Global Phosphorus supply chain dynamics: Sustainability implications for the 21st century

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Abstract

Phosphorus is an essential yet irreplaceable macronutrient for agriculture and thus plays a key role in global food security. Most of the phosphate fertilizers are produced from phosphate rock, a finite mineral resource that is mined and processed at great environmental and social costs. Nonetheless, the present-day phosphorus supply chain transforms this valuable resource also into a major pollutant of water bodies. The research that is presented in this thesis investigated the sustainability challenges of the currently linear phosphorus supply chain and discussed their implications. The main methods used were literature and case study review, semi-structured interviews with stakeholders from the phosphorus sector, stakeholder analysis, systems analysis and system dynamics modelling. Five key messages emerged from this project.

First, it is necessary to close the loop throughout the phosphorus supply chain instead of focusing only on end-of-pipeline solutions. Second, in terms of monitoring data, the global phosphorus supply chain is a black box. This poses serious challenges to designing robust policies in food security. Third, industrializing world regions where most of the population growth is expected to occur in the coming decades are increasingly vulnerable to phosphorus scarcity. Fourth, in a business-as-usual scenario, the global supply chain of phosphorus will produce significant amounts of toxic by-products, will have an increasingly negative impact on the climate and will deteriorate the quality of water bodies. Finally, implementing low-input sustainable farming systems, such as agroecology, was shown to have the potentially largest impact in reducing P requirement and in decreasing the negative socio-environmental impacts of the global P supply chain.

Útdráttur

Fosfór er nauðsynlegt en um leið óútskiptanlegt næringarefni fyrir landbúnað og gegnir því lykilhlutverki hvað alþjóðlegt fæðuöryggi varðar. Flestir fosfatáburðir eru framleddir úr fosfatríku bergi, sem er endanlegt steinefni og er námugrafið og frekar unnið með miklum umhverfis- og félagslegum kostnaði. Engu að síður umbreytir núverandi fosfóraðfangskeðja þessari dýrmætu auðlind í aðalmengunarefni vatnsbóla. Rannsóknirnar sem kynntar eru í þessari ritgerð lúta að sjálfbærniáskorunum núverandi línulegrar fósfórkeðju og fjalla um afleiðingar þeirra. Helstu aðferðir sem notaðar voru í þessari rannsókn voru greining fræðirita, endurskoðun á tilviksrannsóknum, skipulögð viðtöl við hagaðila úr fosfórgeiranum, greining hagaðila, kerfisgreining og kvik kerfislíkanagerð. Fjórar lykilniðurstöður komu fram í þessu verkefni.

Í fyrsta lagi er nauðsynlegt að loka fosfórsbirgiskeðjulykkjunni í stað þess að einbeita sér einungis að lausnum sem varða lokun keðjunnar. Í öðru lagi, hvað varðar eftirlit, er alþjóðleg fosfór aðfangskeðja svartur kassi. Þetta hefur í för með sér alvarlegar áskoranir í að setja fram öfluga stefnu í matvælaöryggi. Í þriðja lagi eru iðnaðarþróunarsvæði heimsins, þar sem búast má við að mest fólksfjölgun eigi sér stað á næstu áratugum, sífellt viðkvæmari fyrir forfórskorti. Í fjórða lagi, í venjulegum viðskiptum (e. business as usual), mun aðfangakeðja fosfórs framleiða mikið magn af eitruðum aukaafurðum, sem munu hafa sífellt neikvæðari áhrif á loftslagið og rýra gæði vatnsbóla. Að lokum, innleiðing lág-inntaks, sjálfbærra landbúnaðarkerfa, svo sem vistlandbúnaðs (e. agroecology) hefur mest áhrif á að minnka fosfórþörf og draga úr neikvæðum félags- og umhverfisáhrifum fosfóraðfangskeðjunnar.

