Phosphorus Scarcity: The Neglected Issue in the Modeling of Future Food Security

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Abstract:

As 2050 drawers nearer, global food production faces growing demand for food, challenges from climate change and globalization. As ensuring food security for a growing global population will require innovative and sustainable solutions, research in this field endeavors to understand the landscape of food security in the coming decades. As such, global food security and computable general equilibrium modelling have partnered to help assess how these challenges will affect our ability to produce food. However, knowledge and research gaps remain. Thus, this paper innovatively highlights that food security analysis using computable general equilibrium modelling can be enhanced by filling one part of the mineral resource gap by including the critical element phosphorus. This paper provides a detailed literature review on current approaches in phosphorus modeling and their contributions to economic modeling and how current knowledge gaps can be bridged by including phosphorus into food security analyses using computable general equilibrium modeling.

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Key Words

Computable general equilibrium, food security, economic modelling, phosphorus scarcity, sustainable phosphorus.

1. Introduction: A Gap in Food Security Modeling

The demand for food is expected to increase by more than 60 percent over the next 30 years, as the global population approaches 9 billion around 2050. This projected growth in global food demand by 2050 will challenge our ability to continue increases in crop production and will cause a serious strain on natural resources (Alexandratos & Bruinsma, 2012). Given the decreasing likelihood of expanding agricultural land and water resources, meeting rising food demand will mainly come from improvements in productivity and resource efficiency (Foley et al., 2011; Tilman, Balzer, Hill, & Befort, 2011). Moreover, as globalization drives integration, global food security concerns and issues become transboundary requiring multinational perspective and strategy. Aside from these additional mouths to feed, growing biofuel production, increased meat and dairy consumption, and climate change all factor into challenging food production (FAO 2017).

Food is produced, traded, transported, sold, and consumed through a complex system with often non-linear, trans boundary interactions. Thus, the ability to link both the physical elements of production with economics becomes vital. As a result, global food security and computable general equilibrium (CGE) modelling have partnered to help assess how these challenges will affect our ability to produce food confronting researchers in this areas is question what is needed in order to consider these nonlinear and global effects?

If CGE modelling is to better examine global food security, then incorporating the most basic inputs in to food production is necessary. However, although resources such as water and land are increasingly analyzed in the food security debate (Schröder, Cordell, Smit, & Rosemarin, 2010), other vital natural resources in global food production have not been fully included leaving us to ask: how do challenges to the most basic of inputs used in food production affect global food supply?

Thus, this article highlights how CGE modelling can be enhanced by bridging the mineral resource gap through the inclusion of one particular, critical element – phosphorus. Section 2 provides an overview of the criticality of phosphorus in global food production. Section 3 showcases the gap in CGE modelling. Section 4 offers a review of the current non-CGE models used to analysis phosphorus scarcity and how they can be used to enhance CGE modelling. Section 4 highlights the gaps that CGE models can fill in the analysis of phosphorus scarcity.

2. The Importance of Phosphorus

Phosphorus is an essential element for all life and is vital to DNA and RNA, the production of cell membranes, energy supply, and the formation of seeds in plants (Childers, Corman, Edwards, & Elser, 2011; Smil, 2000). Humans obtain their phosphorus needs through their dietary intake of plants and animal products, whereas plants obtain phosphorus from the soil, which can no longer provide agricultural activities with sufficient amounts of phosphorus. As the demand for phosphorus far outstrips the biological renewal rate in soils, modern agriculture has almost exclusively turned to inorganic phosphate fertilizers for supply (Seyhan et al., 2012)

Between the end of the 19th and beginning of the 20th centuries, large deposits of phosphate rock – a sedimentary rock with high P concentrations provided the basis for the rapid growth of the fertilizer industry after the Second World War (Childers et al., 2011; Reijnders, 2014). Since then, then mining and refining phosphate rock into fertilizer has caused annual production of phosphate rock to double from 1970 to 2010 (Heffer & Prud'homme, 2015).

Phosphate rock is distributed unevenly across the globe and poses geopolitical risks which may cause market concentration and restrict availability in the future. As of 2016, ten countries accounted for 95% of reserves, with Morocco alone controlling over 72 percent (USGS 2017), giving rise to such concerns as price setting or the impact on agricultural production due to disruptions in supply. Regarding annual production, China, Morocco, and the USA account for 75 percent of global production in 2016 (USGS 2017). Such market concentration means all net phosphorus importing countries are subject to the whims of a few countries, evinced in 2008 when China imposed a 135 percent export tariff that effectively stopped exports of a significant global supplier (Cooper et al., 2011). This is considered to have contributed directly to the 2007/2008 price spike where the price of phosphate rock reached its highest amount at $430 in August and September 2008. High agricultural prices at the time gave farmers an incentive to increase crop yields through applying more fertilizers, demand for meat and dairy products is on the rise, and high oil prices drove up the demand for biofuel crops and again more fertilizers (Von Lampe et al., 2014).

