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Global phosphorus supply chain dynamics: Assessing regional impact to 2050

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ABSTRACT

Phosphorus (P) availability is essential for global food security. A system dynamics model running from 1961 to 2050 was built for this study, linking global P supply to social, economic and environmental dynamics at regional level. Simulation results show that phosphate rock (PR) production needs to double by 2050 compared to present levels, in order to match regional P requirements. South Asia, Latin America and the Caribbean, and Sub-Saharan Africa are regions highly dependent on phosphate imports, yet it is here that most of the population growth and future P requirement will occur. Climate impact, eutrophication and phosphogypsum production are some of the main negative environmental dynamics that are becoming increasingly challenging in the coming decades.

1. Introduction

The 800% price spike in phosphorus fertilizers in 2007–2008 sent a shock wave through the markets and led to a significant increase in food prices (Cordell and White, 2011). It also shifted attention to phosphorus (P) as a scarce resource and prompted the emergence of a “peak phosphorus” discourse, centred around global scarcity of phosphate rock (PR) as source for phosphate fertilizers (Cordell et al., 2009; Ragnarsdottir et al., 2011). A change in reserve reporting methodology proposed by the International Fertilizer Development Centre (IFDC) in 2010 (IFDC, 2010) led to the USGS revising its estimates of Moroccan and Western Saharan reserves from 5.7 to 51 billion tons and the world reserves from 16 billion tons to 65 billion tons (USGS, 2011). The methodology revision has been criticized by some academics (Edixhoven et al., 2014) but it nonetheless moderated the global P scarcity discourse, with some authors highlighting the dynamic character of reserves (Scholz and Wellmer, 2013). Focus on phosphorus has remained at a regional and national level, particularly in the European Union (EU), where the European Commission included P in its list of Critical Raw Materials in 2014 (European Commission, 2014). Some EU Member States such as Germany, Sweden or Switzerland also adopted national strategies to recover P from wastewater and reuse it in agriculture (Nedelciu et al., 2019).

Although aspects of the global scarcity discourse on P have been questioned (Scholz and Wellmer, 2013; Ulrich and Frossard, 2014), there are major inequalities in the geographical distribution of PR reserves and the rates of P consumption globally. Morocco and Western Sahara account for 71.5% of all reported PR reserves (USGS, 2019) and the other major producers of PR – notably the US and China – are decreasing production or halting exports (Rosemarin and Ekane, 2016). Fertilizer outlook reports from the Food and Agriculture Organization (FAO) show that while globally the potential phosphate balance – total supply minus total demand – is positive, there are regions where this balance is negative. These regions are Central Europe, Western Europe, Oceania, Latin America and South Asia (FAO, 2017). In FAO’s analysis the regions of Africa, East Asia and East Europe and Central Asia exhibit a positive potential balance, which is nevertheless a result of only a handful of countries owning large reserves: Morocco and Western Sahara, Algeria, South Africa and Egypt for Africa; Russia for Eastern Europe and Central Asia; and China for East Asia. The regional balance is extremely relevant for food security, particularly in the context of an increasing world population that is also showing different growth rates depending on world region (UN, 2020).

Studies on inorganic P production and use point toward an 80% loss from mine to fork (Cordell et al., 2009) and to only 10% of the processed fertilizers being digested by humans (Scholz and Wellmer, 2015). More than half of the losses from fertilizer application on soil to fork are in runoff from agricultural land (Scholz and Wellmer, 2015). Finally, the

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digested P finds its way into human waste, which can then enter wastewater or – as it is the case for most of the world's population – be discarded outside of a wastewater collection system, including uncontrolled open disposal. According to the UN wastewater assessment, untreated or inadequately treated wastewater is acknowledged to have three main negative impacts, namely on 1) human health; 2) the environment; and 3) economic activities (UN, 2017). Runoff of P and the P in untreated wastewater are some of the main causes for eutrophication and, in the more extreme cases, the development of "dead zones" lacking in oxygen. The International Resource Panel (IRP) estimated that there are around 400 dead zones worldwide, with a combined size similar to that of the UK (International Resource Panel IRP, 2019). Eutrophication and the creation or expansion of dead zones have significant negative effects on the environment and the livelihoods of people living in the affected coastal areas (IRP, 2019). Furthermore, phosphorus-rich runoff from the PR mining sites can negatively impact marine biodiversity and threaten sensitive ecosystems such as coral reefs (Martinez-Escobar and Mallela, 2019).

The climate change impact, as well as the air pollution attributed to the cradle-to-grave of inorganic P have increase by 25% in 2015 compared to the 2000 level (International Resource Panel IRP, 2019). Mining and processing of PR account for almost all of the negative impacts of the P supply chain on the climate and on air quality (International Resource Panel IRP, 2019). In addition to the eutrophication effects, the global P supply chain is responsible for a considerable amount of processing waste. In order to produce phosphoric acid, which is the base for all phosphate fertilizer products, a by-product called phosphogypsum – or calcium sulphate hydrate – is produced. Scholz and Wellmer (2015) estimate that for each ton of phosphoric acid produced, 5.5 tons of phosphogypsum result as a by-product. Most of this toxic waste is kept in tailing ponds and it also contains high rates of heavy metals such as cadmium (Cd) and radioactive elements such as uranium, all present in the composition of PR deposits (de Boer et al., 2019).