Abstrakt

Fosfor är ett väsentligt näringsämne för jordbruket och spelar därför en nyckelroll i den globala matsäkerheten. Huvuddelen av fosforgödselmedlet produceras från fosfatrika bergarter, en icke förnybar råvara, som bryts och renas med stora miljömässiga och sociala effekter. Dagens produktionskedja för fosfor omvandlar en värdefull resurs till en betydande föroreningskälla för hav och vattendrag. Denna avhandling analyserar dagens linjära fosforkedja samt diskuterar de miljömässiga utmaningarna och deras konsekvenser. De använda metoderna är litteratur och case study review, semi-strukturerade intervjuer med avnämare från fosforsektorn, stakeholderanalys, systemanalys och dynamisk modellering.

Fem huvudbudskap identifierades: 1. Det är väsentligt att sluta fosforkedjan längs hela produktions- och användarkedjan istället för att fokusera på end-of-pipe, 2. Fosforkedjan är en svart box vad gäller monitoringdata, 3. Regioner med ökande industrialisering och hög populationstillväxt under de närmaste årtiondena är extra känsliga för brist i fosfortillgången, 4. I ett business-as-usual scenario kommer den globala fosforkedjan att producera stora mängder giftiga biprodukter som har en negativ effekt på klimatet och som försämrar kvaliteten hos hav och vattendrag. Till sist, att införa uthålliga jordbrukssystem, som t.ex agroecology, är den mest effektiva åtgärden för att minska det globala fosforbehovet och den globala fosforkedjans negativa social-ekologiska effekter.

Abstract

Fosforul este un macronutrient esențial și de neînlocuit în agricultură și astfel joacă un rol cheie în securitatea alimentară globală. Majoritatea îngrășămintelor cu fosfor sunt produse din rocă fosfatică, un minereu care există în cantități finite. De asemenea, mineritul și prelucrarea rocii fosfatice Se realizează cu costuri sociale și de mediu importante. Configurația actuală a lanțului de aprovizionare cu fosfor transformă această resursă vitală într-un poluant al corpurilor de apă. Cercetarea de față a investigat provocările legate de sustenabilitatea lanțului de aprovizionare cu fosfor și a discutat implicațiile acestor provocări. Metodele principale de cercetare folosite în acest studiu au constat într-o analiză a literaturii de specialitate și a unor studii de caz, realizarea de interviuri semi-structurate cu actori activi în sectorul fosforului, analiza factorilor interesați în lanțul de aprovizionare cu fosfor, analiza sistemică și modelarea sistemică dinamică. Prezenta lucrare propune cinci mesaje cheie.

În primul rând, este necesară implementarea de măsuri de circularitate pe întreaga lungime a lanțului de aprovizionare cu fosfor și nu doar la capătul acestuia. În al doilea rând, în ceea ce privește monitorizarea și accesul la date, lanțul de aprovizionare cu fosfor este o cutie neagră. Acest lucru periclitează elaborarea unor politici robuste de siguranță alimentară. În al treilea rând, sunt tot mai vulnerabile unui deficit de fosfor regiunile lumii în curs de industrializare unde este preconizată cea mai mare creștere a populației în viitoarele decenii. În al patrulea rând, într-un scenariu de tip status quo, lanțul global de aprovizionare cu fosfor va produce cantități foarte mari de produse secundare toxice, va avea un impact negativ asupra climei și va deteriora calitatea corpurilor de apă. Nu în ultimul rând, implementarea unor sisteme agricole sustenabile cu consum redus - precum agroecologia - are cel mai mare impact în privința scăderii cererii de fosfor și reducerii impactului social și de mediu aferente lanțului global de aprovizionare cu fosfor.