The demand for phosphorus is expected to increase due to an estimated global population of over 9 billion by 2050 and changes in diets towards more meat and dairy from a growing affluence in developing counties (Cordell et al., 2009). Moreover, biofuel production is likely to increase and these challenges are anticipated to be met with agricultural intensification rather than extensification (Alexandratos & Bruinsma, 2012). Assuming a business as usual scenario towards 2050, the price of fertilizer is expected to increase as physical scarcity increases (Huang, 2009; von Horn & Sartorius, 2009). Though scarcity and higher prices in theory induce exploration and development of new mines, it is widely believed that future mining of reserves will be thwart with higher costs due to higher impurities and increased difficulty in extrapolation and refinement (Van Kauwenbergh, 2010).

Agriculture will always be dependent on phosphorus inputs be they organic or synthetic. For the foreseeable future, phosphate fertilizers will be the primary source, and by extension, phosphate rock. Regardless of the longevity of phosphate rock reserves, unless recycling technologies are implemented, the supply of phosphate fertilizers is going to be finite (Heckenmüller, Narita, & Klepper, 2014). However, the current production of phosphate rock may not be enough to guarantee stable supply. The highly concentrated distribution of global phosphate rock reserves creates a dependency on a few nations and the increasingly volatile prices of fertilizer create insecurity for farmers in developing regions as a price shock could again render phosphate fertilizers unaffordable for many farmers. Thus, although we are certain of phosphorus' importance, we are less certain about it sustainability. Phosphorus is not a physically scarce resource but economically scarce as not all deposits are technically or feasibly extractable (Scholz & Wellmer, 2013). If phosphorus scarcity is left unaddressed, global agricultural production could witness higher energy costs for mining and processing of phosphate rock, further pollution and waste, higher fertilizer prices, more price spikes, geopolitical tensions, and decreased access to farmer fertilizers, reduced crop yields (Cordell et al., 2009; Cordell & White, 2011; Heckenmüller et al., 2014; Smit et. al., 2009)

3. The Mineral Resource Gap in CGE Modelling

CGE models are tools used in economic policy analysis that employ inter-sectoral linkages and account for the circular flow of income within an economy. Thus, they able to consider simultaneously all sectors of production within an economy and macroeconomic constraints such as factor markets and income. In terms of food security analysis, a CGE model's strength lies in its inclusion of the entire global food value chain from agricultural production, to processing, distribution, and consumption.

However, understanding why mineral resources such as phosphorus have been neglected involves understanding how the core CGE models used in food security have developed. In the advent of CGE modelling, land, water and energy were used as one directional inputs into food production but, with the birth of 1st and 2nd generation biofuels, challenges to water quality, climate change, etc., the need to understand feedback loops and tradeoffs became paramount (Kling, Arritt, & Keiser, 2017). Thus, CGE models over time began to incorporate the main drivers behind changes in global food security. Table 1 demonstrates the food security drivers incorporated into leading CGE models.

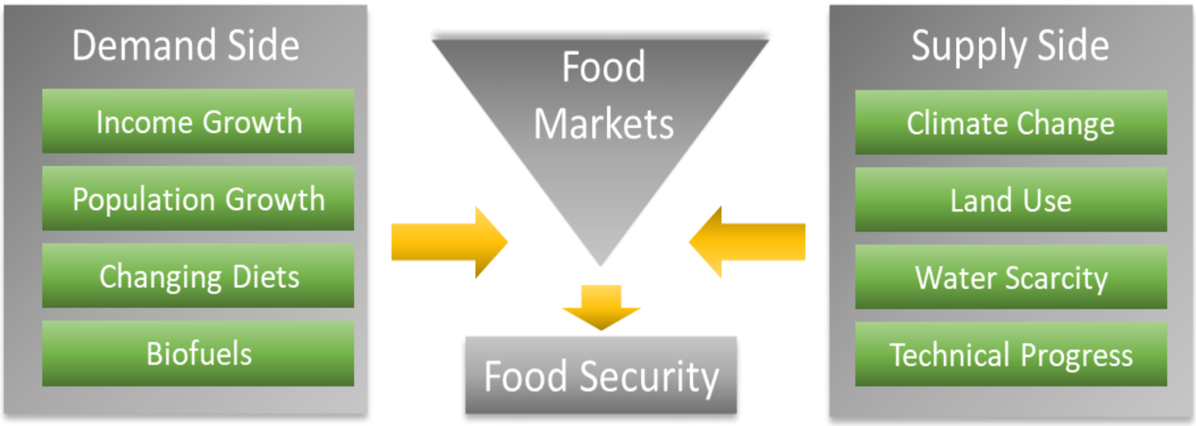
Table 1 Overview of Leading CGE Models and Food Security Drivers