Comprehensive studies on the phosphorus supply chain have included global quantitative models and the results of these studies pointed toward phosphorus scarcity (Ragnarsdottir et al., 2011; Sverdrup and Ragnarsdottir 2011, 2014). In their system dynamics model, Ragnarsdottir et al. (2011) singled out population size as the main driver for P consumption and demand. The authors took into consideration recycling in their quantitative system dynamics model, by which they meant any recapture of P-containing waste, such as food industry waste, human waste and animal manure. Van Vuuren et al. (2010) used a trade and production model to investigate concerns about P depletion and concluded that there were no signs of short-term to medium-term depletion. In their study, the authors compare results of a medium and high resource estimate, which only points toward a 10% decrease in absolute resources by 2100, to that of a low resource estimate, which points toward a 40–60% depletion by 2100. All of the studies referred to above used P data from before the phosphate rock resource revision of the USGS and IFDC took place. Mohr and Evans (2013) ran three scenarios of peak phosphate production in a demand-production interaction resource model and found 2011 (28 million/tons per year), 2027 (50 million tons per year) and 2118 (55 million tons per year) for the low, best and high estimate scenarios respectively. While Van Vuuren et al. (2010) and Mohr and Evans (2013) had a regionalized approach with regard to the production of PR, the relative absence of regional studies in the literature is noteworthy, given the differences in terms of P requirements, supply, price sensitivity of different regions and the environmental impact of P. Regional differences in terms of consumption, supply and environmental impact of the global P supply chain have not been included in studies so far. The need for regional studies for the biogeochemical flow of P was highlighted by e.g. the Planetary Boundaries study (Steffen et al., 2015).

1.1. Aim

This study aims to develop a first regionalized system dynamics model for the requirement and supply of phosphate fertilizers, in order to assess to what extent global supply will be sufficient for regional phosphate fertilizer consumption given population growth up to 2050. In addition, the paper aims to assess the regional and global environmental impact of the mined phosphate for the same period. Thus, the present study aims to contribute to what Wellmer and Scholz (2015) called "the right to know". The authors argued for more transparency and publicly available information with regard to the P supply chain, due to P being a resource essential to a basic human right: access to food. The following sections present the results of the model and discuss their implications, while at the same time comparing the results of this study with results from other relevant studies in the literature. The regional model described in this paper can be used for the elaboration of scenarios based on different agri-food system configurations, thus shedding light on the efficiency of various configurations on resource use.

2. Methods

The quantitative systems approach has a long tradition in resource studies (e.g. Meadows et al., 1972; Randers, 2012; Sverdrup and Ragnarsdottir, 2014; Pinto et al., 2019). System dynamics (SD) modelling allows the transition from theory/conceptualization to a quantifiable evaluation of the interaction between feedbacks, delays, accumulations and non-linearities in the phosphorus supply chain. For the SD modelling stage, the world was divided into eight regions: North America (NA), Europe and Central Asia (ECA), Latin America and the Caribbean (LAC), North Africa and West Asia (NAWA), Sub-Saharan Africa (SSA), South Asia (SA), East and South-East Asia (ESEA) and Oceania. The detailed country composition table per world region can be found in the Supplementary Material.

Sterman's (2000) modelling process was used for the SD model, following a five-stage process. In the first stage, problems are articulated, namely supply of P to the world's regions to match population growth, as well as environmental impact of the P supply chain. In the second stage, dynamic hypotheses are formulated, which in this study are presented as Causal Loop Diagrams (CLDs) and flowcharts. The third stage is the formulation of a simulation model, which in this case is an SD model in STELLA. The CLD, flowchart, model and model data are available open-source at: https://adaptecon.com/publications/ in the "Models" section. In the fourth stage, the model is tested, which in this study implied comparing model results from 1961 to 2019 to historic reporting. The fifth and last stage is policy design and evaluation, where the process is repeated. For the current model, three main policy scenarios are tested: first, the policy of recycling P from wastewater alone, when P requirement overtakes supply in order to match consumption rates, as this solution has covered a significant body of literature. Second, the policy of an increasing mining production alone to match the P requirement. Thirdly, both P recycling and increasing mining production when P requirement overtakes supply. The extended "Methods" section detailing the main assumptions, data sources and calculations in the model can be found in the Supplementary Material.

3. Results

3.1. Population and regional P requirements

The relationship between PR mining and fertilizer production is captured in Fig. 1 and is based on accurate historical behaviour (USGS, 2019); it shows a gently sloping increase for global fertilizer supply but a steeper one for PR mining (Fig. 1). This means that the ratio of mined PR quantity and processed fertilizer is increasing. In other words, more PR needs to be mined for the same amount of fertilizer. In 1961, 43.7 million tons PR had to be mined for 12.9 million tons of fertilizer. By

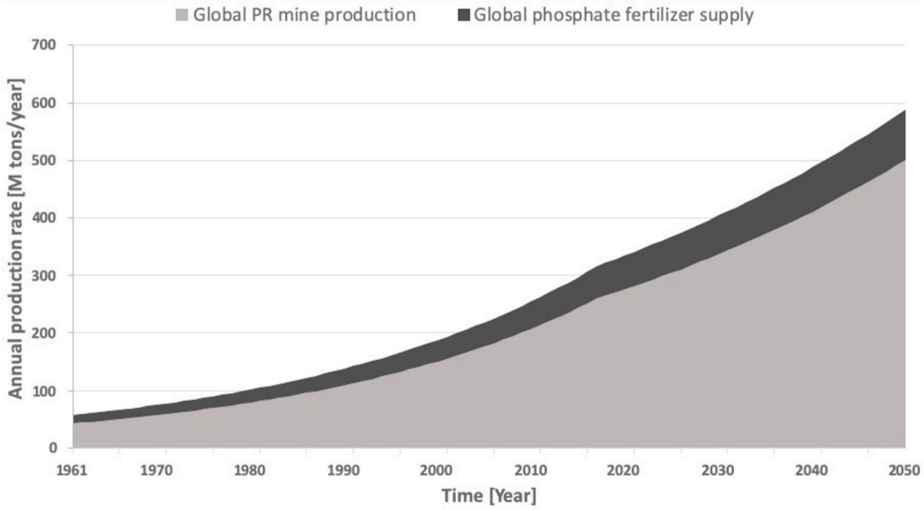

Fig. 1. Business-*as*-usual simulation of global PR mining and global phosphate fertilizer supply (M tons/year) using historical trends and FAO's current CAGR predictions.