To family, friends and all the wonderful people I met during this PhD adventure

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Abbreviations

AGSO – Australian Geological Survey Organisation

AE – Agroecology

AU – African Union

BCG – Boston Consulting Group

Cd – Cadmium

CE – Circular Economy

CEE – Central and Eastern Europe

CEP – Circular Economy Package

CLD – Causal Loop Diagram

CSR – Corporate Social Responsibility

CURIA – Court of Justice of the European Union

DAP – Diammonium Phosphate

ECA – Europe and Central Asia

ESEA – East and South-East Asia

ESPP – European Sustainable Phosphorus Platform

EU – European Union

FAO – Food and Agriculture Organization of the United Nations

FLR – Food loss reduction

GPF – Global Phosphorus Facility

GT – gigatons

GTK – Geological Survey of Finland

ICIS – Independent Commodity Information Services

IDRC – International Development Research Center

IFA – International Fertilizer Association
IFAD – International Fund for Agriculture Development
IFDC – International Fertilizer Development Centre
IGCP – International Geological Correlation Programme
IRP – International Resource Panel
KEMI – Swedish Chemicals Agency
Kg – Kilogram
LAC – Latin America and the Caribbean
LRF – Federation of Swedish Farmers
MAP – Monoammonium Phosphate
MLG – Multi-level Governance
NA – North America
NAWA – North Africa and West Asia
NGO – Non-governmental Organization
NPK – Compound Fertilizers (Nitrogen Phosphorus Potassium)
OCP – Office Chérifien des Phosphates
P – Phosphorus
PVF – Phosphorus Vulnerability Framework
R – Recycling
PB – Planetary Boundary
PR – Phosphate Rock
RP – Recycled Phosphorus
SA – South Asia
SADR – Sahrawi Arab Democratic Republic
SCB – Statistics Sweden
SD – System Dynamics

SDG – Sustainable Development Goal

SEK – Swedish Kronor

SEPA – Swedish Environmental Protection Agency

SSA – Sub-Saharan Africa

SSP – Single Superphosphate

TAPE – Tools for Agroecology Performance Evaluation

TFI – The Fertilizer Institute

TSP – Triple Superphosphate

UK – United Kingdom

UN – United Nations

UNEP – United Nations Environment Programme

URR – Ultimately Recoverable Resources

US – United States

USA – United States of America

USD – United States Dollars

USGS – United States Geological Survey

WSRW – Western Sahara Resource Watch

WTO – World Trade Organization

WW – Wastewater

WWTP – Wastewater Treatment Plant

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This doctoral thesis consists of three published papers and one manuscript, listed below (I-IV). The published papers are reprinted under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/).

I: **Nedelciu, Claudiu Eduard**; Ragnarsdottir, Kristin Vala and Stjernquist, Ingrid. 2019. From waste to resource: A systems dynamics and stakeholder analysis of phosphorus recycling from municipal wastewater in Europe. *AMBIO,* 48: 741-751. https://doi.org/10.1007/s13280-018-1097-9.

II: **Nedelciu, Claudiu Eduard**; Ragnarsdottir, Kristin Vala; Stjernquist, Ingrid and Schellens, Marie Katarine. 2019. Opening access to the black box: The need for reporting on the global phosphorus supply chain. *AMBIO,* 49: 881-891. https://doi.org/10.1007/s13280-019-01240-8.

III: **Nedelciu, Claudiu Eduard**; Ragnarsdottir, Kristin Vala; Schlyter, Peter and Stjernquist, Ingrid. 2020. Global phosphorus supply chain dynamics: assessing regional impact to 2050. *Global Food Security* vol. 26 (online first). https://doi.org/10.1016/j.gfs.2020.100426.

IV: **Nedelciu, Claudiu Eduard**; Ragnarsdottir, Kristin Vala; Schlyter, Peter and Stjernquist, Ingrid. 2020. Regional scenarios for inorganic phosphate requirement decrease in industrializing regions to 2050. Manuscript to be submitted to *Agricultural Systems.*

Author contributions

The following authors have contributed to the papers and manuscripts for this doctoral thesis: Claudiu Eduard Nedelciu (CEN), Kristin Vala Ragnarsdottir (KVR), Ingrid Stjernquist (IS), Peter Schlyter (PS), Marie Katharine Schellens (MKS). The author contributions for each of the papers and the manuscript are divided as follows:

I: CEN defined the idea, scope and methodology of the paper. CEN carried out interviews and stakeholder analysis in two study locations (Stockholm and Budapest), for which KVR and IS provided key contact details. CEN carried out an extra field trip to the HIAS wastewater treatment plant in Hamar, Norway, arranged by KVR. CEN transcribed and coded the interviews from Budapest and Stockholm. CEN conceptualized the results, with the help of KVR and IS during several joint sessions of causal loop diagramming. CEN is the lead author on the paper, writing the drafts with inputs and revisions from co-authors KVR and IS.