Model	Data Source	Spatial Scale (Regions)	AG Products	Calculation of FS Indicators	Trade	Global Food Security Drivers				Reference
						Bio-economy	Pop	GDP	Income Elasticity	
GLOBE	GTAP	19		Equilibrium Prices	Armington equilibrium	Endo	Exo	Endo	Endo	(Mcdonald, et.al., 2007)
ENVISAGE	GTAP	11	10	Equilibrium Prices	Armington equilibrium	None	Exo	Endo	Endo	(van der Mensbrugghe, 2008)
FARM	GTAP	5	12	Equilibrium Prices	Armington equilibrium	Endo 1st generation	Exo	Endo	Endo	(Sands, et al., 2013)
GTEM	GTAP	5	7	Equilibrium Prices	Armington equilibrium	Endo1st generation	Exo	Endo	Endo	(Pant et al., 2002)
MAGNET	GTAP	29	10	Equilibrium Prices	Armington equilibrium	Endo 1st generation	Exo	Endo	Endo	(Smeets-Kristkova et al., 2016)
AIM	GTAP	89	8	Equilibrium Prices	Non spatial, Armington	Endo	Exo	Endo	Endo	(Fujimori et al., 2012)

Abbreviations: AG, Agricultural; AIM, Asian-Pacific Integrated Model; Endo, Endogenous; ENVISAGE, Environmental Impact and Sustainability Applied General Equilibrium Model; Exo, Exogenous; FARM, Future Agricultural Resources Model; FS, Food Security; GTAP, Global Trade Analysis Project; GTEM, Global Trade and Environmental Model; MAGNET, Modular Applied General Equilibrium Model.

Though there are many differences between the models (see Valin et al. 2014; Von Lampe et al. 2014; Hertel et al. 2016 for extensive reviews of models and approaches using CGE model in food security), a commonalty among them - and important to this paper - is the absence of any mineral resource included in the dimensions or drivers. Future challenges such as climate change impacts, yields and water scarcity, population growth, and changing diets and income have largely been incorporated into existing models. However, other aspects such as mineral resources have been largely excluded. Figure 1 show the drivers which have been incorporated into CGE modelling.

Figure 1 Demand and Supply Side Food Security Drivers



The reason for this neglect is perhaps the widespread opinion among industry leaders and economists that raw materials would always be available on the international market. Despite the concerns of supply limits in the 1970s, 80s, and 90s, this opinion remained prevalent until the 21st century when commodity prices began spiking (Humphreys, 2010; Scholz & Wellmer, 2013). However, this may over emphasizes land supply as the primary response to changes in the crop production and under emphasizes the role of inputs into agriculture production (Hertel et al., 2016).

4. Phosphorus Food Security and Global Modeling: Review of the Current Models

4.1 Mineral Resource Dimensions and Phosphorus: Building the Framework

Enhancing CGE modeling with mineral resources such as phosphorus is one step closer in closing the mineral resource the gap in the economic dimension in analyses in food security. Moreover, the debate on phosphorus scarcity is not devoid of models or approaches. While models currently employed in the analysis of phosphorus scarcity detail different dimensions as the next sections showcase, there is a significant gap around the economic dimension. Their shortcomings highlight opportunities for enhancing food security approaches using CGE models.

Thus, the three current approaches to phosphorus scarcity, (1) static and dynamic reserve to production models, (2) curve fitting labelled "peak phosphorus," and (3) substance flow analysis models, are analyzed in the next sections in terms of their strengths, weaknesses and contributions to enhancing CGE modelling and thus better understanding of the challenges facing future food security. Table 2 provides an overview of the three models reviewed. This following review utilizes relevant, recent, peer-reviewed journal papers and reports written in English. Global phosphate rock production and reserve data have also been employed.

Table 2 Overview of Models Used in Phosphorus Analyses

Approach	Technique	Method	Scale	Input	Output	Mineral Resource Dimensions

Static or Dynamic R/P	Demand: Supply Ratio	Estimated Reserves divided by projected demand	National or global	Phosphate rock data	Longevity of reserved, geopolitics	Physical, Geopolitical
Curve Fitting	Growth curves fitted to production data	Numeric and least squares, times series	National or global	Historical production data	Projected production data	Physical
Substance Flow Analysis	Mass Balance	Systems approach	Local, regional, global	Statistical data	Quantified flows, leakage, buildups	Managerial, Institutional

4.2 Static and Dynamic R/P

One of the most common and basic techniques to modeling and predicting the future availability or physical scarcity of a mineral is the Reserves to Production (R/P) Ratio. In essence, it shows the duration of reserves at current production rates. It is calculated as the known available reserves (called the ultimately recoverable resources URR) divided by annual production and thus demonstrates the number of years that current reserves would last assuming nothing else changes. Some authors take a static level of demand while others assume increasing growth of demand, resulting a more dynamic model. Table 3 provides an overview of leading R/P projections