2050, 526 million tons of PR will need to be mined for 90.1 million tons of fertilizer.

Fig. 1 shows that for one unit of fertilizer in 1961, 3.38 units of PR was mined. In 2050, this will increase to 5.84 units of PR per one unit of fertilizer. The literature indicates that this increase in the PR/fertilizer ratio can mainly be attributed to two factors: a decrease in the ore grade - so the P_2O_5 concentration in the mined PR (Ragnarsdottir et al., 2011) - and the losses incurred at the mining and beneficiation stages (Scholz and Wellmer, 2015). Nonetheless, technological advancements at the initial stages of mining, extraction and beneficiation were not considered in the model. Such advancements can decrease the PR/fertilizer ratio by increasing recovery levels for phosphate ores, or by increasing the amount of PR at marketable concentration rates from the initial beneficiation process (Geissler et al., 2018).

Fig. 2 shows phosphate fertilizer requirement tied to population per world region (a) and the population dynamics (b). South Asia (SA), and Latin America and the Caribbean (LAC) are the regions where most growth in P requirement will occur in the future. North Africa and West Asia (NAWA) and Sub-Saharan Africa (SSA) will also experience noticeable increases in P requirement, while in Europe and North America there will be little, or no requirement increase. Note that most of the population growth will occur in Sub-Saharan Africa, Asia and Latin America and the Caribbean. The graph in Fig. 2a also shows a steep decrease in the fertilizer requirement in East and Southeast Asia post-2014, which was preceded by a steep historical increase in demand. Most of the requirement in this region can be attributed to China.

3.2. *Supply and requirement*

Between 1961 and 2014 there have been two instances when the global phosphate rock prices spiked, in mid-1970s and 2007–2008 (Fig. 3a). Both events are linked to an economic trigger. The first instance was during the first oil crisis, and it was driven by the increase in energy prices (Mew, 2016). The second one is attributed to a combination of oil price increase, higher labour costs and insufficient mining capacity (Scholz et al., 2014). However, there is no clear correlation between price fluctuation and consumption by region, as Fig. 3b shows. This can – to a great extent – be attributed to governments subsidizing fertilizers and the largely non-elastic P requirement for food.

In the model, the only factor affecting supply is the relationship between global P requirement and fertilizer production. If P requirement is higher than production, then the model sends a signal for P recycling from wastewater, increased mining production, or both (Fig. 4b). The model assumes that with an increase in global P prices due to higher-than-supply demand caused by P requirement overtaking supply, P recycling from wastewater can become profitable or prioritised by governments for national food security reasons.

The model calculates a higher-than-supply requirement in 2040, when current production rates are not sufficient to satisfy a world requirement for P tied to population growth (see Fig. 4a). With a fully operational P recycling and a minimal increase in PR production to compensate for supply deficiency, world requirement overtakes global P supply in 2045, albeit at a lower deficit rate (Fig. 4b). A fully operational P recycling sector can only provide 10% of the total global supply by 2050 (see Fig. 4c). The percentage is based on 10% of the P fertilizer ending up in municipal wastewater, as the total amount of P digested by humans (Scholz and Wellmer, 2015). It does not take into account P in wastewater associated with industrial activity due to lack of data. This can explain differences with research carried out in Europe, where some studies have suggested much higher rates of up to 20% of the European demand that could be satisfied by recycling P from municipal wastewater (European Commission, 2017).

3.3. *Eutrophication, climate change and toxic by-products*

The model calculates the amount of P reaching water bodies in each of the world regions (Fig. 5a), as a combined sum of P from agricultural runoff and P from untreated wastewater released in water bodies. It uses the numbers advanced by Wellmer and Scolz (2015), namely 50% of the produced inorganic fertilizers in runoff and 10% in wastewater. It does not take into account industrial wastewater or food waste for wastewater (see previous section) and it assumes that no measures to counteract P runoff to water bodies are taken.

The amount of P in wastewater is a minor faction of the total P reaching water bodies, mostly due to the share of runoff from agricultural land. By 2050, the total amount of P reaching water bodies in the world will amount to almost 50 million tons per year (Fig. 5a). This is a scenario in which all water is treated by 2040 or earlier, and is based on the rationale that all regions will reach their SDG 6 Target 6.3 of halving the rate of untreated water by 2030. The regions recording the highest increase in P requirement – Latin America and the Carribean, Southern Asia and North Africa and West Asia – will record the highest increase of P in their inland and coastal water bodies. East and Southeast Asia will continue to have high rates of P reaching water bodies. Steffen et al. (2015) pointed toward several agricultural areas with very high P application rates as the ones responsible for the transgression of the

