovery potential. Areas of little human development, such as the Sahara, Siberia, Australian Outback, Northern Canada, Amazon and Congolese Rainforest, the Tibetan Plateau and the Arabian desert, show almost no phosphorus production potential.

Map 2. *Potential phosphorus recovery from Bovine, Swine and Poultry Livestock in tonnes per square kilometre for 2005.*
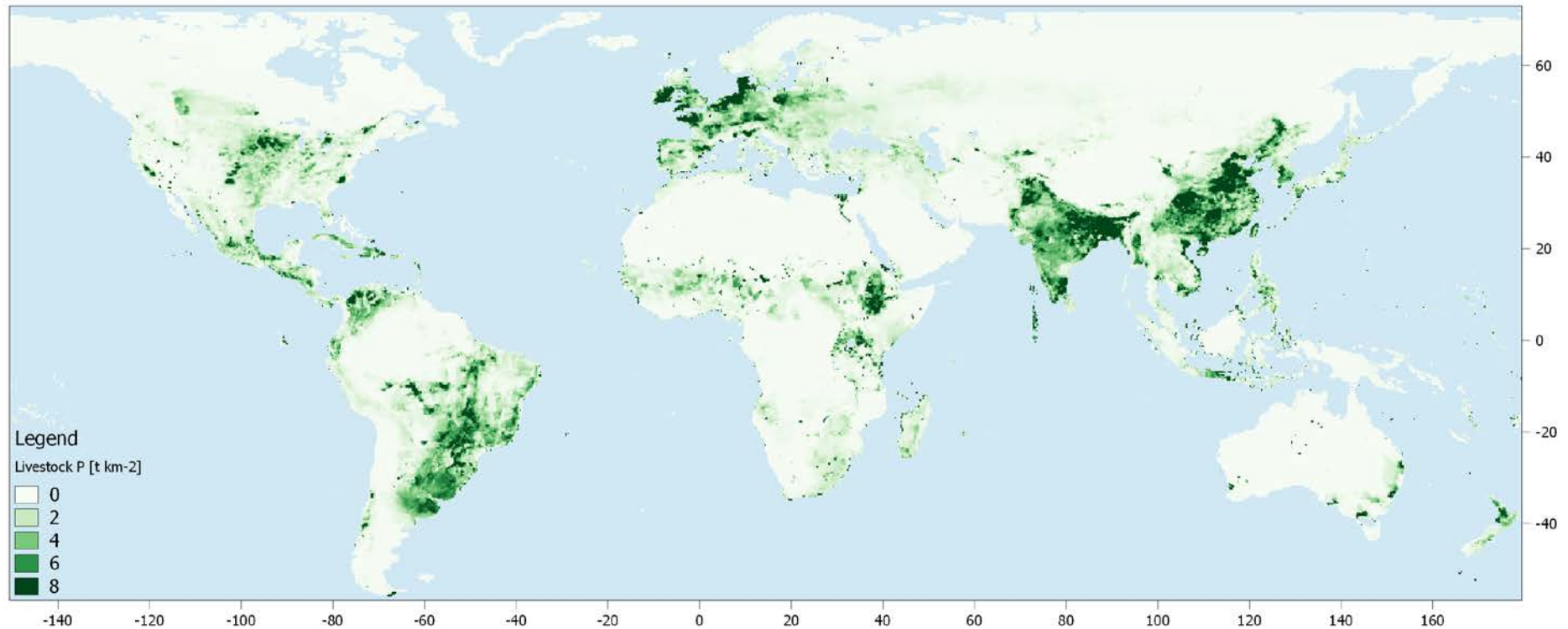
Major livestock production nodes have been determined based off of Map 2 and are presented in Map 3. Nodes with a production of less than one kilo tonne per year are excluded from consideration (not 'significant' enough), while the remaining nodes are stylized to vary in size in accordance to their annual P production potentials [kt a^{-1}]. Large nodes can be found in China, India, Pakistan, Central Europe, Ethiopia, and Latin America, and a high density of smaller nodes is found in Sub-Saharan Africa and the United States. Table 10 presents the cumulative, potential, livestock phosphorus production per continent, as well as the global, potential, livestock phosphorus production of all nodes.

Map 3. *Major, livestock, potential phosphorus recovery nodes for 2005, by size in kilo tonnes P production per year.*
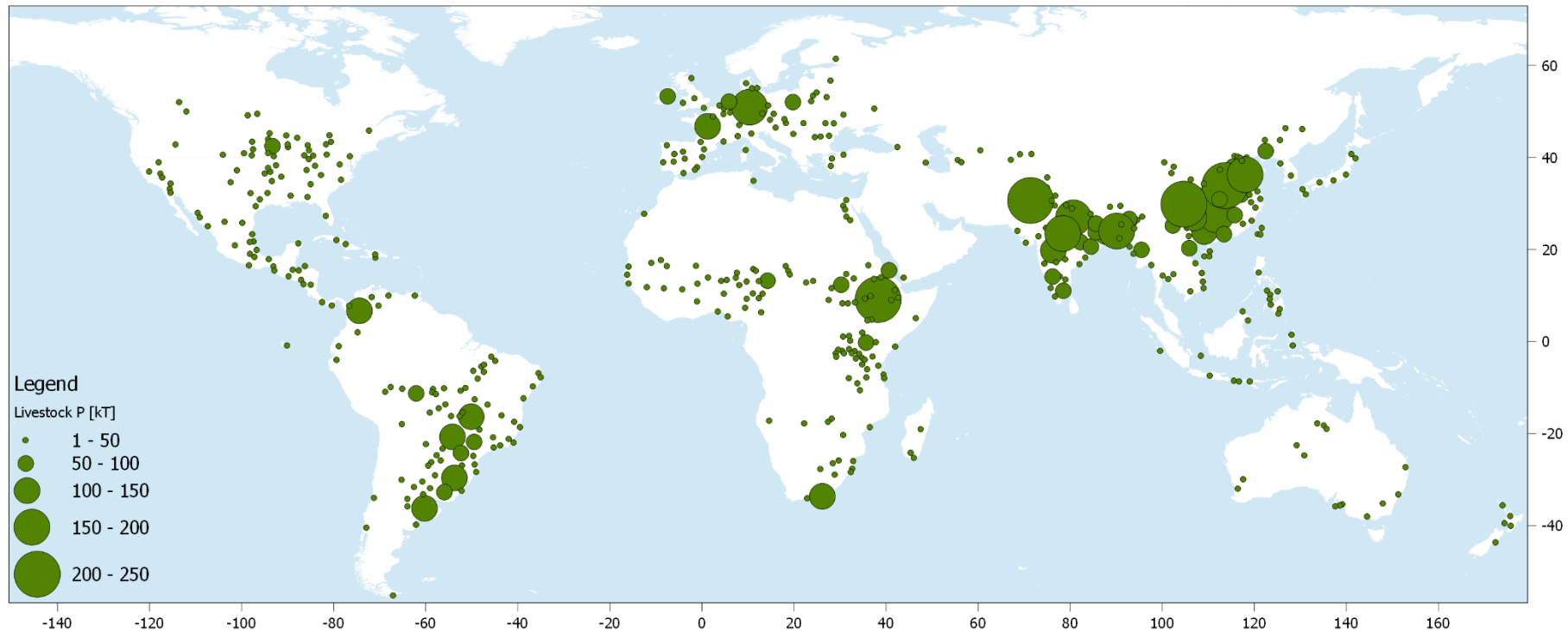

Table 10. *Approximate, maximum livestock recovery potential in Mt P, for 2005, per continent.*

		Asia	North America	Europe	Africa	South America	Oceania	Australia	World
Total Potential Livestock P Production (Map 2)	**[Mt P]**	5.67	1.66	1.62	2.14	2.99	0.08	0.22	14.38
Livestock Node P Production (Map 3)	**[Mt P]**	-	-	-	-	-	-	-	8.8

4.1.2 Mapping Urban Phosphorus Production Potential

The global, urban phosphorus recovery potential [t km^{-2} a^{-1}] is presented in map 4 at a resolution of 0.08 decimal degree in a WGS84 projection. With the same scale as for the livestock map, it is noticeable that the green is significantly less vivid. Relatively darker shades of green can, however, be identified in India, China, the Nile delta, Indonesia and many major cities. Again, the areas of the world with little human development, naturally show little to no phosphorus recovery potential.

Map 4. *Potential phosphorus recovery from Human Population in tonnes per square kilometre.*
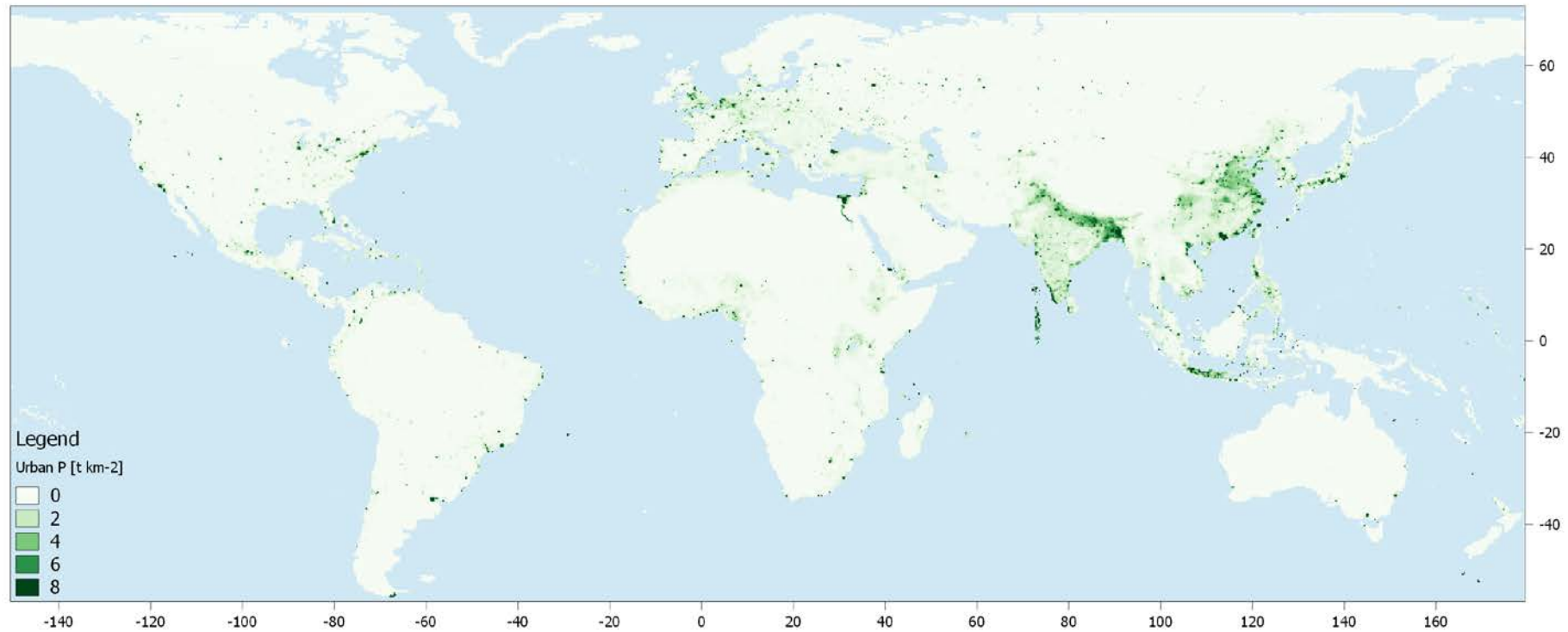
Major, urban production nodes have been created from Map 4 and are presented in Map 5. Nodes with a production of less than 400 [t] P per year are excluded from consideration, while the remaining nodes are again stylized to vary in size in accordance to their annual P production potential [kt a^{-1}]. Large nodes can again be found in India, while a high density of smaller nodes can be found in the rest of Asia, along the African and South American coast, and in Europe. Table 11 presents the cumulative, potential, urban phosphorus production per continent, as well as the global potential urban P production of major nodes.

Map 5. *Major, urban, potential phosphorus recovery nodes for 2005, by size in kilo tonnes P production per year.*
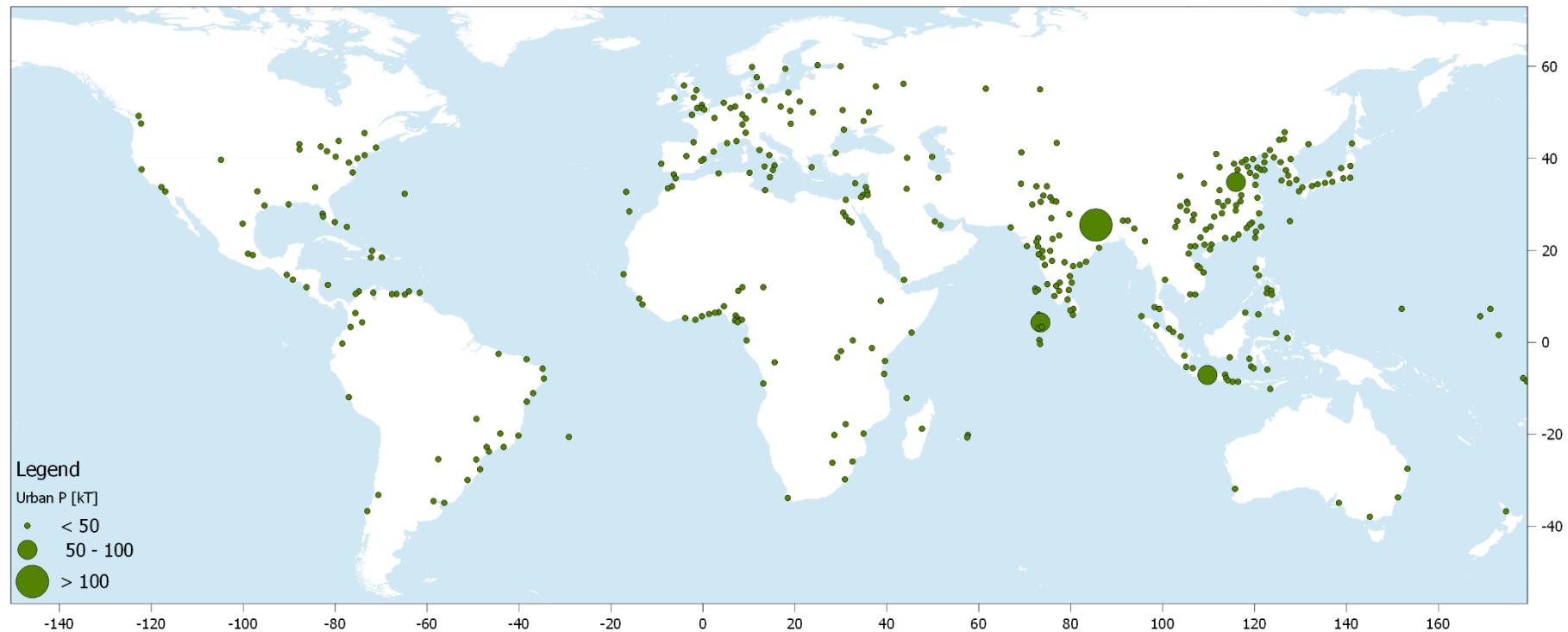

Table 11. *Approximate, maximum human recovery potential in megatonnes P, for 2005, per continent.*

		Asia	North America	Europe	Africa	South America	Oceania	Australia	World
Potential Human P Production (Map 4)	[Mt P]	2.02	0.27	0.35	0.47	0.19	0.00	0.01	3.31
Urban Node P Production (Map 5)	[Mt P]	-	-	-	-	-	-	-	1.53

4.1.3 Agricultural Phosphorus Demand Map

The spatial distribution of global agricultural phosphorus demand [t km^{-2} a^{-1}] is expressed in Map 6 as the aggregation of the individual demand maps for six major crops. The United States corn belt and the Asian rice cultivation are particularly noticeable from the data. The associated *node maps* to each crop are determined individually. These six maps will not be presented here., but the proportion of demand attributed to each crop type is presented in section 3.2.2.