Table 3 Review of Reserve to Production (R/P) Models

Study	Lifetime of Reserves	Depletion Year[a]	Size of Reserves (GT)	Model Type	Assumptions
(Smil, 2000)	80	2080	10.5-24.5	Static	At 'current rate of extraction'
(Fixen, 2009)	93	2102	15	Static	At 2007-2008 production rates
(Vaccari, 2009)	90	2099	15	Static	At 'current rates'
(Van Kauwenbergh, 2010)	300-400	2310-2410	460	Static	At 'current rates'
(Villalba & Liu, 2008)	120	2128	24	Static	At 'current rates'
(Steen, 1998)	60-130	2058-2128	10.5-22.4	Dynamic	3% annual demand increase in phosphate until 2020. Max production reached around 2010.
(Smit et al., 2009)	125-340	2134-2349	18	Dynamic	Exponential population growth rate until 2050. Zero growth rate after 2050 with current consumption patterns
(Bouwman et al., 2009)	"Within Decades"	2100	50	Dynamic	36-64% of phosphate rock reserves are depleted current increase in the use of P.

[a] Depletion year assumes estimated lifetime from publication date.

The R/P ratio operates under some strong assumptions. The first assumption is that estimates of phosphate rock reserves are accurate and static. However, the reserves used in production vary across studies. The reason behind this is the data source for most studies is the United States Geological Survey (USGS) which often updates and reevaluates data. The most notable was a four-fold increase in Moroccan reserves in 2011 from 16,000 Mt to 65,000 MT (Jasinki 2009).

The second assumption is that estimates of current production remain constant until the reserve base is depleted. However, the size of reserves can vary because they are based on estimates for which the current economic and technological situation allows (USGS 2017). Moreover, individual country production rates are also susceptible to change. Thus, as production in different countries can increase or decrease, the estimate is at best a snapshot in time and does not allow for discoveries, technological improvements in extraction or recycling, or changes in prices which could alter the boundaries between marginally economical reserves (Cordell & White 2011; Edixhoven et al. 2014;). Such developments in the phosphate rock market can only be incorporated by first readjusting production rates and then generating a new outlook.

While these models can be updated year to year to show a general production trend over time, this can still be problematic as the critical point in these models is when production comes to an abrupt end. Figure 3 demonstrates the hard landing. Such a hard landing is unlikely as market mechanisms should kick in before this point and induce saving technologies or price increases that make previously non-exploitable reserves now economical (Heckenmüller et al., 2014). The question that still unanswered by these models is what would be the implications to food security should the phosphate rock market witness higher prices and spikes on the road to avoiding a hard landing.

Thirdly, these models assume that global production will maintain pace with global demand. However, as production rates vary across countries (see Table 4), supply in all currently producing countries is not guaranteed indefinitely. The demand for phosphate rock as a source of phosphorus is expected to increase. If we assume a simple one percent annual increase in demand until 2050 (Cordell et al., 2009; Steen, 1998) and if losses in mining over time are not compensated by new production, then a production deficit will develop, placing more strain agricultural production. Figure 2 demonstrates the production deficit arising from a business-as-usual production scenario coupled with rising demand.

Table 4 Differences in R/P Rates by Country for 2016

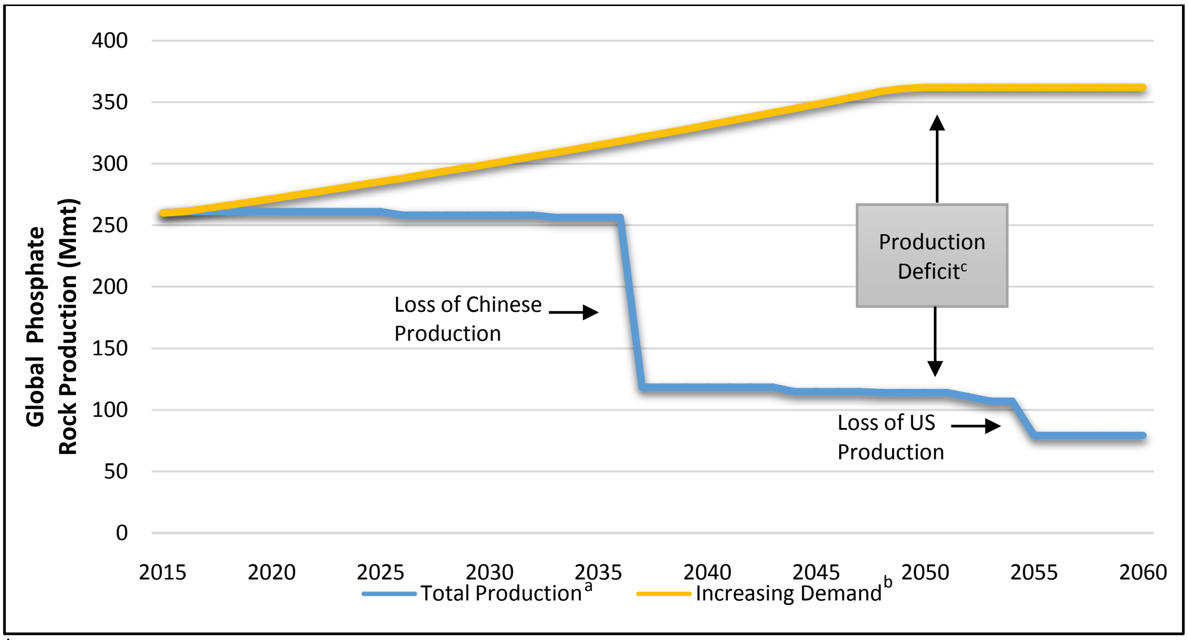
Country	Reserves (Mt)	Production in 2016[b] (Mt)	R/P (years)[c]
Morocco	50,000	30	1,667
China	3,100	138	22
Algeria	2,200	1.5	1,467
Russia	1,300	11.6	112
Egypt	1,200	5.5	218
Jordan	1,200	8.3	145
United States	1,100	27.8	40
Australia	1,100	2.5	440
Peru	820	4	205
Saudi Arabia	680	4	170
Brazil	320	6.5	49
Kazakhstan	260	1.8	144
Other countries	4,545	19.26	236
World Total	67,825	260.76	260