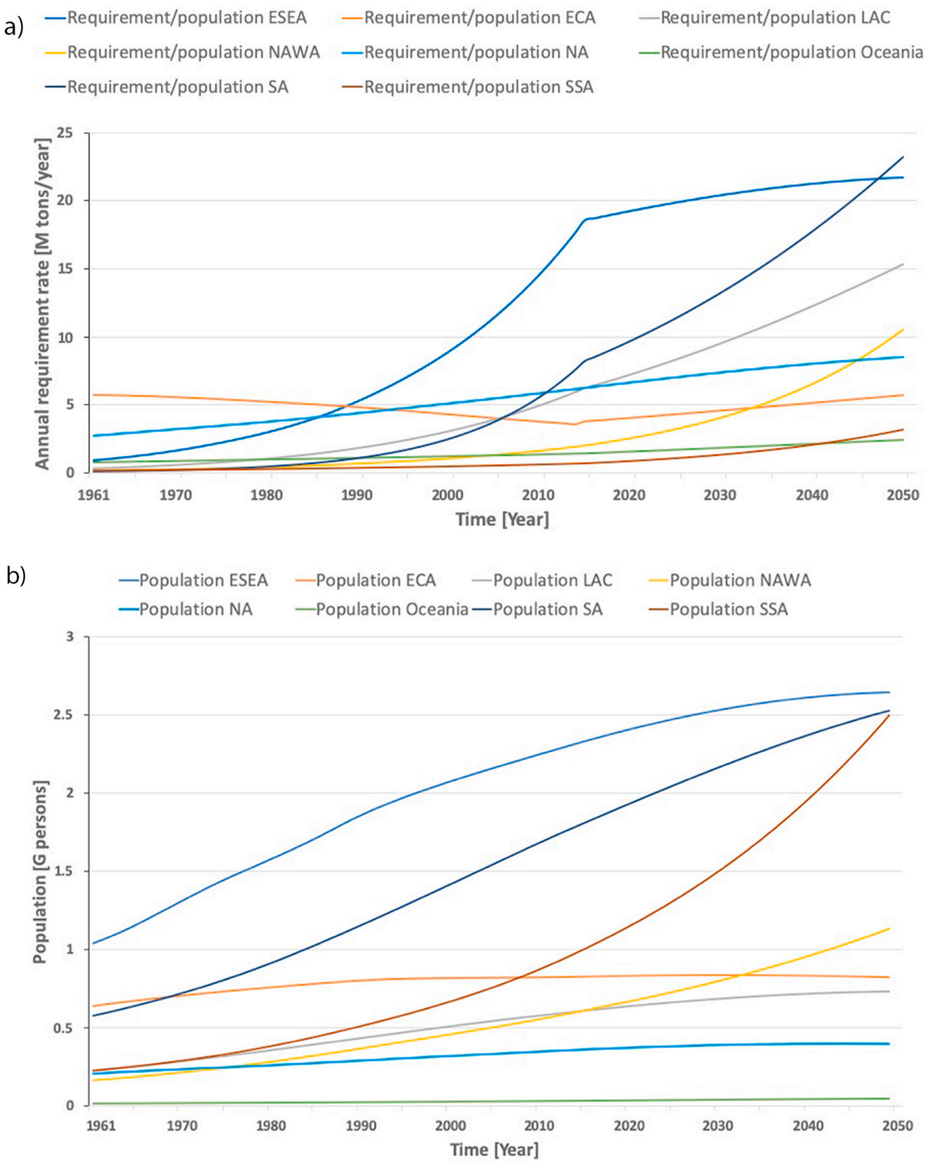

Fig. 2. (a) Business-*as*-usual model simulation of fertilizer requirement tied to regional population, and (b) a simulation of regional population development.

biogeochemical Planetary Boundary for P in a zone of high risk. These regions are, at present, the US mid-West, Western Europe, the Ganges Valley and East Asia.

While in Europe the consumption of P has been constantly decreasing over the years, in North America it has been increasing, albeit at a very low rate (see Fig. 2a). According to the mapping of dead zone carried out by NASA (2010), the location of dead zones corresponds to the drainage coasts for rivers in the high P-application rate regions: Eastern Coast of the US and the Gulf of Mexico for North America; the Baltic Sea, the English Channel and the Irish Sea for Western Europe; and the Yellow Sea and the East China Sea for East Asia.

In terms of the climate change impact of cradle-to-grave P, the model shows a doubling of the climate change impacts associated with mining and processing of fertilizers by 2050 (Fig. 6a), compared to 2000. Due to lack of data, the model does not index this to 1961. Phosphogypsum production rates will follow fertilizer production rates, recording a sevenfold increase by 2050 compared to 1961 rates and reaching 438 million tons per year (Fig. 6b). The total stock of phosphogypsum stored in tailing ponds for the period between 1961 and 2050 will reach almost 11 billion tons by 2050. Similarly, the stock of phosphogyspum that has been dumped in the water reaches over 5 billion tons for the same period (Fig. 6c). The numbers, however, are based on old data used by Scholz and Wellmer (2015) from Rutherford and Samek (1994), who concluded that for year 1980, 14% of the phosphogypsum was reused, 58% stored and 28% dumped into bodies of water. Updated data reflecting technology and processing practices development would yield different results. In particular, if more stringent environmental regulations have been implemented in producing countries, the amount of phosphogypsum reaching water bodies should be much lower. However, phosphogypsum has also been studied as a potential resource pool, with recent studies suggesting recycling it in the construction industry (Campos et al., 2017; Amrani et al., 2020). Agriculture use of phosphogypsum to improve soil structure and crop yield, reduce runoff and decrease soil erosion has also been examined, with some mixed results concerning the safety of phosphogypsum application to soils (Canova et al., 2018).

4. Discussion

4.1. Regional scarcity in P supply

While the results of the model might differ from other models in the literature, they generally point in the same direction. In the most recent