II: CEN set the aim and scope of the paper, based on the challenges with literature data he experienced during his research. CEN defined the methodology, with the help of MKS, who highlighted the "public right to know" as a good theoretical base for the study. CEN is the lead author on the paper, writing the draft versions, with specific inputs on geopolitics and conflict from MKS and general manuscript revisions from co-authors KVR and IS.

III: CEN, PS, IS and KVR set the aim and scope of the model presented in the paper after several workshops in Stockholm. CEN and PS had the idea of a regional model, instead of a global one. CEN developed the system dynamics model, with feedback from IS and KVR on the model structure. CEN is the lead author on the paper, writing the draft versions, with inputs and revisions from co-authors PS, KVR and IS.

IV: CEN set the aim, scope and methodology of the paper, with reflections from IS, KVR and PS. CEN chose the scenarios presented in the paper and carried out an analysis of agroecological case studies. CEN built the scenarios in the model from paper III and wrote the results. CEN wrote the discussion section, with reflections from IS, PS and KVR. CEN is the lead author on the paper and wrote the draft version with general revisions from co-authors KVR, IS and PS.

1 Introduction and Background

Phosphorus (P) is an essential macronutrient used in agriculture as fertilizer. Globally, around 90% of phosphorus comes from mined phosphate rock (Cordell et al. 2009). A growing food demand in the last century has prompted a steep increase in the amount of mined phosphate rock, which reached 240 million tons in 2019 (USGS 2020). The United Nation's (UN) Food and Agriculture Organization (FAO) estimated that by 2050, the growth in world population will cause an increase in food demand by at least 50% (FAO 2017a). This will in turn significantly increase the global phosphate rock demand for fertilizers. Of the total world's phosphate rock reserves, over 70% are found in Morocco and the disputed territory of Western Sahara (USGS 2020). As the United States and China are decreasing or even halting phosphate exports, Morocco's position as world leading exporter of phosphates will strengthen in the future, potentially pushing the global phosphate market towards a Moroccan monopoly (Rosemarin and Ekane 2016). This trend is posing a serious dilemma about the ethical sourcing of phosphate and the social implications of phosphate exploitation in disputed territories such as Western Sahara (Rosemarin and Ekane 2016). Phosphate mining, processing, application and discharge have severe negative environmental impacts. The International Resource Panel (IRP) of the United Nations Environment Programme (UNEP) reported an increase of 20% between 2000-2015 in water, air and soil pollution along the phosphate cradle-to-grave chain, including increased greenhouse gas emissions (IRP 2019). Nonetheless, more than 80% of the phosphorus is lost from cradle to fork, with the remaining part ending up in solid waste or wastewater (Cordell et al. 2009). Eutrophication caused to a great extent by phosphate runoff from agricultural land and untreated wastewater discharge has contributed to the worldwide creation of "dead zones" the size of the UK (IRP 2019). The environmental harm caused by the global phosphorus chain has been also recognized in the Planetary Boundaries Framework, where the phosphorus biogeochemichal flow is well beyond the safe-operating space, in a zone of high risk (Steffen et al. 2015). As such, phosphorus is a valuable resource for food security, but it shows a linear supply chain that transforms it into one of the biggest environmental pollutants. At the same time, the geographical distribution of phosphate reserves poses serious supply questions at a national and regional level and raises a number of ethical questions on import supplies (Cordell et al. 2015). This has prompted calls for the implementation of Circular Economy (CE) strategies aiming at a more sustainable P management (Nesme and Withers 2016; Robles et al. 2020) and has been reflected in the policy of countries such as Germany and Switzerland, which have recently adopted legislation to recover all phosphorus from wastewater. The European Union (EU) also passed a revision to its Fertilizer Regulation, aimed at boosting the market of organic fertilizers and the recycling of P from wastewater (European Parliament 2019a).