[a] The magnitude in the variations of reserves across countries indicates geopolitical concentrations. Figures based on USGS 2017 data.
[b] Production rates are based USGS 2017 data and vary widely across countries.
[c] The rates indicate that over time (ceteris paribus) phosphate rock production will become dependent on a few countries that are not currently global suppliers (i.e China and the US).

Thus, as phosphate rock is a non-renewable resource in economic terms (Scholz & Wellmer, 2013), there is a possibility of a supply side peak in which production reaches a maximum and plateaus or decrease. If current phosphate rock countries maintain current levels of production, then global output of phosphate rock could drop to 79.3 tons by 2055, assuming 2016 production rates (USGS

2017). Thus, conducting a global R/P study can leave a skewed perception of the true economic situation behind reserves.

Figure 2 Global Phosphate Rock Production Deficit (2015-2060)



[A] Production data is based on USGS 2017 data.
[B] Demand for phosphate rock is expected to increase annually until 2050.

Despite these challenges and criticisms, the R/P ratio provides an interesting vantage point for enhancing CGE modelling with phosphorus. They demonstrate an interesting future development in phosphate rock production – a potential supply deficit. R/P models show that at current rates, production in key phosphate rock suppliers will end before we reach 2050 if no new production is added. This is a critical notion because shortages will have a feedback effect through rising prices in the global food chain. These are effects which food security analysis attempt to map.

R/P ratios also offer an understanding of the importance of geopolitical concerns that can be incorporated into CGE modeling. As reserves and production are highly concentrated, supply shortages could result from export restrictions, evinced in 2008 when a 135 percent export tax in China virtually ceased exports of phosphate rock from a major supplier (Cordell & White, 2011).

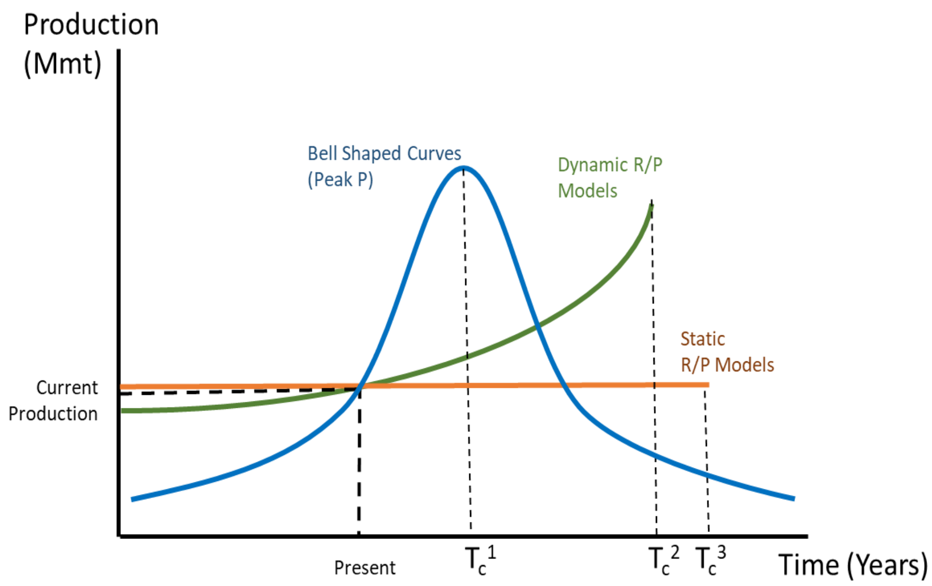
Not only is the amount of reserves for modelling agricultural production important, but also how maintaining or increasing global production levels will affect prices. As phosphate rock has grades (van Kauwenbergh 2010), over time the less expensive, higher quality ore will be extracted leaving the costlier deposits to mine (May, Prior, Cordell, & Giurco, 2012). If rising production costs have a dramatic downstream effect on prices, demonstrating decreasing quality becomes paramount.