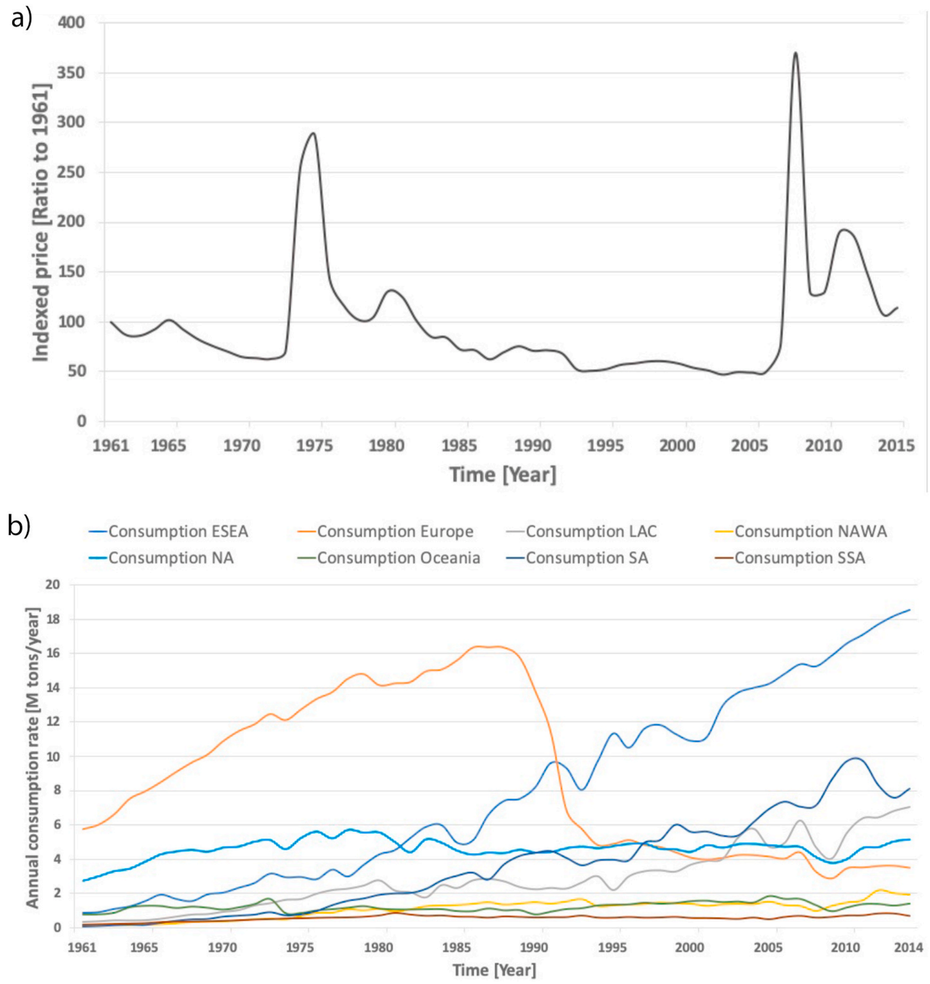

Fig. 3. (a) Phosphate fertilizer in US dollar prices indexed to 1961 and (b) Consumption of phosphate fertilizers by region for the period of 1961–2014 (data compiled from Our World in Data, 2014).

model developed by Sverdrup and Ragnarsdottir (2014), peak phosphate rock production is between 200 and 300 million tons per year (based on USGS P reserves from 2008). In this study, the PR production reaches 520 million tons per year in 2050, with the underlying assumption of fast deployment of regional P recycling sectors and new mining facilities. This difference is because in Sverdrup and Ragnarsdottir (2014), the PR production is tied to the global market and price. Our model assumes that due to the lack of historical correlation between price of PR and consumption of PR (see section 3.2) and because of the paramount importance of the food production sector for national policy makers, phosphate fertilizers will continue to be heavily subsidized. Moreover, in Sverdrup and Ragnarsdottir (2014) mortality is tied to phosphorus availability, while in the present study there are no feedbacks on population from phosphorus availability, or from other limiting factors such as water scarcity, pollution or climate change. Nevertheless, both studies point towards forms of P scarcity. Sverdrup and Ragnarsdottir (2014) point towards global scarcity caused by increased prices and failing PR reserves. Our results point toward a fast-developing P supply scarcity in some of the world regions. Moreover, for the mining rates presented in this study, the model shows a 17% exhaustion of the global PR reserves by 2050 compared to 2020, which is a significant amount considering the timeline of only three decades. In addition, results in both studies indicate a mismatch between P demand/requirement and phosphate fertilizer production.

The fertilizer rate result of 89 million tons/year by 2050 reached in this study is consistent with the default estimate of the Global Orchestration (GO) scenario from Van Vuuren et al. (2010), which places the global consumption of phosphate fertilizers around 95 million tons/year by 2050. However, in Van Vuuren et al. (2010) the world population reaches 8.2 billion people by 2050, which implies higher P requirements per capita in their scenario, compared to those resulting from compound annual growth rates (CAGRs) in this study. This is due to the assumption of the authors, who envisage rapid economic development and rapid expansion of agricultural production in their GO scenario. The results in Van Vuuren et al. (2010) combined with the regional P requirements in this study support the regional scarcity argument. Both regions where most population growth will take place – Sub-Saharan Africa and Asia – and regions where most P requirement is expected – Latin America and the Caribbean and South Asia – are regions with minimal production of phosphate rock and high import dependency. In Van Vuuren et al. (2010), the regions most dependent on P import by 2050 are South America, India, China and South-East Asia. In their study, Africa is a net exporter, however, this is because no differentiation is made between North Africa and Sub-Saharan Africa. Nonetheless, the authors acknowledge that Morocco alone will account for more than half of the PR production towards the end of the century. This is also consistent with the results of Mohr and Evans (2013), who stress the importance of Morocco and Western Sahara to meet shortfalls in production after 2030 and show Africa accounting for almost all supply after 2100.

4.2. *Implications for food security*

Although regional scarcity is a common aspect for many of the resources used by humanity nowadays, when it comes to phosphorus