Map 6. *Approximate, combined phosphorus demand for Maize, Wheat, Rice, Soybean, Sorghum and Potato in tonnes per square kilometre.*
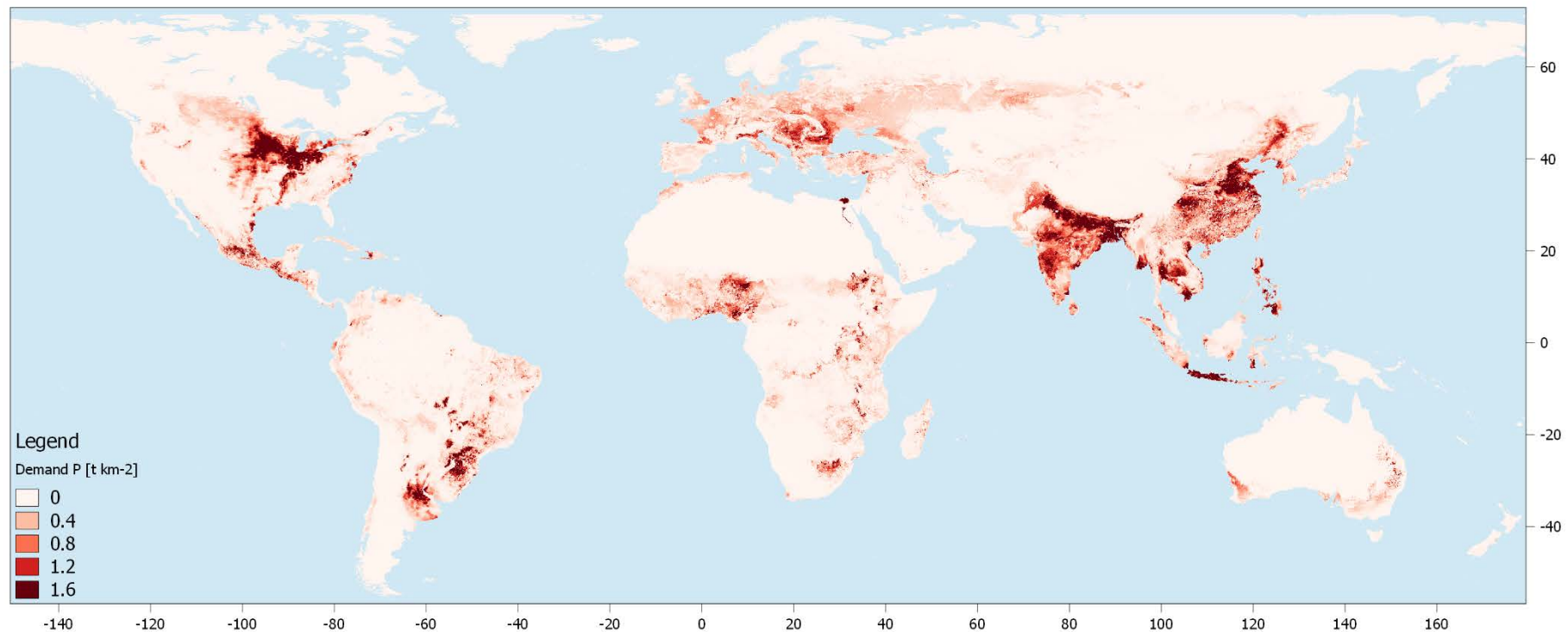

Table 12. *Approximate, phosphorus demand in Mt P, for 2005, per continent.*

		Asia	North America	Europe	Africa	South America	Oceania	Australia	World
Potential Agricultural P Demand	**[Mt P]**	8.30	2.89	1.56	2.20	1.90	0.00	0.21	17.06

4.2. Potential Contribution

The potential contribution of recovered phosphorus to the global demand can be approximated in different ways depending on how one defines *potential.* One can define potential as the maximum capacity under ideal circumstances and thereby disregard all economic factors, or one can limit the total potential to economic constraints. In this section the results with regards to the first, the maximum capacity potential, will be presented. Section 4.3 will present the results in light of relevant economic variables.

4.2.1 Maximum recovery of phosphorus

The spatial distribution of maximum capacity potentials are presented in Map 2, 4, and 6, where the maximum phosphorus recovery and demand is approximated for by generalising the phosphorus excretion rates per individual and correcting this by a recoverability factor. Converting these production densities to total production and demand estimates per continent, yields the data presented in Table 13.

		Asia	N. America	Europe	Africa	Lat. America	Oceania	Australia	World
Livestock (L)	**[Mt P]**	5.67	1.66	1.62	2.14	2.99	0.08	0.22	14.38
Human (H)	**[Mt P]**	2.02	0.27	0.35	0.47	0.19	0.00	0.01	3.31
L + H	**[Mt P]**	7.69	1.93	1.97	2.61	3.18	0.08	0.23	17.69
Agri. Demand	**[Mt P]**	8.30	2.89	1.56	2.20	1.90	0.00	0.21	17.06

Table 13. *Approximate, maximum production and demand in Mt P, for 2005, per continent.*

While considering only the *maximum capacity potential*, and thus disregarding all limitations (i.e.: map 3 and 5) except for the approximated recovery efficiency of struvite precipitation, the data in Table 13 can be used to approximate the proportional contribution of *recovered phosphorus* to the continental and global phosphorus demand (Table 14).

Livestock P	**[%]**	68	57	104	97	157	-	105	84
Human P	**[%]**	24	9	22	21	10	-	5	19
Both P	**[%]**	93	67	126	119	167	-	110	104

Table 14. *Approximate, maximum contribution of recovered P to demand in Mt P, for 2005, per continent.*

Some continents (i.e. South and North America) show significant disproportionalities in recoverable P from waste vs. crop required phosphorus. (Virtual) phosphorus trade can play an important role in determining these continental budget surpluses and deficits as, in the end, the global, recovered phosphorus budget is surprisingly well balanced at 104%. This global surplus, however small, already suggests that there is an inherent overestimation of the phosphorus excretion rates or underestimation of the agricultural phosphorus demand, or that some degree of soil nutrient mining by the crops is considered in the phosphorus requirement values presented in *'Fertilizers and Their Use'* (FAO & IFA, 2000).

4.2.2 Recovery from only concentrated areas

Unfortunately, it is not feasible to recover every ounce of phosphorus excreted, or to fertilize every crop patch everywhere. More realistically recovery will only take place in areas of high population or livestock density while fertilisation will only take place in areas of intensive agriculture. A more realistic assessment of the contribution of recovered products to the global P demand can be made by disregarding production and

demand areas of low P density, and selecting only for *major* production and demand nodes (Map 3 and 5). In this procedure, the following minimum areal P production/consumption and node thresholds have been applied:

Livestock	500 [t] per 61 km^2	1,000 [t] per node
Urban	200 [t] per 61 km^2	0,400 [t] per node
Crops	1.00 [t] per 61 km^2	1,000 [t] per node

The resulting phosphorus recovery rates are summarized in Table 15. As described in the *Materials and Methods* section, the phosphorus demand has been calculated for 6 major crops that constitute only about 56% of the global, agricultural phosphorus demand (Heffer, 2009). These six crop demands have proportionally been scaled up to the demand of all crops so that the actual, proportion of global phosphorus supply to demand may be more accurately approximated for in the economic model. The scaled and non-scaled phosphorus demands per crop type are summarized in Table 16.

P Production

Livestock	8.80
Urban	1.53
H + L	10.33
Mines	16.72

Table 15. *P Production from Nodes*

P Demand

	Maize	Wheat	Rice	Sorghum	Soybean	Potato	Sum
Prescaling	2.80	1.88	1.99	0.60	0.66	0.41	8.41
Postscaling	5.09	3.36	3.56	1.07	1.18	0.74	15.01

Table 16. *P demand from nodes for 6 crops (56%) and scaled to match all crops (100%)*

Table 16. *P demand from nodes for 6 crops (56%) and scaled to match all crops (100%)*

The proportional contribution of each producer or consumer to the net sum of production or consumption is plotted in Figures 24 and 25.
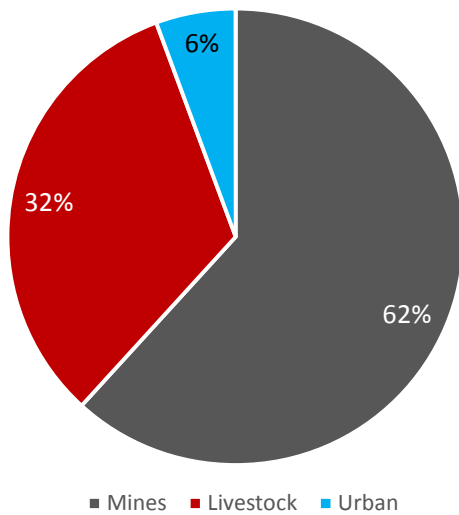

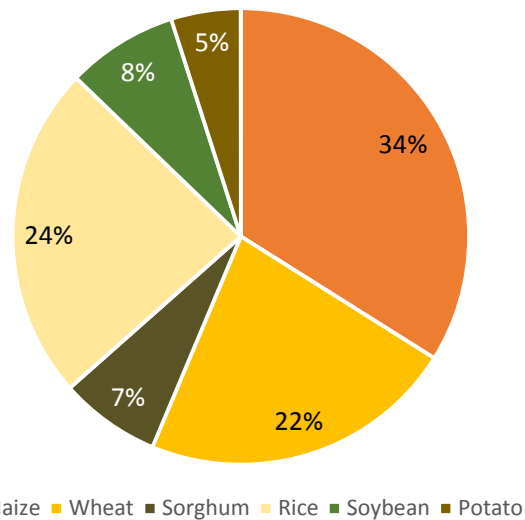**Figure 24**. *Proportion of P supply from different sources.*

Figure 25. *Proportion of P demand from different crops*

The contribution of each recovered source to the global demand for the six major crops as well as the scaled, total agricultural demand, can be approximated (Table 17). Table 17 shows that recovery from all sources can fully satisfy the fertilizer demand for six major crops, and for 69% satisfy the entire global agricultural demand. The effect of recovery from urban sources is limited, with a maximum potential to satisfy only 18% of the demand for 6 major crops and 10% of the global agricultural demand.

	Agr. Demand	Urban	Livestock	Urban + Livestock

	[Mt] P	[%]	[%]	[%]
Pre-scaling (6 major crops)	8.41	18	105	123
Post-scaling (All crops)	15.01	10	59	69

Table 17. *Contribution of recovered phosphorus to global demand for 6 major crops and approximated total demand for all crops.*

While this simple methodology gives some insight into the maximum capacity potential of phosphorus recovery, it is more interesting to consider the realistic influence of economic variables on this potential.

4.3. Economic Feasibility for Recovery

As described in the Materials and Methods, the model-determined economic feasibility for recovery depends on a number of variables. The most important of these variables are the production costs of the supply node and the transportation distance to the buying demand nodes. Depending on how these variables compare with respects to competitor nodes, a production node may or may not be competitive in the market at a given market price.

4.3.1 Determination of Optimal Prices

Table 18 and Figure 26 show the minimum production cost ranges as determined through the equation in section 2.4, for each different source.

Production Costs

	Min [$/t]	Max [$/t]	Median [$/t]
Livestock	1,266	1,521	1,291
Urban	575	998	631
Mines	321	1023	353

Table 18. *Production cost ranges per source*

Mines can offer phosphorus at significantly lower prices than other sources can. Livestock and urban recovered phosphorus costs approximately twice to four times as much to produce per tonne. With established, minimum production costs for each supplying node, it is now possible to estimate the quantity of trade at different prices.

Figure 26. *Production costs by supply type.*

The following numbers and colours are indicative for each scenario for the figures that follow.

1. ⬛ **[red]** Current Scenario   *Mine supplied P only*
2. ⬛ **[blue]** Future Scenario   *Mine and sustainably supplied P*
3. ⬛ **[green]** Far-Future Scenario   *Only sustainably supplied P*

Figure 11 (pag 24) shows the combined supply-demand curves variation of the amount of phosphorus traded globally, at different modelled prices for each scenario. It can be seen that not the entire global demand can be met by sustainable sources only as per far-future scenario (Figure 27). It is also observed
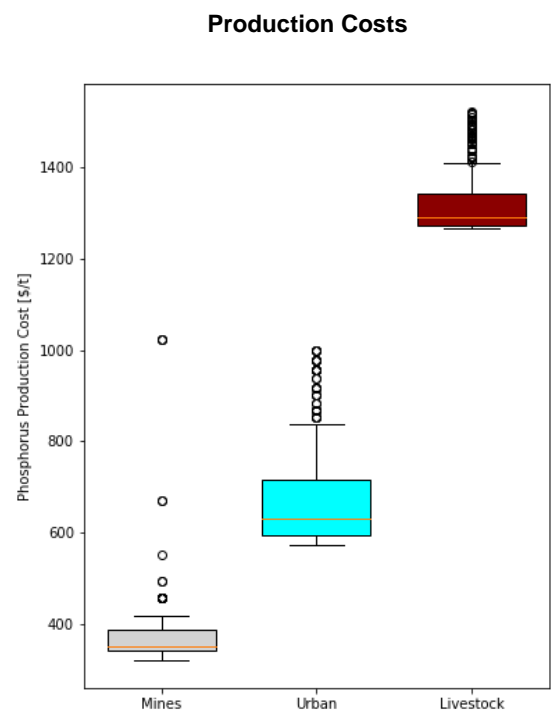
that the global demand can be met along a greater range of prices when sustainable struvite precipitants supplement the rock phosphate-based market.

2005 Quantity Traded vs. Price

Figure 27. *Quantity in market vs. Price for three scenarios in 2005.*

Table 19 lists the price ranges and amount traded in each scenario for 2005. The minimum and maximum limits mark the prices at which 95% of maximum trade can still be met, thereby accoutning for a small potential error in optimum price determination.

| | Determined Phosphorus Price | | | Amount Traded | |
| | Minimum | Optimum | Maximum | At optimum | |
	[$ t^{-1}]	[$ t^{-1}]	[$ t^{-1}]	[Mt]	[%]
Scenario 1	1,000	12,56	2,100	15.01	100%
Scenario 2	900	1,282	2,100	15.01	100%
Scenario 3	1,600	2,133	2,400	10.31	69%

Table 19. *Price ranges and amounts traded per scenario for 2005.*

4.3.2 Price Validation

Given that the model is temporally flexible, it can be run for any year or scenario - provided it is supplied with input data for that year or scenario. Some validation of its temporal flexibility can be done by comparing the model results of different years to those years' observed prices. Unfortunately, because of the many data limitations on livestock and even population density maps for other years, it is difficult to consistently change all the input data for each to-be-evaluated year. By manually adjusting some of the major parameters to approach the reported statistical figures of those years, however, a simple validation can still be executed. In addition to the original simulation year of 2005, this has been done for the year 2006, 2011 and 2015. Table 20 summarizes the manually applied changes to the model parameters.