4.3 Peak Phosphorus Modelling

Striving to overcome the simplistic nature of the R/P ratio models, several studies apply more dynamic modeling techniques to phosphorus scarcity modeling (see table 5). Labelled Peak Phosphorus and based on the Peak Oil concept developed by Hubbert in 1959, time series analyses can be employed to forecast the peak of production (Hubbert, 1959). The underlying premise is that revenue from extraction induces investment in more extraction and thus production rises. As phosphorus has grades (Van Kauwenbergh, 2010), mor

e mining means facing declining ore concentrations (May et al., 2012). At some point, mining costs increase due to decreasing ore grades to a level where extraction is no longer economical and thus declines (Scholz & Wellmer, 2013). In both the beginning and the end, there is low production and a peak occurs to when nearly half of the Ultimate Recoverable Resources (URR) is extracted, thus taking the form of a bell-shaped curve as seen in figure 3.

Figure 3 Graphical Demonstration of R/P and Peak Phosphorus Models and Their Critical Points in Time (T_C)



A key factor in this method is the use of historic production data and a constant URR to predict future production. As the URR acts a constant in the modeling, it will have significant effects on the results. The spread of model results in table 5 with peaks ranging from 2033 to 2136 demonstrates how the various URRs can influence the outcomes. These studies design a best fit production curve using the URR. However, as with the R/P models, the URR is a static estimate based on a dynamic demand and reserve scenarios. Thus, these curve fittings are sensitive to changes in estimates. Moreover, unlike R/P models, curve-fitting models are more likely to describe production patterns they take historical production trends into consideration (Scholz & Wellmer, 2013). Thus, curve-fitting models alongside R/P models can be viewed as early warning indicators, but not predictions.

Table 5 Review of Peak Phosphorus Models

Author	Peak Year	Size of Reserves	Assumptions
(Cordell et al. 2009)	2033	16.5	URR[a] calculated as sum of production and reserve data
(Cordell & White, 2011)	2051–2092	60	URR calculated as sum of production and reserve data
(Déry & Anderson, 2007)	USA 1988 World 1988	2	Aggregated world production data
(Mohr & Evans, 2013)	2020-2136	6.7 - 57	Different URR for regions
(Ward, 2008)	1990	24.3	URR based on USGS reserve estimates
(Walan, Davidsson, Johansson, & Höök, 2014)	Mid 2080s	67	URR calculated as sum of production reserve data

[a] The Ultimate Recoverable Resource is a subjective estimate of total reserves available for extraction within technological and economic constraints.

Curve-fitting approaches also make no mineral-specific assumptions regarding phosphorus production. Phosphate rock is mined largely through surface mining which can have substantial environmental impacts such as water contamination and waste generation (Van Kauwenbergh, 2010). Both phosphate rock production and refinement is water intensive which could raise concern as some countries, such as Morocco, already suffer from water scarcity (Ridder, de Jong, Polchar, & Lingemann, 2012; Walan et al., 2014). Yet both R/P and curve fitting models do not demonstrate these linkages. Thus mineral assessments – and for greater food security modelling- it is important to know how phosphate deposits are located and if regional or global scales are taken as these might cause supply constraints.

Moreover, the market for phosphorus is demand driven largely due to its essentiality, geopolitical concerns, and the current lack of recycling (Heckenmüller et al., 2014; Scholz, Roy, Brand, Hellums, & Ulrich, 2014; Scholz & Wellmer, 2013) This also questions the appropriateness of supply drive curve-fitting models as it is difficult to make accurate estimates of resource lifespans due to the static nature of the model and the dynamic nature of the reserve base.

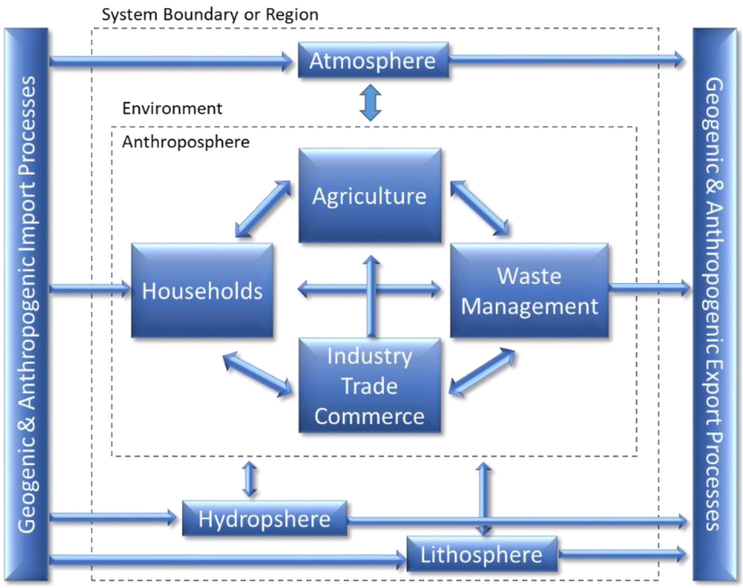
In sum, curve fitting models offer CGE modelling a similar analysis to the R/P models. Both indicate the longevity of reserves and physical depletion need to be incorporated into any economic analysis. Moreover, as both model types are based on dynamic estimates using similar USGS data and both produce widely differing conclusions showcasing the need for reliable and accurate data production and phosphate rock data. A snapshot at best, both do not provide any economic analysis regarding the implications if either model's worst case scenario should occur – a shortage in production.