1.1 Why does phosphorus matter?

There are an estimated 570 million farms around the globe (Lowder et al. 2016), which spread across 4.9 billion hectares of land and produce 4 billion tons of food every year (FAO 2017a). Although agricultural production increased by a factor of three in the last half century, one in nine people still suffer from chronic malnutrition today, most of whom live in developing countries (FAO 2019a). Rather than being a production-related issue, the fact that the global food supply chain cannot tackle hunger is a systemic problem. More than 30% of the 4 billion tons of food produced each year is being wasted or lost, at an annual cost of more than 1 trillion USD (FAO 2019a). The causes of food wastage are varied, but they reflect unsustainable consumption patterns; an unequal distribution of resources, technology and income; knowledge gaps; lack of appropriate regulations; and a number of other social aspects, including but not limited to human behavior (FAO 2019a).

Much has been written on the role of technology in farming and its capacity to extend the limits of the food production system in order to accommodate the needs of a growing population. It has also been frequently argued that as a rule of thumb, resources that become scarce are replaced with substitutes (Aligica 2009). There is, nevertheless, scientific consensus that in agriculture, the main fertilizers - fixed nitrogen, phosphorus and potassium - do not have substitutes (Seyhan et al. 2012). Extensive literature has been written on the limited availability of P (see Cordell et al. 2009; Ragnarsdottir et al. 2011; Sverdrup and Ragnarsdottir 2014) and there are widespread concerns that the P production will soon peak or has already peaked. It is estimated that P availability for crop productivity and plant growth is still suboptimal for 70% of the arable land, which leaves space for further growth in P demand (Herrera-Estrella and Lopez-Arrendondo 2016).

Some authors pointed out the lack of data to assess losses and inefficiencies along the phosphorous supply chain (Cordell and White 2011; Edixhoven et al. 2014). Others pointed out the lack of reliability of current data sources to assess phosphorus scarcity (Van Vuuren 2010). In particular, there are concerns with regard to the existence of only one public entity reporting on phosphate rock reserves and production on an annual basis: the USGS. Studies that highlighted this do not allow for triangulation of results with other reporting entities as there are none (Van Vuuren 2010; Cordell and White 2011). Edixhoven et al. (2014) also raised concerns about the 2010 change in USGS methodology, which brought a tenfold increase in phosphate reserves from Morocco and Western Sahara and – to a great extent – brought controversy into the peak phosphorus debate (Scholz and Wellmer 2013; Ulrich and Frossard 2014).

Even a scenario of plentifulness when it comes to P resources is regarded as troublesome. There are concerns that the world´s nations will become increasingly reliant on Morocco´s vast phosphate rock reserves for imports, as this country consolidates its global position as main exporter (Cooper et al. 2011; Mohr and Evans 2013; Rosemarin and Ekane 2016). Those concerns were exacerbated in 2007-2008 when the phosphate fertilizer prices skyrocketed by more than eight times its previous price, triggering a soar in food prices. The main factors for the price spike were many and included decreased phosphate fertilizer production in the US; an 100% export tax on P fertilizer in China; increased oil and energy prices; disproportionate fertilizer demand for biofuel production; and a disproportionate supply–demand relation (Scholz et al. 2014). Meanwhile, Morocco’s state-owned company in control of all phosphate operations, Office Chérifien des Phosphates (OCP), has plans to cover 50% of the global phosphate market by 2025 (OCP 2017).

Price spikes are not the only concerns when it comes to supply. The current COVID-19 pandemic unraveled the vulnerabilities of our food system, which had already been on the edge (IPES-Food 2020). A report by the Chatham House warned in 2017 about the danger of chokepoints in the global transportation of fertilizers and major crops, caused by an increase in trade (Bailey and Wellesley 2017). The report starts by acknowledging that the global supply of grain and fertilizers is concentrated in a handful of producing regions and thus trade has become essential for global food security. It then identifies 14 chokepoints in the form of maritime corridors, coastal infrastructure and inland transportation infrastructure, quoting three categories of disruptive hazards that increase risk: weather and climate hazards; security and conflict hazards; and institutional hazards (Bailey and Wellesley 2017). The decision of several nations to reduce or halt movement of goods within the current pandemic situation belongs to the latter category. An example is Russia's step to ban wheat exports in order to safeguard domestic consumption (Reuters 2020), raising fears of wheat shortages. Last time Russia instituted a ban on exports in 2010, the world prices for wheat skyrocketed (Welton 2011). These chokepoints in supply are the more worrying as the Potsdam Institute for Climate Impact Research estimates that by 2050, half of the world population could be dependent on food imports (Fader et al. 2013).