Parameter	Units	2005	2006	2011	2015	Source
Cost of RP production	[$ t^{-1}]	40	40	197	115	IndexMundi, 2017
Human Population	[h]	100%	101.5%	109%	115%	-
Livestock	[h]	100%	101.9%	111%	119%	FAO, n.d.
Crop Price Change	[$ t^{-1}]	146	156	229	210	IndexMundi, 2017
Diesel Fuel Price	[$ l^{-1}]	1.05	1.12	1.34	1.29	IndexMundi, 2017
Bunker Fuel Price	[$ t^{-1}]	173	231	485	614	World Scale, 2017

Agricultural Demand[8]	[MHa]	1.14	1.15	1.25	1.27	FAOSTAT, n.d.
Mine Production	[Mt]	147	142	198	241	USGS Min. Com. Summaries

Table 20. *Changed parameters for validation*

Figure 28shows the variation in prices for the different simulation years (scenario 1: red; scenario 2: blue; scenario 3: green) with the observed and reported data (light grey). The boxplots are separated vertically by year.
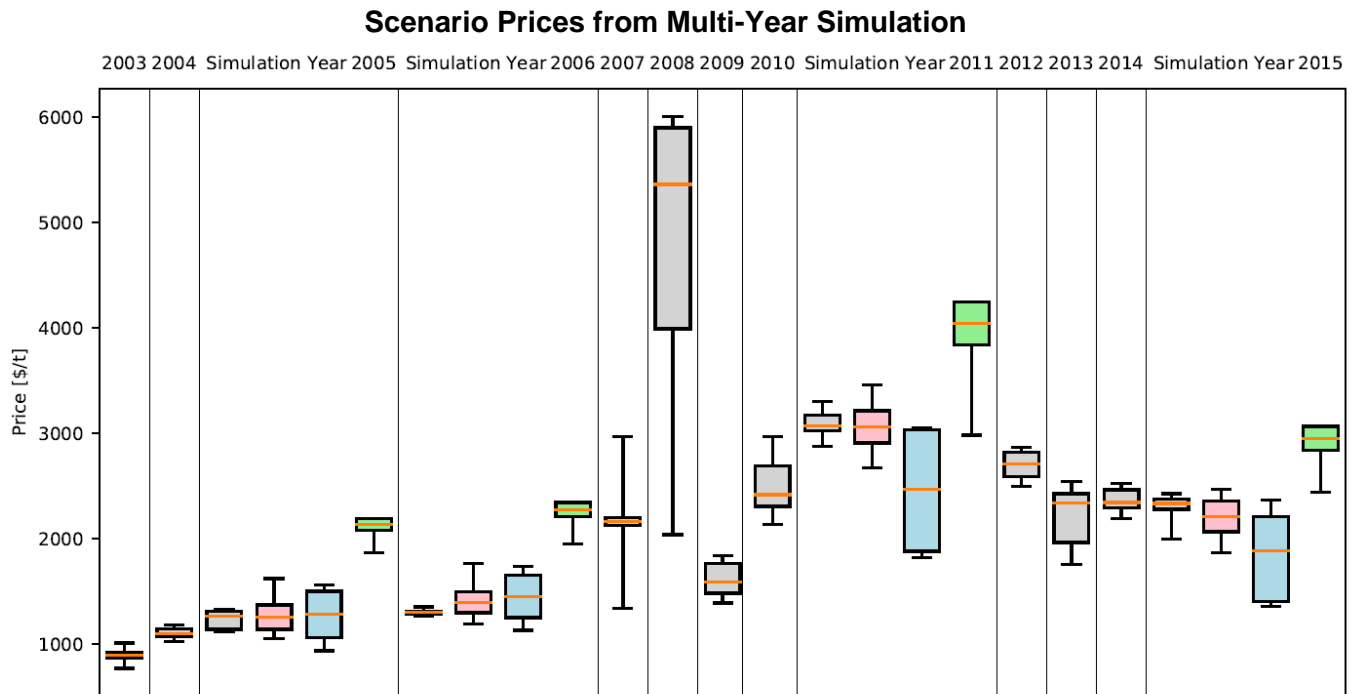

Figure 28. *Comparison of observed (light grey) vs. modelled (Scenario 1, pink Sc. 2, blue; Sc. 3, green) phosphorus price ranges. Noticeable are the accurate price determinations for the current mines only scenario. Scenario 2 and 3 cannot be compared, but show predictable and realistic behaviour.*

Naturally, the representation of Figure 37 is somewhat misleading, as the boxplots that show the modelled data do not have the statistical foundation by which the boxplots for the observed prices are made. Nevertheless, the price estimation by the procedure employed in this investigation results in fairly accurate price approximations. There is no observed price data for the validation of the hypothetical scenarios 2 and 3, so little can be said on that. What can be observed is that they show predictable and realistic behaviour, and that their price ranges are within acceptable bounds.

4.3.3 Trade Flow Patterns

Network maps have been created to show where phosphorus recovery is feasible and at what market prices. The network maps for the optimum market prices as presented in table 19, are presented in Maps 7, 8, and 9 respectively.
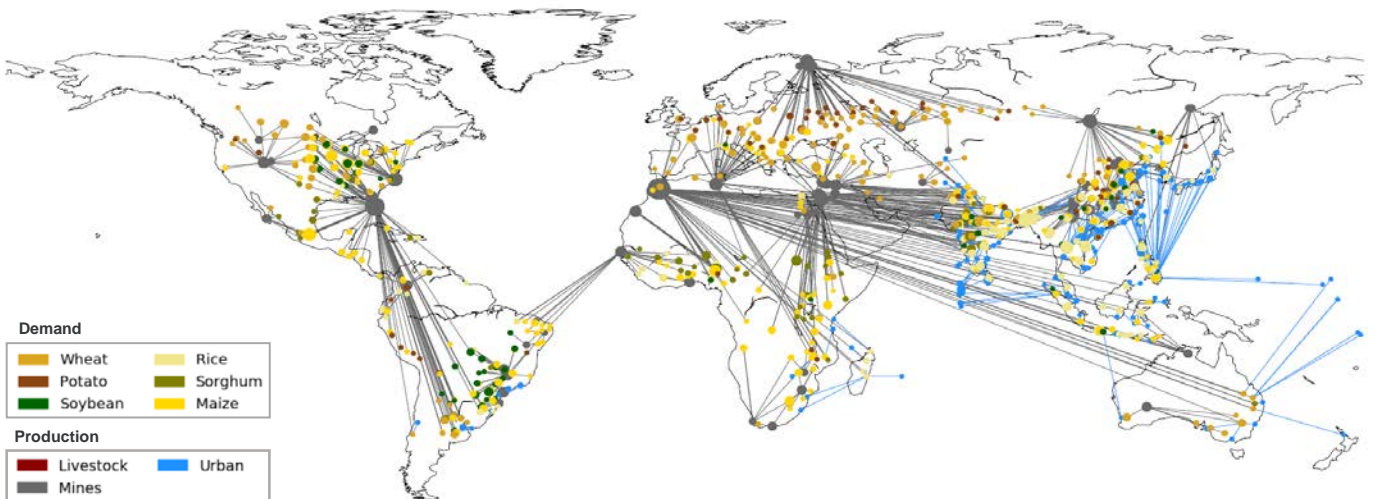
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[8] As Increase in Net Agricultural Production Index.
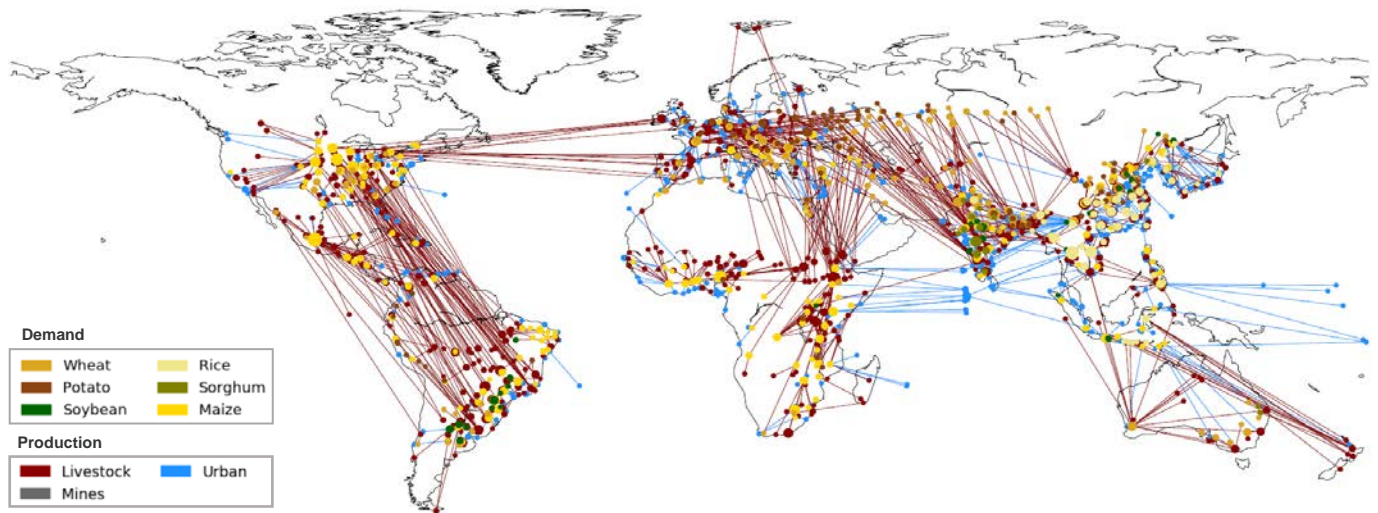
Scenario 1 Optimal Trade
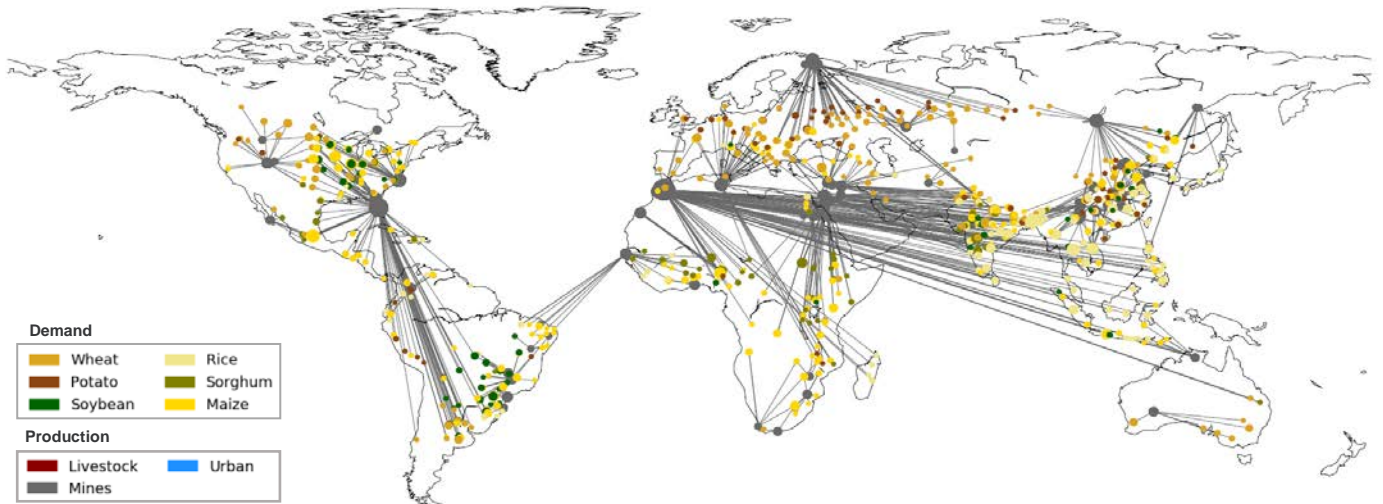
Map 7. *Phosphorus trade network for scenario 1 at a phosphorus price of 1,256 [$ t^{-1}] with 15.01 [Mt] being traded in total.*

Scenario 2 Optimal Trade

Map 8. *Phosphorus trade network for scenario 2 at a phosphorus price of 1,282 [$ t^{-1}] with 15.01 [Mt] being traded total and 1.09 [Mt] traded sustainably.*

Scenario 3 Optimal Trade

Map 9. *Phosphorus trade network for scenario 3 at a phosphorus price of 2,133 [$ t⁻¹] with 10.35 [Mt] being traded in total.*

The subnational resolution of the study makes presentation of results on a global scale difficult. Therefore, with the locations of phosphorus recovery from wastewater being the primary interest for this study, the second and third scenario's are merited a more elaborate presentation of results.

4.3.1 Scenario Two

The second scenario market includes all sources of phosphorus. In this scenario, the entire agricultural demand can be met by the total supply. Assuming a small error of 2.5%, the following prices (Table 20) will allow for at least 97.5% of maximum phosphorus trade.

		Min		**Opt.**				**Max**
Price	[$ t⁻¹]	1,000	1,200	1,282	1,400	1,600	1,800	2,000
Traded	[Mt]	14.83	14.96	15.01	15.01	15.01	14.95	14.74
Sustainably Traded	[Mt]	1.09	1.09	1.09	1.09	1.09	1.09	1.09
Percent Sustainable	[%]	7.3	7.3	7.3	7.3	7.3	7.3	7.3

Table 20. *Prices and associated amounts traded for second scenario.*

It is observed that the quantity of sustainable trade does not increase beyond 1.09 [Mt]. Presumably, the majority of economically feasible urban recovered phosphorus is then already in circulation for the parameters of 2005.

Filtering out the unsustainable trade from the network visualization, will allow for an easier identification of the areas of interest for phosphorus recovery. Map 10 shows the locations of competitive phosphorus recovery nodes at a phosphorus market price of 1,000 [$ t⁻¹] - the lowest price of the optimal price range that will allow for 95% of maximum trade. The high recovery potential and close proximity of recovery nodes to agricultural demand nodes, makes phosphorus recovery in China, Korea, Japan, India, Philippines, SE Australia, SE South America, SE Africa and some parts of Indonesia, the most competitive in a market that offers rock phosphate alternatives. The limited potential of Chinese mines to supply all of Asia and the distance to alternative mines in Morocco and Florida, contribute to the competitive advantage of recovered phosphorus in the region. The mine locations appear decisive for the inability of recovered products to compete on European, North American and African markets at this price. The high population densities that are found in relative close proximity to agriculture also contribute to making recovery in Asia particularly competitive.

Scenario 2 Visualizing Sustainable Flows at $1,000 Market Price
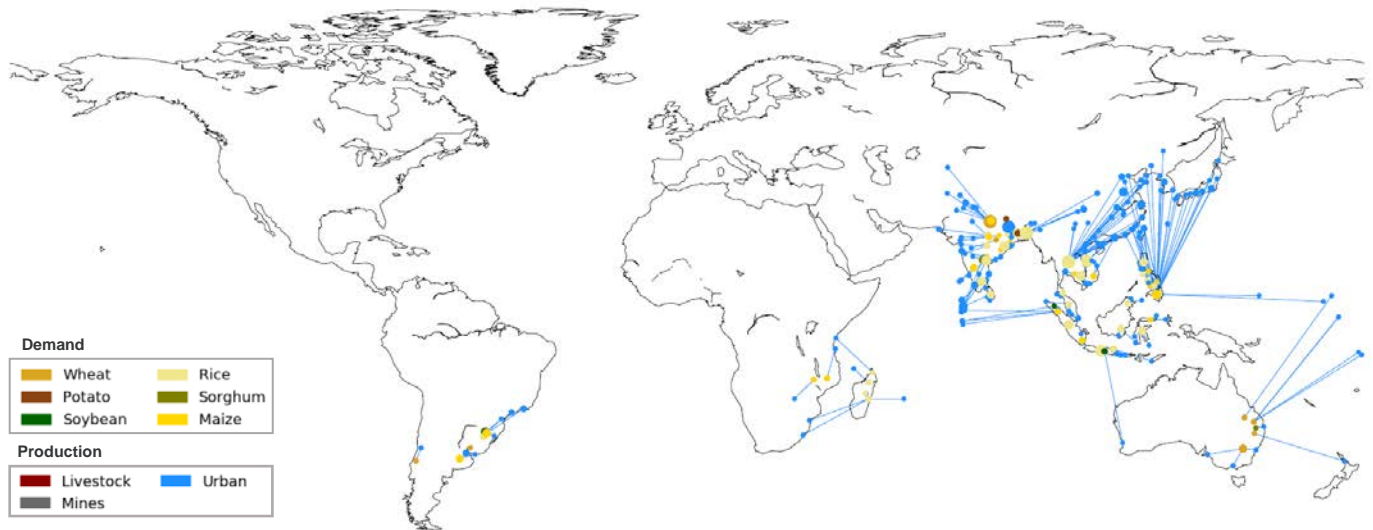
Map 10. *Sustainable trade for scenario 2 at a phosphorus price of 1,000 [$ t⁻¹], with 1.09 [Mt] sustainably traded.*

4.3.2 Scenario Three

Recovered phosphorus from (urban and livestock) wastewater is considered as the only source in the third scenario, and, with this, only 69% of the global agricultural demand can be met. The price range allowing for 97.5% of this maximum trade is presented in Table 21.

Table 21. *Prices and associated amounts traded for third scenario.*

		Min			Opt./Max
Price	**[$ t⁻¹]**	1,600	1,800	2,000	2,070
Traded	**[Mt]**	10.19	10.31	10.31	10.31

Map 11 shows the most competitive nodes of all recovery nodes. At prices as low as 700 [$ t⁻¹], these nodes could already partake in the market supplying 1.38 mega tonnes of phosphorus. In the absence of rock phosphate mines, the world turns to a widespread recovery of phosphate from wastewater to fertilize maize, which has the highest return on P-fertilization. It is noticeable that struvite from Japan could become an export product to China, supplying the Manchurian agriculture. What is also noticeable is the general trend of phosphorus flows from the densely populated coastlines, into the continental inlands.