Where curve fitting models differ, however, is in their focus. Unlike the R/P models that showcase their critical point as when the resource is depleted, the critical point for curve-fitting models is when production reaches a maximum. As it is unlikely that production will abruptly stop as the R/P models show, this highlights the critical point after which we face costlier production and higher prices could be a peak in production that occurs well before reserves run dry. Thus, in adding phosphorus to economic modelling, the ability to show case decreasing supply and changes in prices is paramount.

4.4 Substance Flow Analysis

Borrowed from Industrial Ecology as a tool used to aide environmental management, the Substance Flow Analysis (SFA) is a material accounting tools that analyzes the movement of a particular substance through the anthroposphere. The approach is based on the principle of mass balance and permits a systematic mapping of the flows of a substance through sectors and regions (Brunner & Rechberger, 2005). Figure 5 demonstrates a basic substance flow analysis. It defines the system boundary and the select the processes, materials, and substances that are analyzed. Subsequently, the movements (flows) of the substance and the concentrations (stocks) are identified and quantified. The flows and stocks are then calculated and the results are presented visually in order to facilitate decision making processes (Brunner & Rechberger, 2005).

Figure 4 Demonstration Basic Substance Flow Analysis



SFAs highlight at which scale or level the various dimensions of phosphorus scarcity come into play as SFAs can be designed at different geographical scales (Cordell, Neset, & Prior, 2012). Global studies (see Bouwman et al. 2009; Senthilkumar et al. 2012; Liu et al. 2008; Villalba & Liu 2008) focus environmental pollutants, fertilizer mining and production, and losses from agriculture. Studies conducted at the regional and national levels (see Suh & Yee 2011; Withers et al. 2015; Smit et al. 2010) predominantly focus on sustainable management and pollution. Moreover, at a regional scale, the potential for assessing the largest areas of phosphorus losses in food systems becomes evident. Secondly, SFAs highlight key flows and problem areas and provide a snapshot of where the major losses, leakages, and accumulations of a substance occur (Matsubae-Yokoyama et al., 2009). These demonstrate potential supply concerns as well as indicate that both reducing losses and incorporating recycling technologies offer opportunities for increasing phosphorus use efficiently and reducing losses.

Such scopes can benefit CGE modelling by identifying how phosphorus moves within sectors as well as opportunities where recycling technologies can be implemented. A regional or national study can consider phosphorus imports and exports of phosphorus from a country or region in terms of crops, livestock, and animal feed, etc (MacDonald, Bennett, & Carpenter, 2012). Not only does this demonstrate an explicit trade of phosphorus in terms of imports or export of P fertilizer or phosphate rock but also a hidden or embedded trade of phosphorus in crops and animal products.

However, SFAs are not without limitations. SFAs are only concerned with one substance at a time in one particular zone increasing the risk that a critical linkage or problem area maybe overlooked (Tangsubkul, Moore, & Waite, 2005). Lastly, SFAs do no provide information regarding the drivers and actors behind stocks, flows, and management in phosphorus scarcity (Metson et al., 2015; Senthilkumar et al., 2012). Another issue limiting the SFAs is the availability and quality of data (Cordell et al., 2012). Accurately assessing phosphorus flows and stocks without reliable and consistent data becomes very challenging (Bouwman et al., 2009; Smit et al., 2010; Suh & Yee, 2011; Villalba & Liu, 2008). Moreover, as system boundaries, flows, and processes are specific to the studies and their objectives, then scaling up or scaling down to different levels becomes challenging and thus limits the comparability of studies across zones of study.

5. The Gaps in Phosphorus Scarcity Modelling

Thus far we have seen how the three model types can contribute to enhancing CGE modeling. Static and dynamic R/P models showcase there is a potential future gap between production and demand as well as geopolitical concerns caused by production concentrations need to be considered. Peak phosphorus modeling through its widely differing conclusions demonstrates the need for more dynamic features in modelling and give rise to the concern of the effects of a peak in production. Lastly, SFAs highlight the role that scale and aggregation can play in assessments, the gravity of phosphorus moments and flows, and the part that recycling or loss prevention technologies have to play determining future solutions.