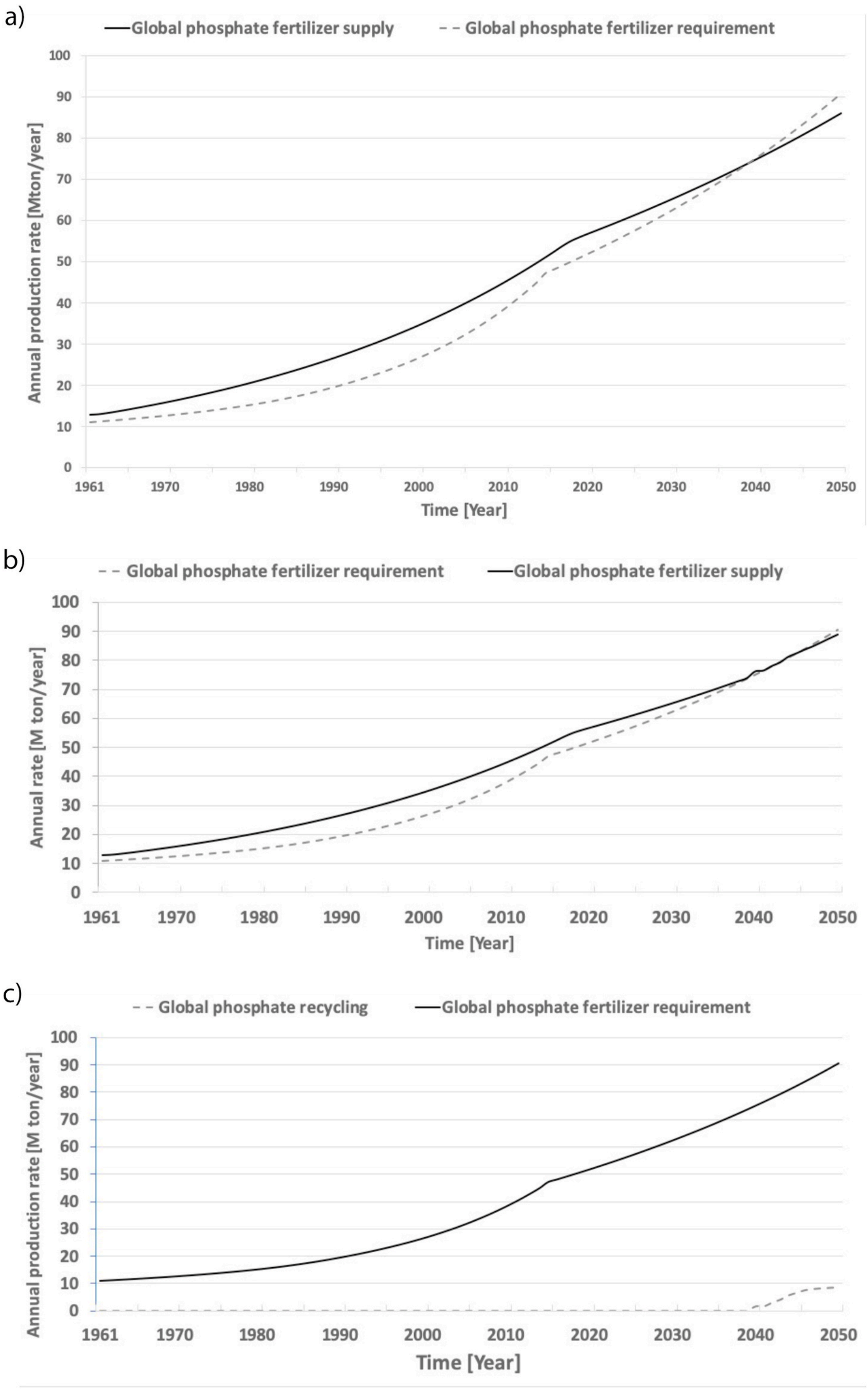

Fig. 4. (a) Requirement-supply relationship in a business-*as*-usual scenario, (b), requirement-supply when more PR production and P recycling are activated and (c) the share of recycled P in the total global phosphate fertilizer supply.

scarcity is connected to food production and thus to a basic human right: access to food. The main question arising from this study is how will the mismatch between world requirement and supply after 2040–2045 affect food security in LAC, SA and SSA. The results in the model show that SSA accounts for a minimal increase in global P requirement compared to the high rates of population growth. Fertilizer use in this region has been historically low and there are no signs that it will increase significantly in the near future. However, it also means that the region is currently at the lower end of the P response curve for crops and minor additions can, with adequate agricultural practices, be translated into significant gains in yields. However, it also poses the question of food security and whether the minor increases in per capita P requirements will enable Sub-Saharan Africa to feed its increasingly undernourished population in the longer term. The World Food Programme estimated that 265 million more people will be facing hunger in 2020 in addition to the already existing 821 million undernourished, partly as a result of the COVID-19 pandemic – a large proportion of this number lives in SSA (WFP, 2020).