Countries and regions are increasingly recognizing their phosphorus vulnerability. With the exception of Finland, European Union countries have little or no phosphate rock reserves, a factor that has made Europe highly dependent on phosphate imports. There are valid concerns with regard to the dependency of European agriculture on a handful of leading phosphorus exporters. The EU assessed that for 2011 the 28 Member State block was 92% dependent on phosphate fertilizers import (European Commission 2013). In 2014, phosphorus was added to EU's Critical Raw Material List, signaling a recognition that it is a resource of high economic importance with high supply risks (European Commission 2016). Europe is, however, not the only import-dependent region. As Fig. 1 shows, South Asia, Latin America and the Caribbean and Oceania are also regions where phosphorus demand is higher than the supply.

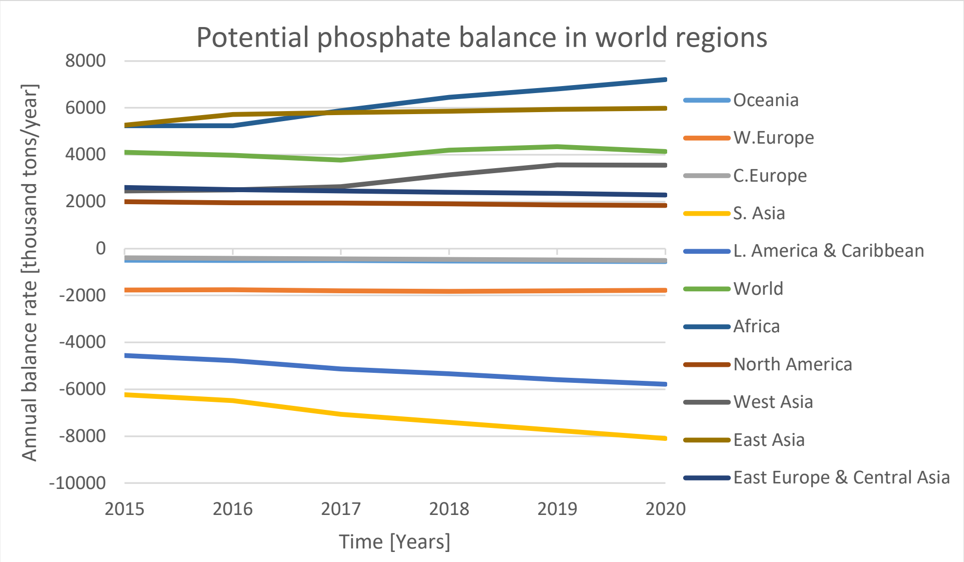

Figure 1. Phosphate (P_2O_5) balance in the world regions. Potential balance is calculated as total supply minus total demand, including P_2O_5 demand for non-fertilizer use. The four regions below zero show deficit (data from FAO 2017b)

The situation points to an even higher unequal distribution of resources and supply dependency at a national level. A closer look at the country level data provided by the FAO for 2016 shows that while Africa records a positive net balance for phosphate, only five countries were net exporters in 2016: Morocco, Algeria, Egypt, Senegal and Togo (FAOSTAT 2017). The continent thus has 49 import dependent nations, overwhelmingly in the Sub-Saharan region. This is of significance for global food security, as Sub-Saharan Africa and South Asia are regions where most population growth is expected in the coming decades (UN 2019).