Maize	0.2	97	17	22
Wheat	0.17	141	10	15
Rice	0.07 (KOSTAT, 2015)	288	8	15
Sorghum	0.17	97	12	15
Soybean	0.12 (Purdue University, 2017)	250	5	35
Potato	0.09 (UNIDO & IFDC, 1998)	100	50	35

Scenario 3 Visualizing Most Competitive of Recovery Nodes
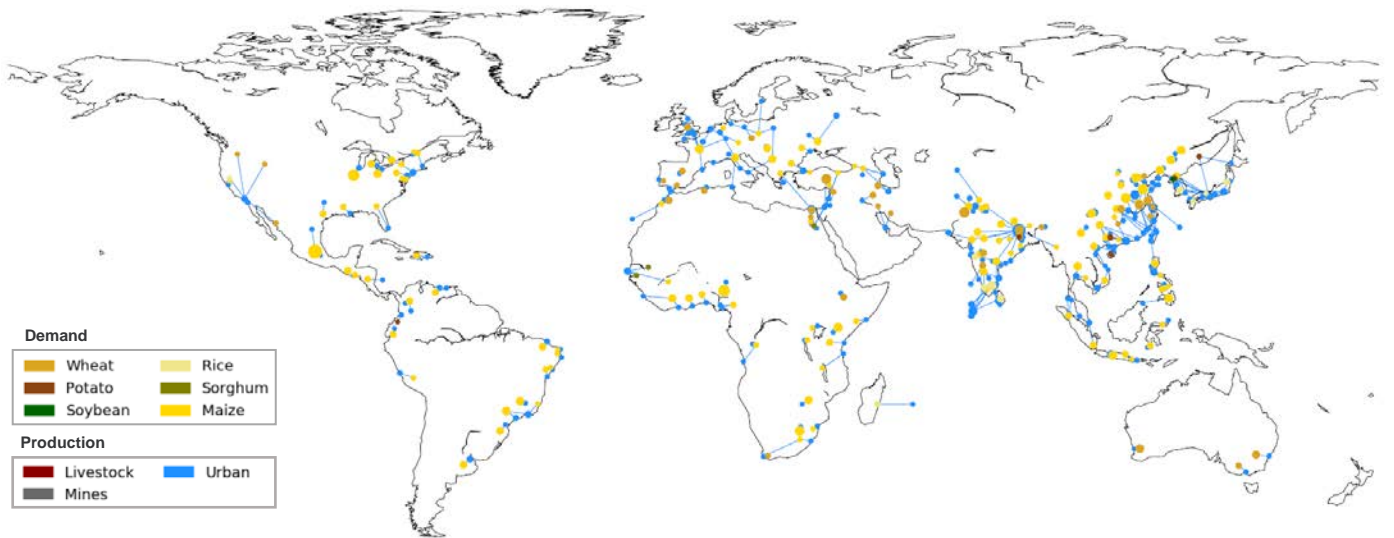
Map 11. *Sustainable trade for scenario 3 at a phosphorus price of 700 [$ t^{-1}] with 1.38 [Mt] of sustainable trade*

4.4. Transportation Emissions

The transport distances between nodes are determined as straight lines. Considering this simplification applies to all node pairs, regardless of their origin, some realistic approximation of the comparative and proportional difference in transport associated CO_2 emissions, between the different scenarios, can be made. Figure 30 shows how the total CO_2 emissions vary per scenario, per market price. The black dotted line intercepts each curve at the point where optimal trade is occurring as defined previously in Table 19, page 49. The global quantity of transport associated CO_2 emitted for these prices are summarized in Table 22. The solid part of the line shows the range that allows for 95% of maximum trade. As the total amount traded varies per scenario, it may be of interest to consider the amount of CO_2 emitted per tonne of phosphorus traded phosphorus, as well. This is determined by dividing the total cumulative CO_2 emissions by the total amount of phosphorus traded at optimal price (Table 22).

CO$_2$ Emissions by Transportation vs. Market Price
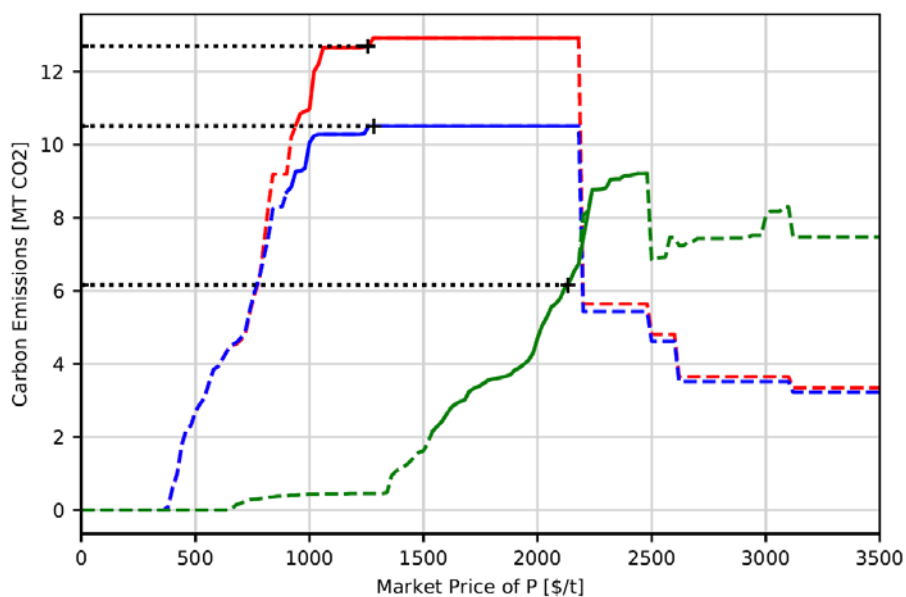

Figure 30. *Cumulative transport distance at different prices, for different scenarios. Black line intercepts curve at optimal price.*

'

	Total CO$_2$ [Mt]	Reduction [%]	Transport CO$_2$ per P [kg t^{-1}]	Reduction [%]
Sc. 1	12.67	0	847.5	0
Sc. 2	10.51	17	700.2	17
Sc. 3	5.48	57	531.5	37

Table 22. *CO$_2$ emissions at optimal prices.*

Struvite (~14% P) is less dense in phosphorus than DAP (~20% P). This implies that a greater mass of struvite needs to be transported for the same amount of phosphorus demand. Despite this, comparing the first and second scenario with each other, it is remarkable that the 1.09 [Mt] of phosphorus sustainably traded (7% of total traded) in the second scenario, still results in a drop in CO$_2$ emissions of 17% when compared to the mines only scenario. The introduction of recovered phosphorus to the current market therefore reduced the transport sector's total carbon footprint by 2 mega tonnes despite that technically more is transported. As the most isolated agricultural nodes are the first to acquire locally recovered phosphorus products from the more geographically spread urban and livestock nodes, it appears that a significant drop in transport distance appears to far outweigh the effects of the additional volume that need to be transported. Even though not nearly as much phosphorus is traded in a market scenario of only recovered phosphorus, the proportional reduction in CO$_2$ per tonne phosphorus is significant. The per tonne amount of CO$_2$ is reduced from 850 to 530 in a recovered P only scenario (3) – and that is not even including the CO$_2$ savings from the mine extraction and fertilizer production chain.

While these numbers give some indication of the CO$_2$ emissions, realistically, these values will likely be much greater. The CO$_2$ emissions per trade varies largely by the distance that needs to be bridged. The total distance transported will in fact be much greater when trucks and ships have to follow and existing infrastructural network of roads and shipping routes, as opposed to the straight lines that currently determine the emissions. Especially the total carbon footprint of transport in a mine supply only scenario (1) is expected to be significantly higher considering that carriers often have to make long detours past capes, peninsula's, and entire continents in getting to their destinations all over the world. Furthermore, while CO$_2$ emissions are naturally important given the many benchmarks, NO$_x$ and fine particulate are at least worth a mention also. The reduction in cumulative transportation distances in the far-future scenario will likely result in a decrease of these and all other forms of emissions, thereby offering yet another benefit to the recovery of phosphorus from wastewater over conventional, non-sustainable sources.

4.5. Financial Policy Measures

Global trade in sustainable phosphorus products can be stimulated through financial policy measures. These may take form as subsidies for recovered products or tax penalties for mine-based products. Also, as the long transportation distances from mines put mine-based products at an inherent disadvantage to the geographically spread wastewater products, changes in fuel price may be of significant benefit to recovered products also. This sub-section explores the model's sensitivity to varying these financial parameters.

4.5.1 Sustainable Subsidy

As a supporting measure, governments may choose to implement a subsidy for sustainable fertiliser use. In this part of the sensitivity analysis, the cost of Magnesium Chloride - the primary ingredient for struvite precipitation in this study - is subsidized at 20, 40, 60, and 80% of the original cost of 250 [$ t^{-1}] MgCl$_2$. This results in a reduction of this component of struvite precipitation cost by $ 50 at each interval. Figure 31

shows the effect of a subsidy on the optimal market price for scenario 2, where all supply nodes partake in the same, single market.
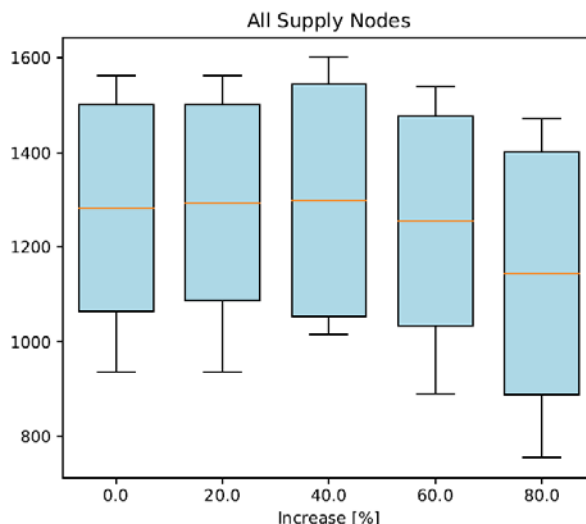

Figure 31. *Changes in price for Sc. 2 at varying subsidies.*

Subsidization is implemented to promote sustainable phosphorus consumption over rock derived phosphorus use. Table 23 presents the proportion of sustainable trade for the different intervals for scenario 2 and the associated total costs.

				Scenario 2 Varying Subsidies for MgCl$_2$			
Subsidy	**MgCl$_2$ Cost**	**Market Price**	**Total Traded**	**Sustainably Traded**	**Percent Sustainable**	**Total Subsidy Cost**	**Marginal Subsidy cost**
[%]	**[$ t^{-1}]**	**[$ t^{-1}]**	**[Mt]**	**[Mt]**	**[%]**	**[million $]**	**[kg $$^{-1}$]**
0	250	1,282	15.01	1.09	7	0	0
20	200	1,294	15.01	1.24	8	186	0.8
40	150	1,299	15.01	1.54	10	462	1.0
60	100	1,255	15.01	1.78	12	801	0.9
80	50	1,144	15.01	2.95	20	1,770	1.1

Table 23. *Prices and quantities traded for Scenario 2 while varying subsidies for MgCl$_2$*

Sustainable trade is most significantly and efficiently fostered at the highest subsidy of 80%, where 1.1 kg of phosphorus is additionally traded per dollar of subsidy invested. This investment amounts to 200 [$ t^{-1}] MgCl$_2$, of which three tonnes are required per tonne of P in struvite, resulting in 1.7-billion-dollar cost worldwide. A lower, but nearly as efficient, subsidy is that of 40%, which results in 150,000 tonnes of extra sustainable trade at 1 kg of P from struvite extra, per dollar of subsidy invested.

The total effect of a Magnesium Chloride subsidy, however, appear minimal for all rates. Although it is a cheap measure, the bureaucracy and implementation costs will likely outweigh the benefit.

4.5.2 Rock Phosphate Tax

As a punitive measure, governments may choose to implement a tax on rock-based fertilisers. In this part of the sensitivity analysis, the production cost of DAP is taxed at 20, 40, 60 and 80% of the exploitation cost of 381 [$ t^{-1}] mined P. This results in increase of this component of the mine exploitation cost by $ 76 at each interval.

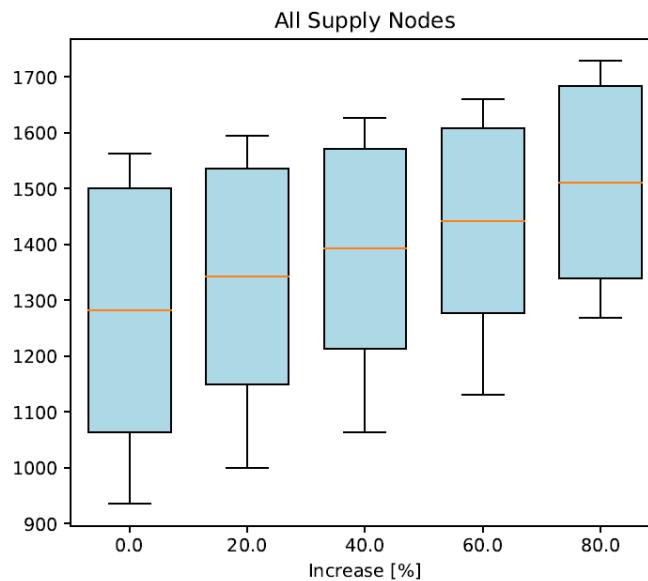**Figure 32.** *Changes in price for Sc.2 at varying taxes.*

Figure 32 shows a steady increase in market price with the introduction of taxes for this scenario. A summary of the effect of the taxation on the sustainable component of trade in this scenario is presented in Table 24.

Scenario 2 Varying Taxes for Mine Exploitation

Tax [%]	Exploit Cost [$ t^{-1}]	Price [$ t^{-1}]	Total Traded [Mt]	Sustainably Traded [Mt]	Percent Sustainable [%]	Total Public Gain [million $]	Marginal Benefit [$ kg^{1}]
0	381.0	1,282	15.01	1.09	7	0	0
20	457.2	1,343	15.01	1.13	8	1,058	0.04
40	533.4	1,392	15.01	1.22	8	2,102	0.06
60	609.6	1,443	15.01	1.28	9	3,139	0.06
80	685.8	1,511	15.01	1.45	10	4,133	0.09

Table 24. *Prices and quantities traded for Scenario 2 while varying taxes on mine exploitation.*

The influence of a tax on the exploitation cost is again minimal considering the small improvement in sustainable trade. Where 7% is sustainably traded at no tax, only 8% is traded sustainably at 20% tax. The global phosphorus prices increase with each tax increment, but the total global demand can still be met at all of these prices. Once the global demand cannot be met, it is likely that it will result in an increase in food prices instead so that the demand *can* still be met. The data above implies that perhaps the transportation cost or yearly fixed cost component of phosphate mines play a more important role in determining the competitivity of unsustainable phosphorus products, or that no single variable is all determining in enabling the economic feasibility of world-wide struvite recovery.

4.5.3 Transportation Tax

Considering the long transport distances for mined phosphorus, fuel price may be of significant influence on also. In this part of the sensitivity analysis, fuel for transportation is taxed at 20, 40, 60, and 80% of the original diesel and bunker costs of 1.2 [$ l^{-1}] and 250 [$ t^{-1}] respectively. This results in increase of the fuel cost component of transportation by 0.24 [$ l^{-1}] and 50 [$ t^{-1}] at each interval.
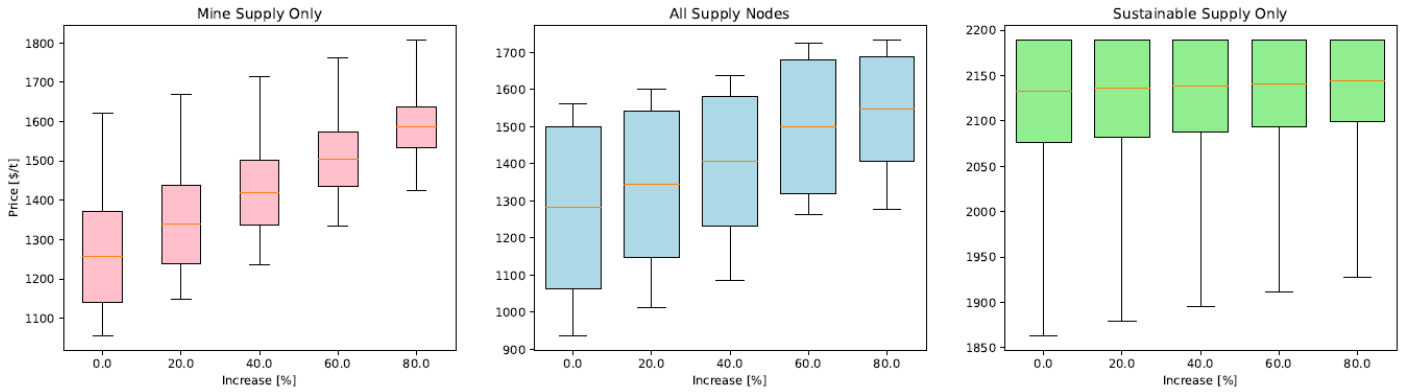
Figures 34, 35 and 36. *Price progression while varying a fuel tax for scenario 1, 2 and 3 respectively.*

Figures 34 and 36 demonstrate that the global market prices for fertilisers from mines (scenario 1), where market prices increase much more drastically, are much more susceptible to changes in fuel prices than recovered phosphorus (scenario 3). Table 25 shows how the proportions in trade vary when both sustainable and non-sustainable sources partake in the same market (scenario 2).