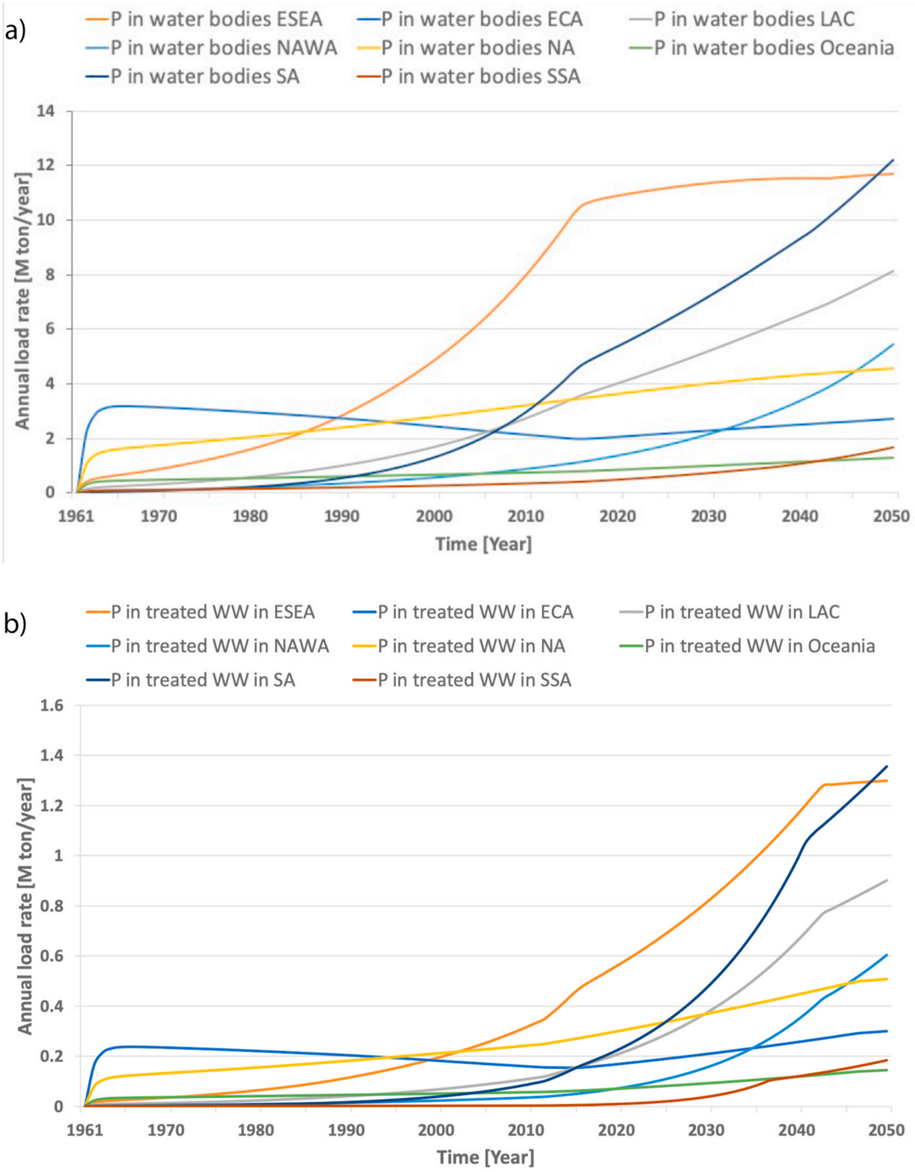

Fig. 5. (a) Phosphorus load in water bodies due to runoff and untreated water and (b) Phosphorus load in treated wastewater.

The potential increase in fertilizer prices combined with a high import dependency for LAC, SA and SSA will not only provide challenges to producing enough food but it can also threaten the livelihoods of small to medium scale farmers, who form the bulk of growers in these areas. It is worth mentioning that the CAGRs for P requirement tied to population could be higher than presented in the study. First, the CAGRs after 2014 are based on FAO Fertilizer Outlooks, which are generally lower than the historically observed CAGRs for 1961-2014. Second, in Van Vuuren et al. (2010) CAGRs would also be higher if their demand was tied to population. Thus, it is possible that the world requirement for P is higher than presented in this paper. At current production rates and with the population dynamics presented in this study, global phosphate requirement could overtake supply much earlier than 2040. In this scenario, the role of technologies aimed at making mining and processing of phosphate rock more efficient can be central to delaying the supply deficit. Moreover, developing safe processes to recycle phosphate from the growing phosphogypsum stocks can play an important role in adding considerable fertilizer amounts on the market.

When it comes to the regional scarcity of P supply, two processes can emerge from regions lacking enough P to produce their food. First, a higher dependency on international trade and food aid, with a transfer from regions that are either rich in phosphate reserves such as NAWA or from regions producing a surplus of food, such as ECA or NA. The former can be challenging considering the general aridity of the region, which poses limitations to soil productivity and water availability for agriculture. Further reliance on the latter can make P deficient regions more vulnerable at times where the global or regional food trade is affected by disruptive hazards, such as the current COVID-19 pandemic.

The second process is a reduction of the losses in the P supply chain, from the fertilizer market stage to the wastewater level – in other words, a move toward circular economy at national and regional level. Most of the losses in this supply chain segment occur as runoff from agricultural land. Tackling those losses by making fertilization more efficient and by recovering the P, which would otherwise reach water bodies, should be central to food security and circular economy policies. It also offers the benefit of decreasing or avoiding the negative environmental, social and economic impacts derived from the contribution of P-load to eutrophication.