Phosphorus vulnerability has also been recognized in the literature. Cordell and Neset (2014) formulated a qualitative framework to assess phosphorus vulnerability at a national and regional level, which comprises 26 biophysical, technical, geopolitical, socioeconomic stressors and drivers for P vulnerability. The qualitative framework was further developed with a series of indicators of phosphorus vulnerability, which range from phosphate price, supply risk and eutrophication potential to national phosphorus equity and soil phosphorus legacy (Cordell and White 2015). With the advent of the Circular Economy, particularly through the launch of EU’s action plan for the Circular Economy in 2015 and the Circular Economy (CE) Package in 2018, a rich body of literature promoted CE as a solution for a more sustainable P management, with the main focus being on recycling P from wastewater (see Jedelhauser and Binder 2018; Smol 2019; Robles et al. 2020). Other authors pointed out that CE should be considered along the whole supply chain of P and not only focus on end-of-pipeline circular solutions (Nesme and Withers 2016; Geissler et al. 2018).

1.2 An overview of the global phosphorus supply chain

According to the latest USGS report, 240 million tons of phosphate rock were mined in 2019 (USGS 2020). Of the total amount of mined PR, approximately 85% is used for fertilizer production (Cordell et al. 2009). Mined PR usually undergoes a primary processing in the form of beneficiation, which increases the grade of the mineral which is most frequently apatite ($Ca_5(PO_4)_3(OH,F,Cl)$). The next step is the chemical processing into phosphoric acid or with phosphoric acid, into several types of fertilizers, including monoammonium phosphate (MAP - $(NH_4)H_2PO_4$), diammonium phosphate (DAP – $(NH_4)_2HPO_4$), compound fertilizers (N:P:K) and single superphosphate (SSP – $CaH_6O_8P_2^{2+}$). However, fertilizer plants are not always in the main PR mining countries. While most of the PR production takes place in the US, China, Morocco and Western Sahara and Russia (see section 1.1.1), some of the largest fertilizer companies can also be found in Germany, Israel, Norway, Canada, Saudi Arabia and New Zealand (Jegede 2019). This means that significant marine and terrestrial transport is required between the main mining sites and the main phosphate fertilizer producing sites. Phosphate fertilizers are also transported to the farm gate for application on agricultural land, requiring once more substantial transport. The fertilizer market operates as a constant flow, with phosphate fertilizers being on a constant move between the different supply chain sectors. Facilities from the fertilizer industry have limited storage and thus, in general, only an amount expected to be sold in spring is stored in the summer and winter of the previous year. When crops or livestock feed are harvested, phosphorus enters a new chain sector in the food production, processing, and retailing. Ultimately, it reaches the end-consumers – the people – and ends up as either solid waste or in wastewater.

The cradle-to-grave global phosphorus chain is thus long and fragmented, which is reflected in the way analyses of the global phosphorus supply chain have been carried out. Cordell et al. (2015) for instance, considered six key sectors (see Fig. 2): phosphate rock mining; phosphate fertilizer production and trade; fertilizer application in agriculture; food production, processing and distribution; food consumption; and sanitation, food waste and pollution management.

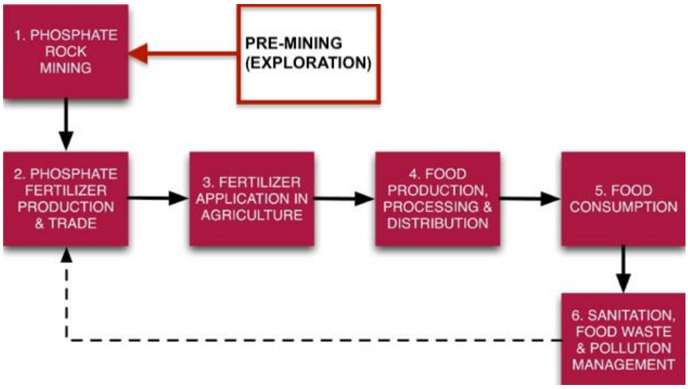

Figure 2. Seven key sectors of the phosphorus supply chain (adapted from Cordell et al. 2015 and Steiner et al. 2015). Arrows show material flow, with the dotted arrow indicating phosphorus reuse from organic sources

In the phosphorus supply chain of Steiner et al. (2015) there is a pre-mining sector that deals with exploration of phosphorus resources (see Fig. 2). However, the authors do not take into account most of the sectors 4, 5 and 6 from Fig. 2. Similarly, IRP recently made an analysis of phosphorus cradle-to-grave in its 2019 Global Resource Outlook. It includes phosphate rock mining, phosphoric acid production, fertilizer production and fertilizer application with a baseline for the analysis in 2000. It does not include the exploration sector found in Steiner et al. (2015) or the post-harvest sectors from Cordell et al. (2015).