Gap 1: Missing Demand and Demand Drivers

Although the phosphate rock market one day may succumb to a supply driven peak as the models indicate, the geopolitical nature, unsubstitutability, and limited recycling technologies of phosphorus are evidence that the phosphate rock market is demand-driven (Heckenmüller et al., 2014; Scholz, Ulrich, Eilittä, & Roy, 2013; Scholz & Wellmer, 2013). However, in the models in this review, demand is represented though production rates and neglects the dynamic drivers behind demand. However, incorporating phosphorus into CGE modelling offers an opportunity to evaluate how demand changes such due to shifts in prices increases from pressures, technological change, or levels of consumption affect the level of demand as demand in CGE modelling operates on utility functions derived from economic theory as functions of consumption, income, and a consumption minimum.

Gap 2: The Role of Prices

In a market economy, prices act as signals for shortages and surpluses aiding firms in responding to changing market conditions. Thus, when utilizing a market (supply: demand) viewpoint on resource scarcity, it is paramount to consider the role prices play as the linkage between changing demand and constraints in supply. However, as the models in this review only demonstrate the supply side, it is impossible to fully explore the extent of any price effects caused by changes in demand or constraints in supply. For example, as the price of mineral commodities increase, producers strive to augment production in order to increase profits. This occurred in the phosphate rock industry in the 1970s (Rawashdeh & Maxwell, 2011). What remains unclear if the recent price increases will have the same effect as the price increases in the 1970s.

While these models may act as 'early warning indicators' that signal a need for urgency for changes in technology or efficiency, with regards to prices the economic implications rely mostly on microeconomic theory (e.g. a supply shortage will cause prices to rise). However, once incorporated into CGE models, studies could show the effects of price changes due to shortage or bumps in supply, productivity changes due to new technology, and effects of the fluid boundaries of reserves, etc. On the demand side, CGE modeling can show how prices are affected by demand side factors such as changes in population and diets, policies, environmental regulations.

Gap 3: Flows and Movements

A spatial redistribution of nutrients occurs both explicitly through a physical transfer a nutrient needed to produce a commodity and implicitly via the nutrients embedded in traded commodities. Phosphate rock and phosphate fertilizers are two heavily traded commodities with 29 million tonnes traded globally in 2015 (IFA 2017). Although phosphate fertilizers remain the predominate way through which phosphorus moves within the anthroposphere (Schröder et al., 2010; Van Kauwenbergh, 2010) , transfers of phosphorus also occur through both through imports and exports of agricultural products. However, the models reviewed lack traded commodities. Conversely, as CGE models employed in economics utilize imports and exports both from countries and regions, this provided an opportunity to showcase concerns in international trade. This is could be of particular concern for countries or regions which are net exporters of agricultural products but net importers of phosphate rock and fertilizers. Moreover, as trade depends on low cost fossil fuels (Rawashdeh & Maxwell, 2011), in a carbon-limiting future, transporting millions of tons of phosphate rock and fertilizers may become more challenging and costly.

Gap 4: Technologies

Innovations into phosphorus mining processes or recycling technologies are well explored in the debate on phosphorus (see Cordell et al. 2009; Metson et al. 2015; Scholz et al. 2015; Withers et al. 2015) but again what lacks are the economic implications of implementing these technologies. The models in this review highlight the need to include changes in technologies and opportunities for recycling but fall short of the analysis potentially offered by a CGE model.

When there is a shortage of a good in a market economy, prices will rise signaling a feedback effect through the economy that, on the supply side, will induce new efforts for exploration, new mining and production processes, and developing or enhancing recycling technologies. On the demand side, this will induce more efficient usage, waste reducing processes and, if possible, substitution to others goods. As better recycling technologies may play a greater role in making phosphorus use more sustainable, CGE modeling can simulate and analyze these effects such as changes in phosphate rock reserves and technological developments due recycling and new technologies.

6. Concluding Remarks

This paper highlights the mineral resource gap in computable general equilibrium modelling and proposes filling this gap can enhance food security analyses. As sustainable phosphorus management is becoming a growing concern, understanding the implications of changes to the price, supply, technology of this most basic input in food production is key. Moreover, while phosphorus management is not itself devoid of models, the analyses currently employed focus predominately on the longevity of phosphorus supply and environmental pollution and neglect the economic implications. This paper highlights those models and demonstrates how they can contribute to enhancing CGE modeling. Thus, the framework in this paper permits researchers to build a broader understanding of the context within phosphorus management and thus our understanding of phosphorus in our economy.

Summarizing our findings, we can state four main gaps exist in current phosphorus analysis that can be filled by incorporating phosphorus into CGE modelling. Understanding linkages between demand, drivers, prices and technologies can help identify relationships and feedbacks, and thus recognize positive or negative effects on multiple aspects of sustainability. The ultimate goal is to achieve food security and our framework takes an important step in achieving this.

There is much to be studied in this field. More in-depth analysis of how reserves in China and Morocco and the effect that policies in these countries could have on global supply would aid in estimating the future of phosphate rock production and the possibility of a shortage. Moreover, as mining phosphate rock is water and energy intensive, a study of how limits in these factors affect the maxim limit of production would be beneficial. Lastly, studies for other nutrients such as nitrogen or potassium could also be conducted as it is not impossible that one could generate a constraint for future food production.

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