4.3. Environmental implications

Another aspect that can be discussed is the extent of increase in

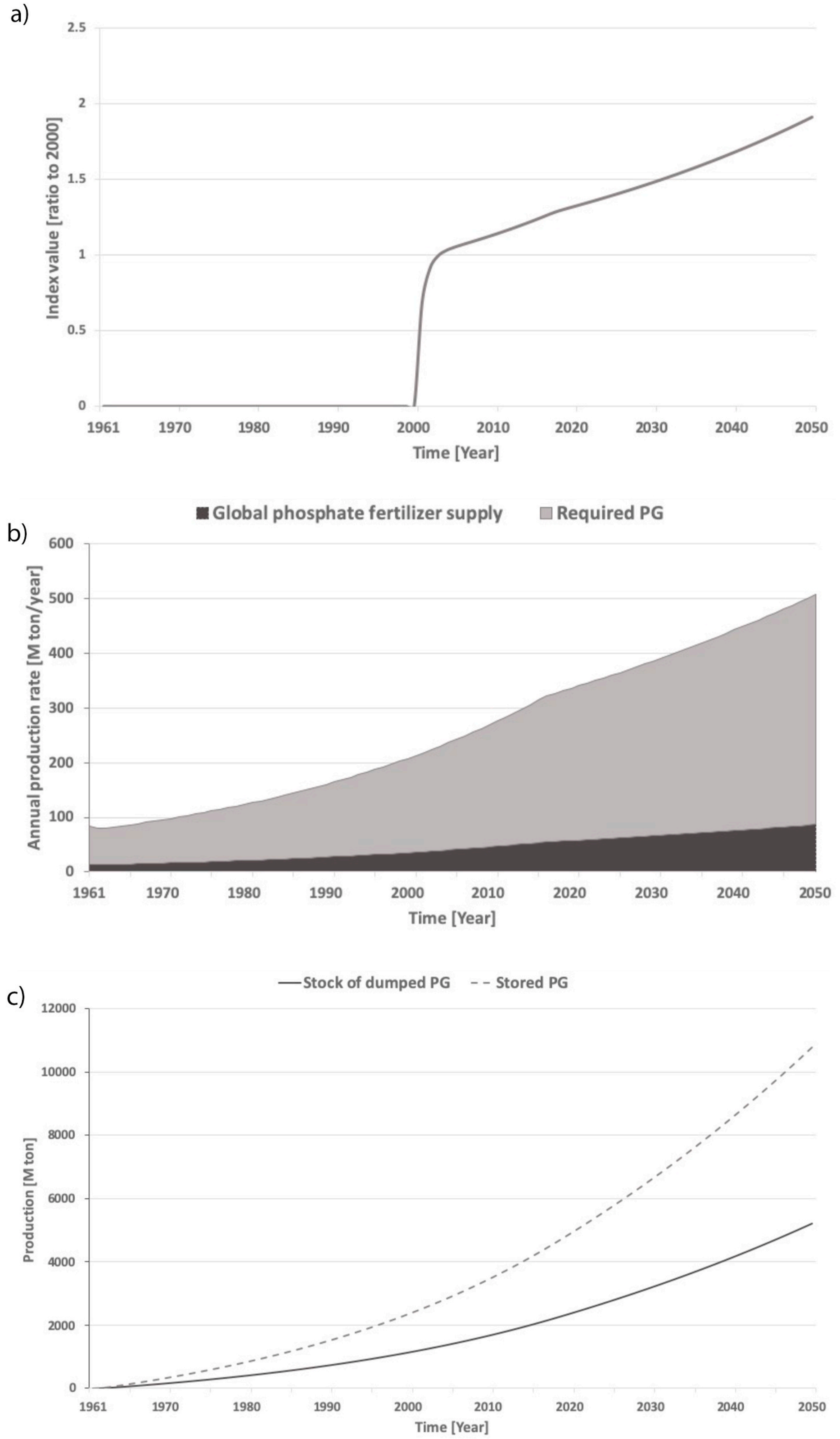

Fig. 6. (a) Impact of PR mining and fertilizer production on GHG emissions indexed to 2000, (b) phosphogypsum (PG) production per year required to produce fertilizers and (c) the total stocks of stored and dumped phosphogypsum.

phosphorus use in regions such as LAC and SA, which can pose serious environmental problems in the future and accelerate the present ones. Without radical measures to reduce P runoff from agricultural land and without ambitious wastewater treatment targets, these regions are likely to see further degradation of their inland and coastal aquatic ecosystems. In particular, the Gulf of Mexico and the Ganges Valley with the Bay of Bengal can be expected to experience additional P loads and further eutrophication. This would not only have further harmful environmental implications, but likely to negatively impact the economy and livelihoods of coastal communities in these regions.

At the same time, the almost doubling of PR mining rates from now to 2050 poses questions related to greenhouse gas emissions of the fertilizer sector, environmental degradation and energy consumption for mining and processing activities. Achieving carbon neutrality by 2050 – a pledge that an increasing number of countries are moving toward – will be challenging in the phosphate sector, considering that the model simulation indicates a doubling of the climate change impact by 2050 indexed to 2000. The increase is mostly due to the mining and processing PR sectors. It also raises the issue of the need to improve the management of by-product waste from mining and processing PR. There is already a considerable amount of toxic phosphogypsum in tailing ponds in producing countries. More updated information on how phosphogypsum is being managed is needed from the industry or state authorities responsible with regulating the phosphate industry. In addition, an increase in PR processing and fertilizer production is likely to lead to increased rates of water extraction for the chemical processes. In arid and water scarce producing countries like Morocco, Algeria or Egypt, this could pose a problem. On the other hand, ample groundwater resources in North Africa may make such concerns unwarranted in the longer term (MacDonald et al., 2012).

Recycling P from wastewater and phosphogypsum tail ponds could become viable in the future if requirement surpasses supply, a trend that in the model occurs after 2040 in a business-*as*-usual scenario. An increase in price due to higher-than-demand-supply could enable the recycling sector to become financially viable. Even so, however, the amount of P available for recycling from wastewater is a minor fraction compared to the amount available in phosphogypsum tail ponds. The latter are present in production areas, which can consolidate the global market share of the few exporting players.

Future research is needed to investigate in detail the impact of P supply on the feasibility to recycle P from phosphogyspsum and reduce runoff rates. For the former point, a feasibility analysis should not only investigate costs and technology availability, but also the health implications connected to using P recycled from a highly toxic by-product. For the latter point, a quantification of reduction in runoff rates by simulating different runoff-prevention measures would help in identifying the most viable regional solution. On the other hand, questions would arise with regard to the status of P runoff that is prevented from entering water bodies and whether this P can be reused on the land, whether it mineralises, or whether it becomes trapped in biomass, such as in tree strips.

5. Conclusions

The SD model presented in this paper indicates that fertilizer requirement will increase in regions experiencing high population growth rates, most notably LAC, SA and SSA. All three regions are highly dependent on phosphate imports, and the next decades will reinforce their dependency on imports. In a business-*as*-usual scenario, global P requirement will overtake global P supply after 2040. In a very optimistic scenario where fast deployment enables full P recycling from wastewater and additional mining facilities, global P requirement overtakes global P supply after 2045. The climate change impact from the mining and processing of PR will double by 2050 compared to 2000. Managing the large amounts of phosphogypsum by-product is on one hand a considerable challenge, but on the other hand a significant resource pool of P that in the future might become viable to recycle from. Phosphorus runoff accounts for half of the phosphate fertilizer losses in the supply chain segment starting at the fertilizer market stage and ending at food consumer level. At current P runoff rates and without ambitious prevention measures, more coastal areas and inland water bodies are likely to be subject to eutrophication. Tackling P runoff by means of increased efficiency use and circularity can be key to reducing reliance on P imports, and to decreasing environmental, social and economic impacts. The results of this study are particularly relevant for decision-makers working with food security and environmental protection at an international and regional level. However, they are also useful to policy makers at national level, in order to understand the broader regional dynamics deriving from the global phosphorus supply chain.

Declaration of competing interest

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Appendix A. Supplementary data

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