Scenario 2 Varying Taxes on Fuel

Tax [%]	Price [$ t^{-1}]	Total Traded [Mt]	Sustainably Traded [Mt]	Percent Sustainable [%]
	1,282	15.01	1.09	7
20%	1,343	14.97	1.14	8
40%	1,407	14.88	1.25	8
60%	1,500	14.79	1.55	10
80%	1,548	14.76	1.99	13

Table 25. *Prices and quantities traded for Scenario 2 while varying taxes on mine exploitation.*

Like with DAP prices, fuel prices also fluctuate significantly within a year and within a decade. In 2011, the price for crude oil was approximately $ 104 dollars per barrel, while four years later, in 2015, it was less than half that, namely $ 49 (MacroTrends, 2017). The prices of bunkers and other refined oil products can fluctuate even more. Ship 'fuel oil (*380 cst)'* cost approximately 173 [$ t^{-1}] in 2005, and 614 [$ t^{-1}] (355%!) in 2015 (World Scale, 2017). An 80% increase in fuel costs already nearly doubles the amount of sustainable trade (1.09 [Mt] to 1.99 [Mt], and is therefore likely the best cost-component to manipulate by policy in encouraging sustainable products over non-sustainable ones.

5 Discussion

Although the model offers concrete answers to the study objectives, there are many points to consider when evaluating its products. This section of the thesis presents how the findings compare with other studies (5.1), the weaknesses of the investigation in setup and methodology (5.2), and a summary of recommendations for similar, future studies (5.3).

5.1. Other studies

While there are no similar global phosphorus trade studies at subnational resolution, there are studies on phosphorus recovery potentials and struvite pricing whose results can be used to compare with the model output. There exist a handful of studies on phosphorus recovery potentials that all share similar conclusion. The general consensus is that current, maximum phosphorus recovery from humans currently amounts to approximately 3 P [Mt], as first determined by Smil (2000). This then accounts for a 20-25% of the global agricultural, phosphorus demand. Below is a short summary of how the results of some studies compare to the results of this investigation.

Shu et al., 2006 approximate that at a world population of 7 billion people, at human phosphorus excretion rates of 0.91 PO_4^{3-} [kg a^{-1}], 2.69 P_2O_5 [Mt] is maximally recoverable. This translates to roughly 1.18 P [Mt] , as opposed to this study's 3.31 P [Mt] – more than double. This is not surprising given that Shu et al. apply rates of 0.3 P [kg a^{-1}] P, as opposed to this study's 0.77 P [kg a^{-1}] - or at WWTP recovery rates of 85%, 0.65 P [kg a^{-1}]. This difference in excretion rates causes a large difference of 2.13 [Mt] P in approximated, maximally recovered phosphorus. Shu et al. also estimates an agricultural demand of 26 [Mt] P, with 1.48 billion hectares of arable land (Wild, 1993) that have a flat-rate fertilizer requirement of 40 P_2O_5 [kg ha^{-1} a^{-1}]. This study's crop phosphorus demand is approximately 10 P [Mt] less, with rates corrected for water limitations, which amount to a total of only 17 [Mt] of agricultural phosphorus demand -more closely resembling Heffer's (2009) reported fertilizer use estimate of 16.7 [Mt] P for 2006.

Mihelcic et al. (2011), through a study on diets and phosphorus excretion, concludes that the phosphorus excretion rates per individual can vary as much as from 0.18 P [kg a^{-1}] in the Democratic Peoples Republic of Congo to 0.73 P [kg a^{-1}] in Israel. This confirms that our 'western' approximation for phosphorus excretion of 0.77 P [kg a^{-1}] is on the global high end. For 2009, nonetheless, Mihelcic approximates that 3.4 P [Mt] of human waste produced could account for 22% of the 15 P [Mt] global phosphorus demand. These values are in good range to the approximated 3.31 P [Mt] urban waste and 17 P [Mt] phosphorus demand of this study, yielding a slightly lower, 19% (as opposed to 22%) potential satisfaction of global demand through human recovered waste.

Koppelaar and Weikard (2013) estimate the potential of use reduction and recycling measures on the global phosphorus balance through a flow model for 2009. In this balance, the phosphorus loading into human excreta amounts to 4.2 P [Mt], which is 25% of the agricultural demand by their usage of IFA's (2012) approximated, agricultural phosphorus demand of 16.7 P [Mt]. The total domestic animal manure production is estimated at 28.3 P [Mt]. This is significantly higher than this study's 14.38 P [Mt] livestock P production. This study limits livestock production to that of cattle, swine and poultry excreted phosphorus, with recovery rates of 75-85%, and a cattle stable and pasture period of 180 days. Provided the aggregation of beef and dairy cattle in the population density map, and the significant difference of phosphorus excretion rates of both beef and dairy cattle, it is not unlikely that the phosphorus production rate of all cows is in total much higher than currently approximated.

Though there exists a general consensus on the maximum potential of phosphorus recovery and the potential contribution to agricultural demand, no study has evaluated the potential of recovery at global scale given the price dynamics of the phosphorus fertiliser market. Instead, there exist a few studies that have executed case-studies on the feasibility for phosphorus recovery, which are presented below.

Price estimates for competitively recovered struvite vary. Struvite obtained from wastewater in Japan is sold to fertilizer companies at rates of 300 [$ t^{-1}] (Ueno & Fujii, 2001). A market study by Münch and Barr (2001) reveals that struvite can be sold in Australia for between 220 and 370 [$ t^{-1}], while Shu et al. (2006) estimates that the market price of struvite is around 550 [$ t^{-1}]. Based on fertilizer market estimation, Dockhorn (2009) approximates far higher than the aforementioned prices, and values recovered struvite at 900 [$ t^{-1}]. Translating these struvite prices into prices per tonne phosphorus, and plotting these, as well as the model predicted optimal price ranges for global phosphorus recovery, against the observed and predicted price of phosphorus from DAP, yields Figure 38.
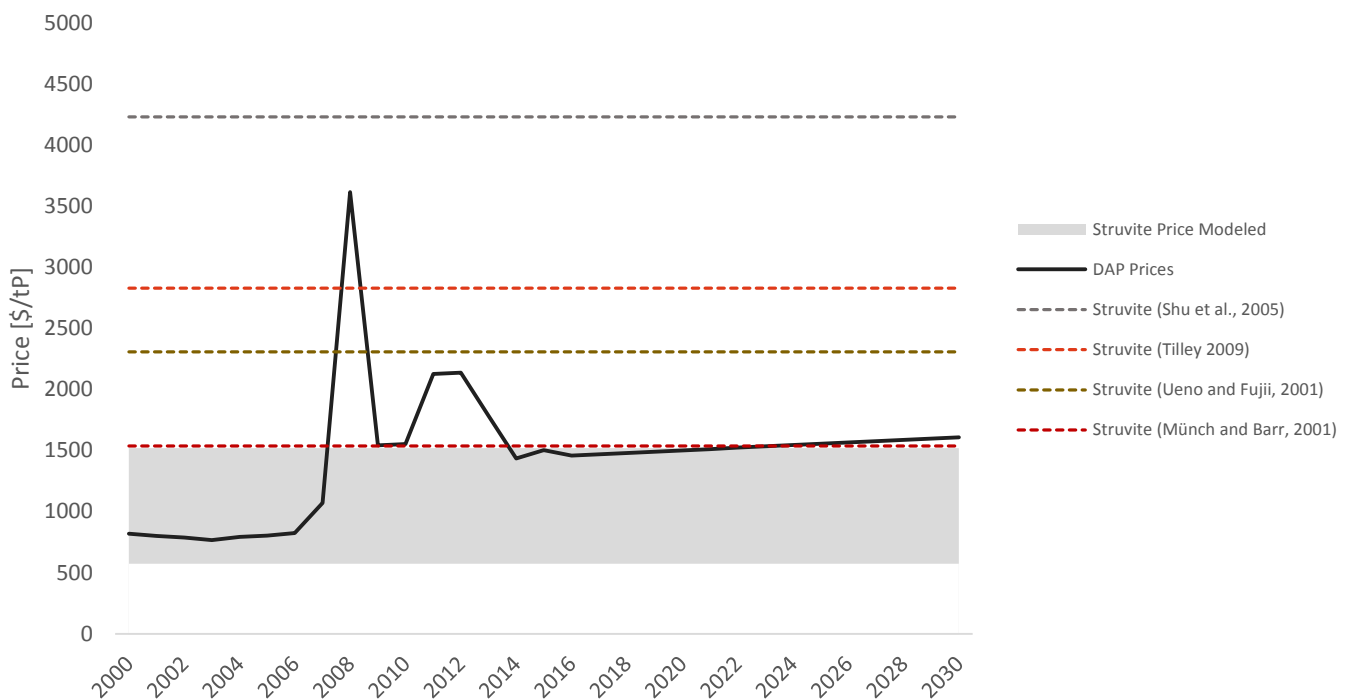

Figure 38. *Competitive phosphorus from struvite market prices from literature and the model compared to conventional DAP phosphorus prices.*

It is noticeable that the model determined price range for struvite production is below the production cost as determined by the other studies. There are numerous possible reasons for this, the foremost being a difference in methodology or in defining what is or is not included in the struvite price. The model defined price range for struvite is: 1) determined for the most phosphorus intensive production sites in the world; 2) explicitly does not include transportation cost; 4) incorporates the reduction in operational maintenance of 600 [$ t^{-1}] P that comes with phosphorus recovery (Shu et al., 2006); 5) assumes no profit - revenue equals costs; 6) assumes annual operational costs of 176,000 [$ a^{-1}] (L. A. Egle, n.d.); and 7) imposes a standard cost for magnesium of 1,246 [$ t^{-1}] P (Seymour, 2009). Munch and Barr (2001) already assume higher magnesium costs of 330 [$ t^{-1}] Mg, while the cost calculation details for most other studies is either unclear or undiscussed.

From research, it appears that there are no other, published studies in the databases on the creation and modelling of trade interactions of phosphorus production and consumption sites globally at a sub-national

resolution. This introduces a lack of materials for comparison of the trade flow maps. Map 13 and 14 at national resolution, nevertheless, can give some indication of the spatial organisation of phosphorus trade.

Map 13 shows a general fertilizer trade map for 2015 that has been developed by ICIS and IFA (ICIS & IFA, 2015). Phosphorus trade can be identified in the components of RP (orange) and DAP (blue) trade. Noticeable is the absence of transatlantic trade, and the presence of transpacific trade (U.S.A. to India) in DAP. The trade in RP is more abundant and complex, which would suggest that many of the nations have their own fertilizer manufactories as RP is almost never applied directly as fertilizer without any form of processing. India can be identified as a large importer of RP from many different places but especially Jordan; while Morocco is, of course, one of the largest exporters in general. We identify more transatlantic RP trade than DAP trade. Brazil, Mexico, U.S.A. and Canada are all importing from across the ocean, from Morocco. This is something the model doesn't capture, likely because of the disregard for cheaper sea transportation.

Map 14 shows the most major trade flows in phosphatic fertilizers for 2005 (Chatham House, 2017). It again shows different flows than that of the model, as well as that of Map 15. Bangladesh is a major importer of phosphorus while Morocco's export is fairly matched with that of Israel and Tunisia. As this map shows only the most major flows, it is very possible that the visualization of a large number of smaller flows would accumulate to make morocco the biggest exporter of phosphate yet again.

Aggregation of the model's current nodes to a national level would make the dataset more comparable with other sources. This comes at the cost, however, of the fine spatial scale it currently employs. Many intranational, phosphorus dynamics in large countries like China, Russia, Canada and the United States, would be lost in aggregation, and the flow going to or coming from these countries will be different only in magnitude from smaller nations as Andorra or Luxemburg (equal weighting). Provided the high production/demand variability within nations, as well as the significant distances that may have to be traversed in transporting within a large country, an accurate modelling of phosphorus flows requires a resolution finer than that of national scale.
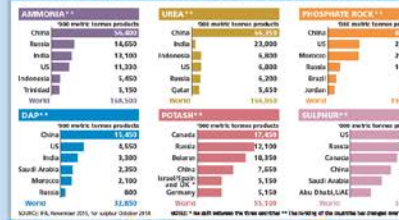
ICIS Global Fertilizer Trade Map
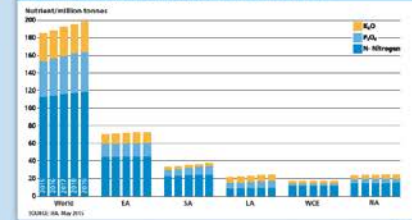

Map 13. *Global fertilizer Trademap* (ICIS & IFA, 2015)

Chatham House Phosphatic Fertilizer Tradeflow Map
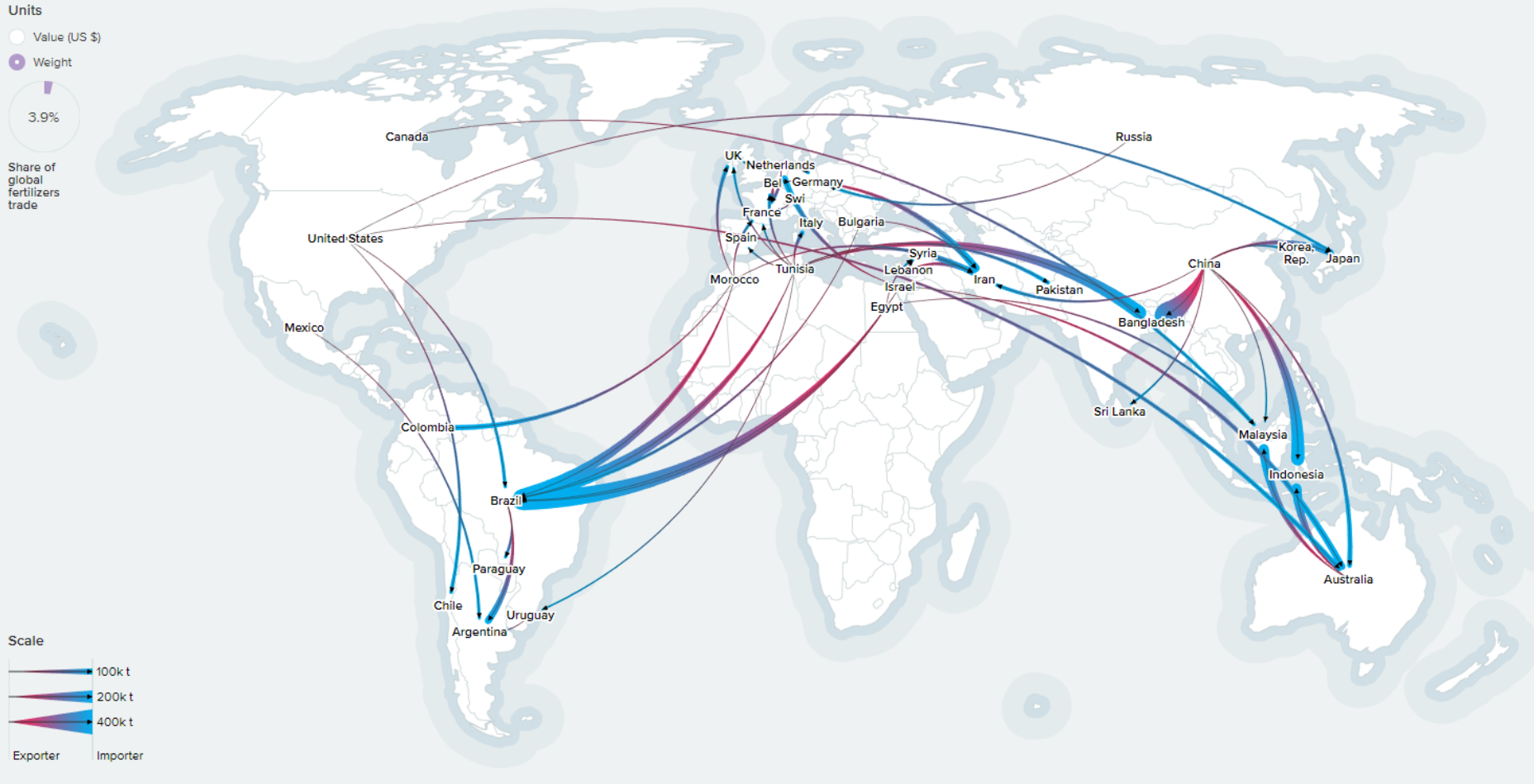
Map 14. *Major phosphatic fertilizer tradeflows for 2005* (Chatham House, 2017)

5.2. Weaknesses

The model has many weaknesses in methodology and setup. Some of the most major implementation errors can be summarized in the: non-spherical earth environment, straight-line transportation distances, and some of the more general assumptions.

5.2.1 Flat-Earth

In the current, flat-earth model, setup the 0/180th degree longitude marks the vertical boundary of the earth system across which cannot be traded (edge of the map). In reality, the earth is spherical and has no non-geographic movement impeding boundaries. In the current 'flat-earth' model, transportation across the 0/180th longitude would require a complete circumnavigation of the earth in the opposite direction. For this reason, one has to be critical of the visualized phosphorus flows at the perimeter of the maps, as these are likely to be subject to some error. Fortunately, however, the 0/180th longitude crosses the middle of the Pacific Ocean, an area with relatively low human population and livestock density, and little to no intensive agriculture. The induced errors in trade paths are therefore expected to be only minor. Yet despite this, in the case of a realistic, spherical-earth environment, it is not impossible to imagine the occurrence of transpacific trade of Japanese, Filipino or pacific island recovered phosphorus to the United States corn belt, especially once U.S. mines run dry.

5.2.2 Straight Path Transport

Another issue that regards transportation in the model, is that of straight path transportation. Transportation paths in the model are shortest, straight line paths, and therefore do not follow existing road or shipping network infrastructure. Although programmatically, the framework to apply Dijkstra's shortest-path algorithm (Dijkstra, 1959) for more realistic transportation along the SEDAC gRoads project road network (CIESIN - ITOS - University of Georgia, 2013) is in place, the processing power required to do this calculation is too great and too precise for the shallow character of this investigation. Instead, saving on processing power, the transportation distances are determined as straight-line distances. Unfortunately, this simplification does induce an error. The transport distances reported by the model represents only a fraction of the actual transportation distances, as realistically there are no straight roads connecting phosphorus mine to agricultural cropland. It was considered to correct the distance by some non-preferential-flow-like parameter, but instead it was decided not to complicate the simple and understandable assessment currently made. In effect, this simplification results in lower transportation prices than what would be observed in reality. Especially due to the geographic concentration of phosphate mines, the transportation cost of mined phosphorus is expected to actually be much higher.

5.2.3 Phosphorus Balance

Due to the multifaceted nature of this study, this report has covered at least aspects of resource management, soil chemistry, sanitary engineering, chemistry, water management, network modelling, and micro- and macroeconomics. As a result, an essential investigative component that has not received the attention and detailing that it deserves is that of the general phosphorus balance. A nutrient flow model would most appropriately be developed for the research question at hand. Yet, for the purpose of the time and economic argument, simplifications and assumptions have been introduced and excused with the emphasis of the study on 'maximum potentials'. This implies that both the phosphorus demands as well as phosphorus production rates are subject to great uncertainty, as they are currently determined independent of each other, while in reality they both take part in one large cycle resulting in feedback on each other.

Apart from the assumptions in production and demand rates, other assumptions adressed in the next section are expected to have an impact on the results also.

5.2.4 Assumptions

The model premises of *potential* allow for several assumptions that make comparison between the modelled results to observed data difficult. Listed in summary, some of the main assumptions and their impacts are presented below:

Free-trade - No trade sanctions, embargoes, import tariffs, quotas or other restrictions are accounted for in the economics of the model. In reality, fertilisers are not a commodity that are often tariffed or subject of an embargoment. Doing so may hurt a nation's food security, and thus the civilian populace, which is often not the intention of such economic warfare. The poorly referenced case of Scandinavian embargoment on the import Western-Saharan phosphorus, however, is an exception to this. The model shows few major agricultural sites for Scandinavia. If there were significant sites, then it is likely that Scandinavia would import from Russia or Finland either way. The model does not account for (economic) politics and from that arises a limited uncertainty in trade pattern.

Non-preferential trade - Nodes select trade partners out of pure economic self-interest and thereby disregard any national interest. In the model, national borders therefore do not play any role except for dividing the production and demand areas in the node creation process. In reality, national markets are sometimes of greater importance than the international market. Implications of this non-preferential trade assumption is significant. It can be observed from Maps 7 and 8 that Chinese agricultural nodes often import phosphorus from Siberian Russia, while Western Russia imports its phosphorus from Finland. In reality, Russian produced phosphorus is used to satisfy much of their own demand and supply the European market instead, while Northern Africa supplies much of Asia (Map 17). Non-preferential trade causes for a disregard of national interest in protecting satisfying national phosphorus demands first, which is uncharacteristic of the observed, global phosphorus trade.

Near-optimal fertiliser management - In the model, farmers fertilize at optimal rates as defined in the IFA and FAO's *Fertilisers and Their Use*. In reality, over-fertilization, under-fertilization, or inability to fertilize altogether, occurs commonly (Map 12). These discrepancies in management practices lead to entirely different geospatial distributions of phosphorus demand than mapped in Map 6. European and American nutrient management is typically characterized by consistent over-fertilization, while fertilizer use in Africa is very low despite the soils nutrient deficiency (Syers et al., 2008; van der Eijk et al., 2006). Since the model determines the optimal phosphorus demand, in reality more phosphorus flows would deviate towards areas over-fertilization than is currently modelled. At the same time, less phosphorus will flow towards areas of under-fertilization assuming persistence of the historical trends. A shifting of international phosphorus trade due to a difference in geospatial phosphorus distribution, as caused by imperfect nutrient management practice by farmers, will almost certainly result in different optimal price ranges. The extent, degree, and direction of changes in optimal price ranges, however, are difficult to evaluate for and therefore remain uncertain.
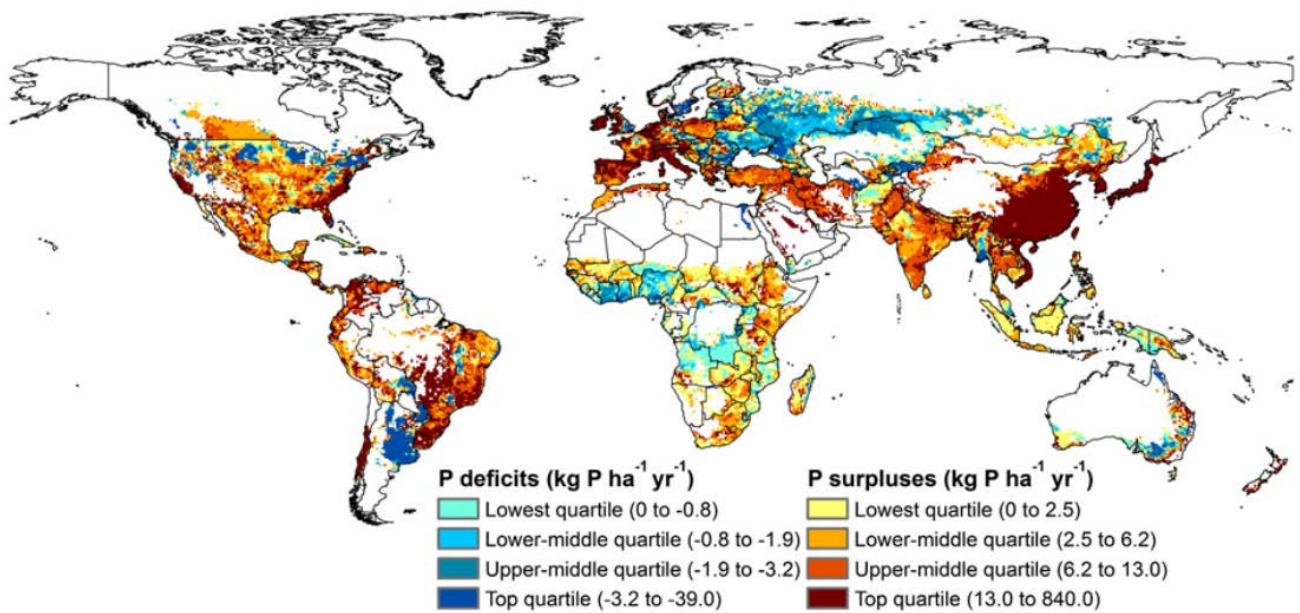
Map 12. *Global map of agronomic P imbalances for the year 2000 expressed per unit of cropland area in each 0.5° grid cell. The P surpluses and deficits are each classified according to quartiles globally (0–25th, 25–50th, 50–75th, and 75–100th percentiles)*(MacDonald et al., 2011)*.*

A second aspect of nutrient management that causes for uncertainty, lies in the soil stored phosphorus. The introduction introduced the complexity of soil-plant-phosphorus dynamics. Constant weathering of soil and crop nutrient uptake cause for surpluses and deficits of phosphorus. Most soils contain some degree of phosphorus and therefore make fertilisation not always necessary. In this study, the choice was made the adopt the nutrient requirement parameters of the IFA and FAO's *Fertilisers and Their Use,* thereby assuming the soil phosphorus reservoir to remain constant and requiring farmers to fertilise for all the nutrients crop need. This also contributes to the uncertainty in the phosphorus demand maps and quantities.

Omniscient actors - It is assumed that all nodes in the model are completely aware of each other's actions and intent. This awareness allows supply nodes to modify their phosphorus sale price according to the behaviour of their competitors and buyers, keeping the net difference as a profit. In reality, not all supply nodes are aware of what prices intermediaries or final beneficiaries are buying phosphorus at. This leads to overpricing or the undervaluation of certain sales, which in reality may lead others to incorrectly adjust their price or not adjust their price at all. In summary, actors of trade are not perfect merchants and do not always know what the other party or their competitors are doing, yet the model assumes them to be such, and assumes them to know precisely what others are doing. Furthermore, the model has all actors trading in the same market. Although there is a significant global economy in phosphorus, the existence of a single market price for all nodes is hardly a believable claim considering the spatial distribution of mines and the significant transport costs. Many smaller markets realistically develop around a global market, which each have their own small influence on the global market - something which the model does not consider. The effect is that the model determined price represents a price not realistic of real-market dynamics, but possibly of a strongly regulated market, with widely available, free information, and highly, economically intelligent actors.

Dual-Actor system - The model recognizes two actors: the producing nodes and agricultural demand nodes. In the absence of fertilizer manufactory nodes, it is assumed that mined phosphorus is processed to DAP fertilizer on mine-site and traded directly to the agricultural demand nodes from there. More realistically, fertilizer manufacturing occurs at different sites, and often by different parties before being

traded to individual trade companies that then sell these products to the farmers. Simplification of the entire process to two nodes allows for an easier evaluation of the phosphorus balances, but represent a false reality when it comes to the dynamics of markets, economies and actual phosphorus flows. A very large fertiliser manufactory is, for example, located near Oslo in Norway. Refined rock phosphate would initially be transported to Norway for further processing, after which it is distributed to warehouses and sold farmers. Additional actors involved, as in reality, would increase the final market price. Including off-site fertilizer manufactories would also drastically increase the total transportation distance of mined phosphorus. This would again put wastewater recovered phosphorus at a logistical advantage over mined phosphorus.

Simplified Economics - The economics involved in modelling the phosphorus market are highly simplified. The model does not account for commodity speculation on phosphorus, inflation rates over the years, monopolies, cartels, price agreements, taxes, subsidies, effects of corporate lobbying or smaller influences on prices such as storage costs. The effects of these vary depending on the nature of each of these disregarded economic variables.

5.2.5 Input Data

A final note should be made with regards to the input data, and especially the phosphorus requirements per crop type. Although the choice has been made to use the phosphorus requirements per crop type as recommended in the IFA and FAO's *Fertilisers and Their Use* pocket manual for extension officers, one would imagine there are other sources that list slightly different values. Of course, as explained in the introduction, the phosphorus application rates for crops varies highly with the type of phosphorus fertilizer, crop species and breed, crop growth stage, soil pH, etc., and it would therefore not be surprising that there are different recommended amounts published in different sources. Unfortunately, other, reputable sources that either provide general phosphorus/phosphate requirements/uptake/removal rates for all six crops at conventional units, or even optimal yield approximations for these crops, are incredibly difficult to come by as they could not be found - perhaps due to the actual complexity of soil-plant-nutrient dynamics.

Other input data that requires scrutiny is the phosphate mine locations and production data. The current dataset comes from a USGS inventory assembled in 2002 and is therefore outdated even for the modelling year of 2005. The dataset was incomplete in the year of creation and the yearly production rates reported are inconsistent in units. In the absence of other alternative sources, the shapefile was extensively reworked to match 2005, USGS reported, national production rates as described in the Mineral Commodity Summaries. (USGS, 2007). Provided that each year, old mines close and new mines open - albeit often in the same approximate location on the same geological formation – a new spatial mine dataset should be used for every simulation year for an accurate assessment of the development of the global trade network, but that is currently not the case.

5.3. Future studies

Although studies on the unsustainability of the current phosphorus cycle, the global recovery potential, and technology development, are numerous, there are very few studies that assess the impact of recovery on global phosphorus market dynamics. The economic feasibility of phosphorus recovery from wastewater is considered as a major hurdle to the technologies' implementation, yet are surprisingly few studies that assess under what conditions, or by implementing what global changes, an enabling environment for phosphorus recovery can be created. While this study is primitive due to the many assumptions and flaws discussed above, it does serve a suitable purpose as a premier foundation on which future flow and price modelling studies may be built. The model can be adapted on numerous fronts to provide more accurate

and meaningful products, if only even by correcting for the discussion points introduced above, i.e. flat-earth, and transportation paths. It is also recommended to run the model at coarser resolution by introducing 'national' nodes, simply to make comparison with other studies at national scale possible.

On the phosphorus recovery subject, a political study or agent based model exploring social and/or political variables that affect adoption of phosphorus recovery technologies could further strengthen the case for phosphorus recovery. Also, globally contextualized case studies could contribute significantly to the research field.

6 Conclusion

The human impact on the natural phosphorus cycle is unsustainable and poses significant threat to future food security. The dwindling of rock phosphate reserves will reduce future phosphorus production, while phosphorus demand continues to rise as populations grow and living standards improve (Mew, 2016). Despite this, the vast majority of phosphorus accumulated in urban and livestock wastewater is currently lost to the ocean and open surface waters. Phosphorus recovery from wastewater, however, is technologically feasible and offers the opportunity to prolong these reserves and negate much of the other, negative, human impacts on the natural phosphorus cycle. The recovery of phosphorus from wastewater, regardless of the implementation technology, offers at least the following benefits:

- Reduction of global dependence on unsustainable sources of phosphorus - thereby prolonging the exploitability of depleting rock phosphate reserves.

- Enhancing of phosphorus- and food security by reducing dependence on foreign, rock phosphate imports.

- Stimulating circular, economic development of the agricultural sector.

- Reducing air pollution associated with global transport of conventional P-fertilizer products.

- Promoting the building of multipurpose wastewater treatment facilities for wastewater treatment and fertilizer production.

- Improving water quality of open surface waters by reducing phosphorus loads in wastewater treatment plant effluent.

The adoption of phosphorus recovery technologies is hampered by perceived economic constraints and lacking economic incentives. The economic and environmental appeal for recovery will improve over time as environmental regulations becomes stricter with intensified pollution and as rock phosphate prices increase with the diminishing of natural reserves. Despite this, there few studies that evaluate what the effect of this recovery on the existing phosphorus trade network could be, or where recovery can already most efficiently take place. In this study, maps have been created that reveal areas of high phosphorus recovery potential and of high phosphorus demand at subnational resolution. Major phosphorus production and consumption sites have been converted into nodes, after which a simple model was developed to evaluate and visualize the development of global phosphorus trade amongst these nodes, at different phosphorus prices. The model is run for three scenarios that have been designed to represent the current, near-, and far future, human-phosphorus relationship. The *current* scenario includes only phosphate from mines, while the *near-future* scenario includes both phosphorus from mines as well as phosphorus recovered from urban and livestock wastewater through struvite precipitation. The *far-future* scenario

assumes the depletion of rock phosphate reserves and thus excludes all rock-based phosphate sources, leaving only struvite recovered phosphorus options.

The maps reveal that recovery of all human excreted phosphorus, regardless of the economic feasibility for recovery, can potentially accommodate a maximum of 19% of the total agricultural phosphorus demand. Phosphorus recovery from livestock offers greater opportunities, due to the high phosphorus content in animal waste. Approximately 59% of the global agricultural demand can potentially be satisfied through the recovery of phosphorus from cattle, poultry and swine manure.

The historical, recorded price of phosphorus is unstable. Records show significant fluctuations within and among recorded years. The observed, 2015 market prices for phosphorus from conventional P-fertilizer, DAP, ranged between 1,970 and 2,400 [$ t^{-1}] P. In 2005, the year around which the model is designed, reported prices ranged between 1,100 and 1,300 [$ t^{-1}] P. The long transportation distances, accumulating from the beginning of rock-based fertilizer production processes to the final distribution of the product over croplands, allow for opportunity gaps where local phosphorus recovery through struvite precipitation becomes economically feasible in some areas of the world. The high potential and close proximity of recovery areas to agricultural sites, make that phosphorus recovery in 2005 in many parts of Asia could have been competitive at market prices as low as 1,000 [$ t^{-1}] phosphorus. Furthermore, it is determined that at optimum prices of 1,280 [$ t^{-1}] P, the global phosphorus trade for 2005 could consist of 1.09 [Mt] of competitive and sustainably sourced phosphorus from wastewater, which is 7% of total phosphorus trade.

In the third scenario, of only recovered phosphorus products, 69% of the total agricultural demand can be met. By 2005 parameters, the best approximation of the optimum price for such a scenario lies around 2,130 [$ t^{-1}] P. Phosphorus recovery from urban centres contributes at lower prices to the global market. At higher prices, the immense potential of livestock recovered phosphorus becomes available to the market. The most competitive nodes in a sustainable-supply-only market are in India and China.

Price ranges produced by the model for the *current* scenario, for the years 2005, 2006, accurate match the observed price ranges for DAP. Despite the as-the-crow-flies distances, simplified economics, dual, omniscient actor system, and free, non-preferential trade assumptions, the model relatively accurately simulates the DAP prices for the different years using a limited amount of easily adjustable parameters.

Phosphorus issues are gaining increasing attention globally. While many soils are characterized by a soil phosphorus deficit, leading to suboptimal crop yields, other areas cope with phosphorus saturation of the soil due to overfertilization in the past or a practice of intensive livestock husbandry, leading to severe water pollution issues. The recovery of phosphorus concentrated in livestock and urban wastewater offers a win-win opportunity to combat a multitude of such phosphorus related issues. Recognizing that there is no single solution to solving phosphorus pollution and insecurity (Cordell & White, 2013), a reassessment of how we use and treat wastewater will provide an important contribution. Given that the will, the technology and the knowledge are already there to facilitate the large-scale implementation of phosphorus recovery, it is important to identify the economic conditions that enable the large-scale implementation thereof, and what such a development may come to look like. Until then, cases where phosphorus recovery for agricultural reuse has already been implemented will serve as prime examples from which government can learn how to regulate phosphorus recovery in such a way that maximum benefit is achieved for both the environment and the urban community, as well as the livestock and agricultural sectors.

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Appendix I - *Additional Background Information*

Environmental Implication of Phosphate Mining

The land intensive form of open cast mining has gained poor reputation over the course of its history. Its typical scarring of the landscape and well known, long-term environmental implications, however can be largely negated provided new regulations. This often requires mining projects to plan a reclamation phase after concluding mining operations, for topographic restoration and to minimize persisting contamination and pollution of downstream environments (Nicolau, 2003). Contrary to common intuition, a greater threat of phosphate mining to environment stems not from the form of mining but from the waste products created in the ore cleaning and fertilizer production chain.

The phosphorus fertilizer production chain consists of various steps. Initially, a beneficiation and washing process cleans the phosphate rock of sand, clay, carbonates, organics, and iron oxides. Then, phosphoric acid (P_2O_5) is extracted from the produced concentrate through the common, Wet Acid Process, as opposed to the Thermal Acid Process. The USGS reports that more than 95% of the phosphate rock mined in the United States was used to manufacture phosphoric acid and superphosphoric acid through the wet-process (USGS, 2016). The details of the process will not be discussed.

The original rock phosphate, intermediate products or the final phosphorus extract account for 74% for the production of fertilisers, 7% industrial phosphates (feed additives, detergents, pharmaceutical ingredients, and munition manufacturing), and 3% for other uses, while the remaining 10% is lost in transport and processing (van Enk et al., 2011).

The entire phosphoric acid extraction process creates two major waste products: wastewater and phosphogypsum (EPA, 1992). Although most of the wastewater is recycled, the Florida mines in the United States use a reported 8 - 15 tons of freshwater per tonne of phosphate rock (van Kauwenbergh, 2010). The more dangerous of the two waste products is phosphogypsum, as this can potentially have a level of radioactivity associated with radon gas (IFA, n.d.). Utilization of phosphoygypsum was for this reason prohibited in the United States[9] resulting in the further accumulation of unusable, radioactive, phosphogypsum stacks and landfills. These forms of permanent storage accumulate rapidly as approximately 4.5 tonnes of phosphogypsum are produced per tonne of P_2O_5 (EPA, 1992). The utilization of phosphogypsum in construction is recently becoming more accepted as reports have deemed it safe use below certain threshold levels of radiation intensity (IAEA, 2013). Other dangers in the production chain arise from non-radioactive constituents, notably fluorides and heavy metals, such as arsenic, cadmium, lead and mercury (IAEA, 2013). The nature and amount of the waste in the cleaning and beneficiation process of phosphate rock, however, depends largely on the quality and quantity of the ore processed.

Phosphorus Pollution

Phosphorus is a limiting nutrient and thus the improper or insufficient removal of phosphorus from wastewater effluent can spark pervasive growth of cyanobacteria, algae and waterweeds. When these die, their decomposition depletes the water of oxygen, slowly suffocating aquatic life. These deoxygenated "dead zones" can be found in both lakes and seas, and affect an estimated 245,000 km² of marine ecosystems (Corcoran et al., 2010). Phosphorus pollution has received a lot of attention in the 70's when

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[9] National Emission Standardars for Hazardous Air Pollutants for radionuclides promulgated at 40 CFR Part 61, Subpart R, National Emissions Standards for Radon Emissions from Phosphogypsum Stacks (54 FR 51654, December 15,1989)

the algal blooms pestered the Great Lakes until bilateral environmental protection acts were passed by the United States and Canadian governments. The new ban on phosphorus in detergents and cleaning products and stricter wastewater effluent standards have led to a technological shift in wastewater treatment procedures, where phosphorus removal is now becoming a mandatory, standardized final treatment step in many wastewater treatment plant designs. This provides greater incentive for recovery also.

While many countries set strict phosphorus limits on wastewater effluent, in all but the most highly developed countries, is the vast majority of wastewater released directly to the environment without adequate or any treatment (WWAP, 2017). The United Nations Agenda 2030 for Sustainable Development target 6.3, *Improve water quality by reducing pollution*, and goal 14, *improving water quality*, synergize well together as the removal of phosphorus is recognized as a fundamental step in wastewater treatment in order to improve the water quality of open water bodies.

Despite efforts of stricter effluent standards and other pollution control measures, phosphorus often still finds its way to open surface waters through means other than through wastewater. This introduces a second issue related to phosphorus management in agriculture, namely that of fertilizer over-application, or overfertilization. While many soils globally suffer from a phosphorus deficiency (section 1.5) many others suffer from phosphorus excesses due to heavy fertilisation in the past. This phosphorus percolates into surface water through seepage and runoff processes. Provided the environmental consequences thereof, the education on good nutrient management practices are not only relevant to farmers of nutrient deficient areas in developing world, but also to farmers that have excessively fertilized in the past - predominantly in the developed world. The Netherlands exemplifies a worst-case scenario of phosphorus soil pollution due to the large, intensive agricultural and dairy sectors and their close proximity to an abundance of water. In 1990 about 43% of the grassland and 82% of the maize land in the Netherlands was approximated to be saturated in nutrients due to over fertilisation (Breeuwsma & Silva, 1992). As a result, the nutrient concentrations in surface waters in The Netherlands still consistently exceed water quality standards (O. Oenema & Roest, 1998; Oene Oenema, Oudendag, & Velthof, 2007). In early recognition of this problem, the Dutch Manure Law was enforced in 1986, and the European Nitrates Directive was adopted in 1991 - resulting in measures that include a ban on applying fertilisers outside the growing season and maximum limit of 170 kg of nitrogen applied per hectare per year (European Commission, 1991). 25 years later, nutrient pollution rates in the Netherlands are still falling as a result of the policies, but many open surface waters still routinely fail to meet environmental quality standards (Rozemeijer, Klein, & Broers, 2014). A study by Rozemeijer et al. (2013), showed that even though phosphorus concentrations are reduced by 0.02 [mg L[1]] per decade, 76% of 167 rivers where agricultural fertilisers are the main cause of pollution still did not meet water quality standards. With the recent growth of the livestock sector due to the dismantling of the milk quota, the Dutch government has introduced new and firmer 'phosphate decree' to limit the total dairy population in the country. By the new decree, the amount of phosphate that farmers can produce may not exceed the 2015 reported amounts. It resembles the policies on CO_2 emission rights, in that phosphate rights may be traded with other farmers. The case of The Netherlands demonstrates the long lasting impact soil phosphorus pollution may have on surface water quality, and the extent of policy, regulation and economic restrictions necessary to prevent further deterioration of the environment.

Plant Available Phosphorus

Soil-plant-phosphorus dynamics are complex, as not every form of phosphorus can be extracted from the soil by plants (Figure I).
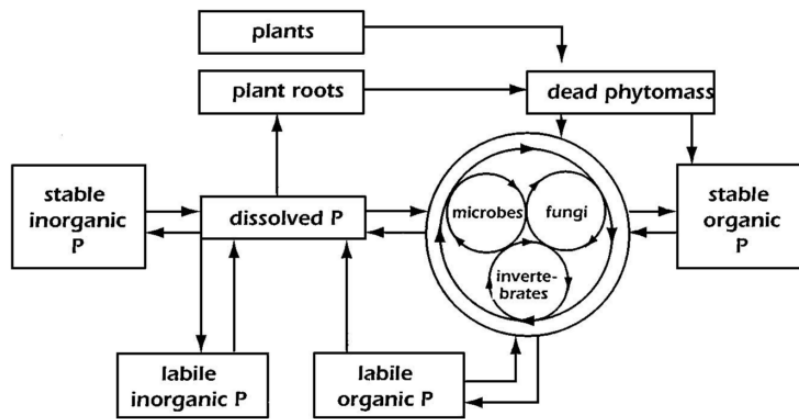
Figure I. *Soil phosphor interactions, adapted by Smil (2000) from Paul & Clark (1989).*

The *plant-available soil phosphorus* describes the portion of P in soil that can be taken up from soil by crop roots, as well as the portion of P in soil extracted by various methods in soil testing laboratories (Mckenzie & Middleton, 2013). This plant-available soil phosphorus varies depending on a number of variables. Phosphorus has both organic and mineral forms, of which only the inorganic, mineral form (PO_4) is available for plant uptake. Micro-organisms consume the other, organic phosphorus, which over time, as the organisms die and break down, mineralize into the plant-available, inorganic phosphates. Aside from the form, the place of the phosphorus in the soil also determines whether phosphorus is available for plants. As phosphorus is relatively immobile, it important that the fertilizer is placed in close proximity to the roots if it is to be absorbed. In addition to this, the soil moisture and temperature, as well as soil pH are significant in whether it can be absorbed. Lastly, depending on the soil characteristics, some P is fixed to the soil thereby also becoming unavailable for plant uptake. These such aspects of soil Chemistry however will not be delved into in this thesis.

Phosphorus Security

Phosphorus is essential for intensive and efficient agricultural practice. Unfortunately, the limited rock phosphate reserves are geographically concentrated, making phosphorus not only a non-renewable resource, but also a strategic one. The nation with the *largest reserves* is Morocco & Western Sahara which poses over approximately 75 % of the global total (Figure II). By USGS approximations (USGS, 2017), China is by far the *largest producer* of phosphate accounting for approximately half of the total global production (Figure III).

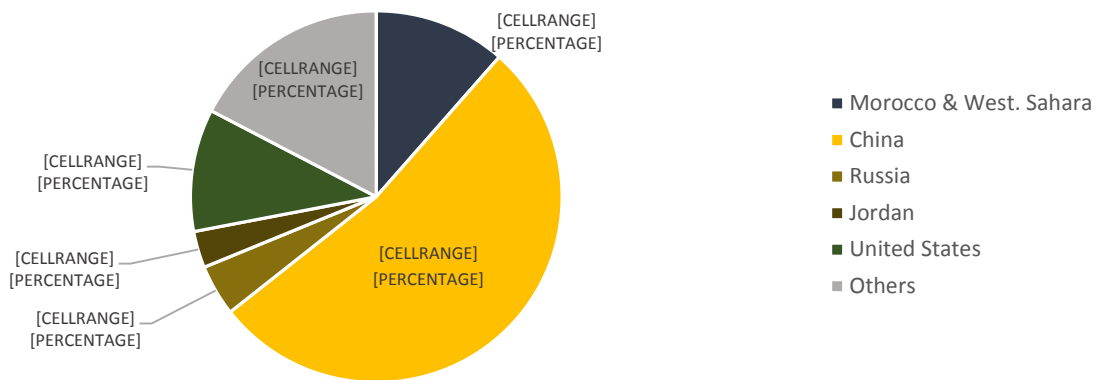**Figure II**. Estimated global phosphorus reserve distribution (USGS, 2017).

Figure III. Estimated global phosphorus production (USGS, 2017).

Western Sahara exemplifies the complexity in form that phosphorus politics may take. The country (or region to others), has been on the United Nations list of Non-Self Governing Territories since 1963, following the transmission of information on Spanish Sahara by Spain under Article 73e of the Charter of the United Nations (United Nations General Assembly, 1963). Shortly after repatriation of the Spanish occupants, a Moroccan insurgency resulted in the Western Sahara War. With a ceasefire signed in 1991, Morocco administered itself the governmental rights over the half million inhabitants that long for their own state, as well as among the greatest phosphorus reserves on Earth, which make up the territories. Several Scandinavian and Australian firms have responded with a boycotting of Moroccan exported phosphorus in expressing their condemnation of the occupation and Morocco's disregard for international law (Cordell, 2010; Rosemarin, Bruijne, & Caldwell, 2009). Many other nations, however, remain powerless to do so as they are completely dependent on Moroccan phosphorus imports in the absence of similarly priced alternatives. This dependency, where a nations agricultural sector is left in the graces of another country's goodwill marks a low phosphorus security. This low security can be defined as a high demand with little supply options, which is naturally unfavourable.

Nevertheless, although many Western European countries also suffer from a low phosphorus security, they have large surpluses of phosphorus in their soils due to overfertilization in the past (Sattari, Bouwman, Giller, & van Ittersum, 2012; Withers et al., 2015). These legacy 'reserves' can be utilized in agricultural production without fertilization, for subsequent decades without compromise to crop yields (Sattari et al., 2012). Determination of precisely how long one these soil reserves would last, requires an extensive study on how effectively the accumulated soil P is used (Oscar F. Schoumans et al., 2015). Despite this phosphorus saturation of the soil, over fertilization remains an issue. Addressing the imbalance of P inputs to rice, maize, and wheat globally would save 38 % of P fertilizer use without reducing crop yields (Mueller, Gerber, & Ray, 2012). With and increasing demand for agricultural products and prospective decline of phosphorus resources, countries are looking for ways to guarantee their own food security in a phosphorus market that is confined to only a small group of global suppliers. This endeavour to enhance national phosphorus security requires and budget assessment of phosphorus demands and supply options.

Enhancing Phosphorus Security

There is no single solution to meeting the world's future phosphorus needs for food demand. Rather, an integrated approach that involves the right combination of supply and demand measures in key sectors of the food system will be required' (Cordell et al., 2009). There exists a broad variety of different measures that can be implemented to enhance the global phosphorus security (Childers et al., 2011; Cordell & White, 2013). In general, they can be summarized in the 'reduce, reuse and recycle' format of sustainable practice

(WWAP, 2017). Cordell (2013) emphasizes, however, that 'Some of the most basic of these measures will include: A ploughing of crop residues (stems, leaves, stalks and roots) back into fields, or using it as livestock feed; applying fertilizer in amounts that better align with growth and stoichiometric needs; bioengineering crop strains that require less P for the same crop production or that more efficiently take up P from soils; better control of erosion losses of P-rich soil from farm fields; reducing human meat consumption; composting food waste; and recovering phosphorus from wastewater streams (Childers et al., 2011); producing food closer to points of demand; awareness campaigns; and settings stricter phosphorus regulations (Cordell & White, 2013).

Phosphorus Removal and Recovery Technologies

Current, water-based sanitary systems dilute and mix most phosphorus in our wastewater streams. While average P concentrations of urine range between 0.2-0.21 [g L^{-1}] (Kirchmann & Pettersson, 1995), the average concentration of P in municipal wastewater ranges between 0.010-0.020 [g L^{-1}], and are thus diluted by 90% (most optimistically)(Rhodes, 2013). The composition of wastewater is important as the application of recovery technologies varies accordingly. Toxic elements such as the heavy metals lead and cadmium limit the range of applicable recovery technologies, or inhibit the use of the phosphorus product as a fertilizer by fertilizer regulation designed to prevent heavy metal build up in the soil (Hukari, Hermann, & Nättorp, 2015). Many factors influence the composition of wastewater and potential heavy metal load. The piping material, proportion of municipal to industry that is connected to the network, the nature of the industry, whether the sewerage system is of combined or separated design, regional climate, and/or regulations all affect the composition of wastewater. Furthermore, each technology comes with its own nutrient recovery potential, associated costs, resource requirements, emissions, waste- and/or by-products. The implications of these on wastewater and the environment are often neglected or insufficiently explored (L. Egle et al., 2016), which further complicates the decision making process in selecting the most effective technology per recovery case. There exist over 50 different recovery approaches (L. Egle et al., 2016). Biological removal or chemical precipitation followed by solids separation are the most common principles on which they are based.

> **Biological phosphorus removal** *(BPR) is accomplished by encouraging the growth of phosphate accumulating organisms (PAOs). Under anaerobic conditions, PAOs uptake and store simple carbon food sources such as volatile fatty acids (VFAs) using the energy in phosphate bonds, and release phosphorus to solution. When the PAOs are subject to aerobic conditions, they metabolize the stored carbon to generate energy for cell growth and maintenance and store excess energy by taking up phosphate ions and creating polyphosphates. The phosphorus uptake by PAOs in the aerobic zone results in a net reduction in phosphorus in the wastewater when sludge is wasted.* (EPA, 2010)

> **Chemical precipitation processes** *for phosphorus removal involve the addition of various chemicals to wastewater that react with soluble phosphates to form precipitates. The precipitates are removed using a solids separation process, most commonly settling (clarification). Chemical precipitation is typically accomplished using either lime or a metal salt such as aluminium sulfate (alum) or ferric chloride. The addition of polymers and other substances can further enhance floc formation and solids settling. Operators can use existing secondary clarifiers or retrofit primary clarifiers for their specific purposes.* (EPA, 2010)

Some of the most basic forms of recovery are amongst the most effective. The immediate source-separation of urine from wastewater through urine diverting toilets prevents the dilution of a large portion of human excreted nutrients (88% of the N and 66% of P from human excreta, (WWAP, 2017)). Urine contains all the essential plant nutrients (Nitrogen, Phosphorus and Potassium), is essentially sterile and can be applied directly to croplands (WHO, 2006). Another benefit for water scarce regions is that urine is 91-96% water (Rose et al., 2015). Its application to croplands therefore potentially lowers its irrigation needs. Urine, however, is acidic, difficult to store, voluminous to transport and has a strong odour. Partly for these reasons, it is often assumed that there is little public acceptance for such approaches to fertilization. However, a study in Switzerland found a rather high willingness to both use urine-diverting toilets and to consume food fertilized by urine (Pahl-Wostl, Schönborn, Willi, Muncke, & Larsen, 2003). Furthermore, the government of Sweden has aimed to recover and reuse 60% of all P in sewage, leading to two cities already requiring the use of urine diverting toilets (Cordell et al., 2009). However, Transitioning to urine separation alone does not make use of the maximum phosphorus recovery potential. Urine only accounts for 40% of the total anthropogenic phosphorus load, and therefore the remaining 50-60% should be removed from wastewater or recovered via other means at the wastewater treatment plant (WWTP). It is, however, a cheap and effective solution that may be more easily implemented in small agricultural communities, rather than highly urbanized areas.

Phosphorus recovery from sewage sludge ash is a more commonly implemented technology. Sewage sludge ash (SSA) is what is left after mono-incineration of dried sewage sludge. Mono-incineration rids the sludge of all organic pollutants. Not all sewage sludge is incinerated, however. Even in the EU-27 and Switzerland the differences are substantial with Greece landfilling more than 90 % of the sludge, United Kingdom, France and Spain using above 65 % of the sludge in agriculture and the Netherlands and Switzerland incinerating 100 % of the sludge (Herzel, Krüger, Hermann, & Adam, 2016). Direct application of SSA to fields is often not possible due to heavy metal loads and low P bioavailability (Ulrich, 2016). A **thermochemical treatment process** (ASH DEC) can convert SSA to a P fertilizer of low pollutant content and high bioavailability. The SSA's heavy metals in chloride form can be brought to complete vapour phase at temperatures below 1000 C (Adam, Peplinski, Michaelis, Kley, & Simon, 2009). The conversion of the portion of heavy metal oxides to chlorides before heating will allow for the full separation of heavy metal pollutants from SSA through evaporation. The running of the rotary furnace, however, is energy intensive and therefore costly. An alternative SSA treating process for phosphorus recovery is known as Leaching (Leachphos)**,** a **wet-chemical process**. Sulfuric Acid is added to the SSA creating leachate mixture that absorbs 70-90% of the phosphorus. The solid fraction of the mixture is separated through belt pressing after which the phosphorus in the liquid fraction is precipitated with the dosing of lime (CaO) or caustic soda (NaOH) (Herzel, 2015).

The EPA *Nutrient Control Design Manual* (2010) further summarises and describes the following recovery technology principles: P recovery through conventional gravity clarifiers (tertiary), lime clarification, dense sludge high-rate tertiary clarification, ballasted high-rate tertiary clarification, pho-redox (A/O), ditch oxidation with anaerobic zone, 3 stage pho-redox (A2/O), 5 stage Bardenpho, University of Capetown (UCT), modified UCT, Virginia Initiative Plant, Westbank, ditch oxidation with anoxic and anaerobic zones, sequencing batch reactors, blue plains process, and wet or thermochemical SSA treatment (EPA, 2010). Not all of these produce a product that can easily be repurposed as fertilizer, nor are they necessarily developed for business case implementation.

While thermochemical treatment and leaching have been demonstrated effective and are considered technologically feasible, they are not often implemented. Struvite Precipitation technologies (Pearl, AirPrex, NuReSys, etc), however, are being implemented at full scale (Hukari et al., 2015) (Figure IV).
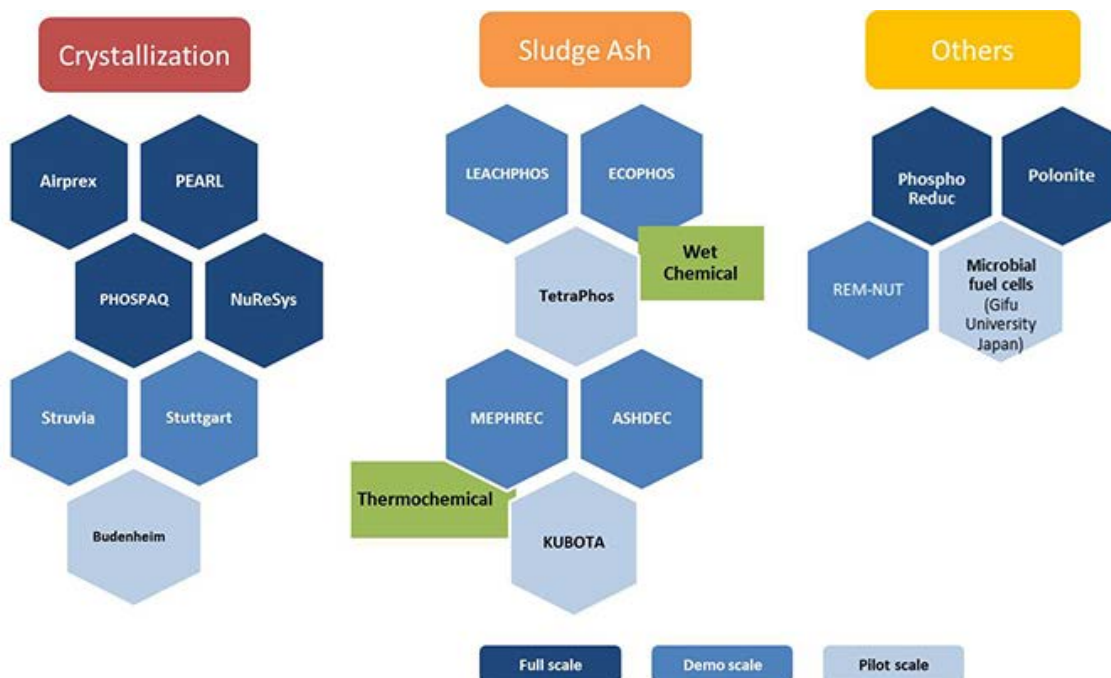

Figure IV. *Emerging phosphorus recovery technologies* (Aquatech, 2015)

Struvite Precipitation WWTP Cost Savings

Phosphorus recovery beneficially influences the finances of wastewater treatment facilities in multiple ways. Recovery reduces operating costs by reducing downtime for cleaning struvite precipitants, reduces sludge disposal costs, and offers profits from a marketable fertiliser product.

Struvite precipitates naturally in WWTP pipes and pumps at rates varying with the pH and temperature, as well as the degree of pressure changes in wastewater flow. These uncontrolled struvite deposits cause for flow restrictions, operational inefficiencies and maintenance procedures that are costly in time, materials, and labour. Struvite scaling inside the digester sludge pipeline at the Hyperion Wastewater Treatment Plant in Los Angeles caused a pipe diameter reduction of 50% after only one year of operation (Jaffer, Clark, Pearce, & Parsons, 2002), while the Sacramento Regional Wastewater Treatment Plant in California had to replace 3.5 miles of pipe after failed struvite scaling removal attempts (Bird, 2015; D., Kath, John, Colin, & A., 2003). System downtime has to be scheduled in order to chisel, or flush with acid, the struvite encrustations from the interior infrastructure and equipment. Cleaning and downtime costs a WWTP in Australia some AUD $2,860 ($2,240 USD) to AUD $14,285 (11,200 USD) [$ yr^{-1}] (Benisch, Clark, Sprick, & Baur, 2000). The problem is then only temporarily remediated as new build-up accumulates directly when normal operations resume. Left unchecked, struvite accumulation can foul mechanical equipment and clog pipes again within months, so beginning the cycle anew (Westerman, Safley, & Barker, 1985). Controlled struvite precipitation severely counteracts struvite scaling problems. Controlled precipitation can be initiated in specialised crystallizer reactors by manipulation of the sludge digestion process. The scaling maintenance-cost savings achieved with struvite precipitation range from $500 to $2500 for every cubic meter of wastewater treated (Chanan, Vigneswaran, Kandasamy, & Johir, 2013).

Apart from reducing the maintenance cost of struvite scaling, recovery also reduces sludge handling costs by enhancing sludge dewaterability. While 1 kilogram of struvite sludge will have a volume of 0.7 litres, the sludge produced by precipitation (at a solid content of 20%) will have a volume of 3.5 L (Shu et al., 2006). This not only translates to a direct reduction in sludge handling costs, but also into a reduction in required landfill area and associated costs (Shu et al., 2006).

Operational cost savings of phosphorus recovery vary according to wastewater composition and the individual, convention WWTP business case. Dockhorn (2009) approximates the savings of recovery to be around 2–3 [€ kg^{-1}] P, (2.3-3.5 [$ kg^{-1}]). Shu et al. (2006) estimates a broader range of 0.79 and 3.92 [AUD $ kg^{-1}] P, (0.6-3.1 [$ kg^{-1}]).

Appendix II — *Presentation of Optimum Price Approximation*

Unless the supply and demand curves intersect each other before maximum trade is achieved, the optimum price is identified to lie between the prices at which the supply and demand curves reach maximum trade. The optimal price can be further differentiated from this (potentially large) range. Depending on the proportion of global phosphorus supply to demand, it is possible to determine whether the optimum price will lie in the upper or lower half of this range. When the total supply is far greater than the demand, then the demand nodes are in a stronger bargaining position, and are able to shift the prices downward in their favor. The opposite is true when the demand is far greater than the supply, then the supply nodes can shift the prices to the upper end of the spectrum, to their favor. By this premise, we can reduce the large range to either the top half or lower half (UR1 and LR2, Figure V(a)). Depending on the slope of the supply curve as it meets the satisfiable demand, a large reduction in price may lead to only a minor reduction trade. Extending therefore the upper and lower boundaries (LR1 and UR2) to the price that allow for 95% of maximum trade, some small possible errors in accuracy or market flexibility are more appropriately accounted for. How the definition of this new, smaller reach relates to the supply-demand curve is illustrated in Figure V.
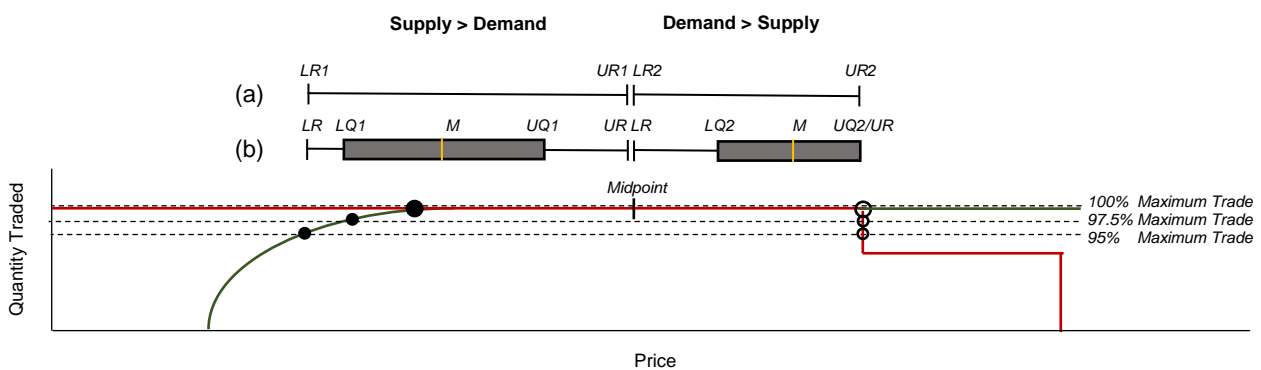

Figure V. *Conceptual Illustration of supply (green) and demand (red) curves with maximum limit on demand.*

We can further refine this reach (a) by taking a greater confidence interval of 2.5%. Hereby we shorten the lower boundary of the 'supply greater than demand' reach, and possibly also the upper boundary for the 'demand greater than supply' reach, to the price that allows for 97.5% of maximum quantity traded (LQ1 and UQ2). Having defined one new boundary, the opposite boundary should be redefined also (UQ1 and LQ2). The other boundary is scaled with the supply:demand ration ($\frac{Supply}{Demand}$) such that if the difference is more extreme, the price will shift more significantly to one end or the other of the spectrum. The most extreme a shift that can be occur is when the supply is at least 50% greater (or 50% less) than the demand. Any percentage between 0-50% will alter the other boundary of each range proportionally to be in between the lower and upper limits of each reach in (a). To not complicate matters further, our most accurate guess of the optimal price is to occur exactly in the middle of this second, most precisely defined range (LQ to UQ), indicated as the yellow line (M) in Figure V(b).