1.2.1 Environmental and health impacts of the global phosphorus supply chain

There are a series of environmental challenges connected to the global phosphorus supply chain. An IRP cradle-to-grave analysis names impact on climate change, ecotoxicity, human toxicity and air pollution as the main negative environmental impacts of the phosphorus chain (IRP 2019). As shown in Fig. 3, all negative impacts of the supply chain segments considered in IRP's analysis have recorded an increase of 20-30% by 2015 compared to 2000. Phosphor fertilizer application is the main cause for ecotoxicity, human toxicity and eutrophication. Phosphate rock mining and phosphoric acid production are responsible for most of the climate change impact through air pollution.

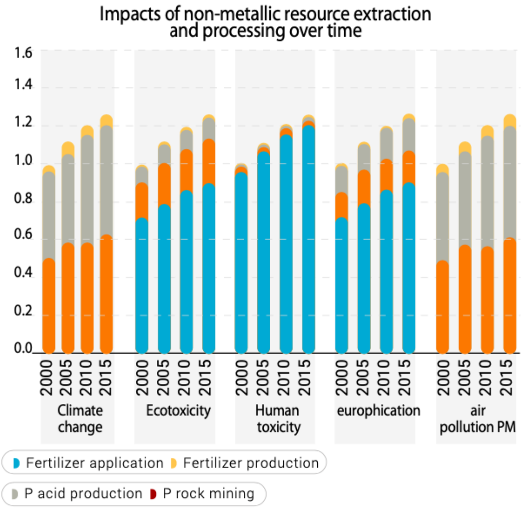

Figure 3. A cradle-to-grave analysis of the global production and application of phosphate fertilizers between 2000-2015. Values from 2000 are indexed to 1 (IRP 2019)

Phosphate rock is mainly extracted through surface mining, which involves a range of processes with direct impact on the landscape and the environment, such as the removal of topsoil and overburden. Phosphate mining generates millions of tons of waste, while the beneficiation process creates a large volume of phosphate sludge, all of which are deposited in rock piles and ponds in the vicinity of the mining area (Hakkou et al. 2016). It also leads to rock desertification, an aesthetic depreciation of the landscape and increases the potential hazard for landslides and ground erosion (Yang et al. 2014). In the Republic of Nauru (formerly Pleasant Island) in the Pacific Ocean, for instance, the environment was critically destroyed by surface-mining for phosphate rock. Biodiversity-rich habitats were scrapped off in the search for the phosphate ore and with no post-mining restoration strategies, the formerly mined land was made inhospitable for most life forms (Gale 2016). In the US´s largest phosphate mining site in Florida, a sinkhole opened underneath a gypsum stack in 2016, leading to more than 215 million gallons of contaminated water to enter the Floridan Aquifer, which supplies water to 60% of the people in Florida (Sierra Club 2014). In addition to water pollution, large amounts of water are used in the processing of phosphate rock, which can compete with other water uses, such as for drinking or agriculture.

Sedimentary phosphate rock, which constitutes the majority of the world PR resources, has high Cadmium (Cd) concentrations. Cadmium is a heavy metal that has adverse effect on human health. When ingested via food, it can form kidney disease and has harmful effects on the musculoskeletal system (Roberts 2014). A high Cd concentration in the soil can lead to higher concentrations of Cd in the harvested crops. Due to human health concerns, the European Commission has recently set a limit to Cd concentration in phosphate fertilizers to 60 mg kg^{-1} from 2022 (European Parliament 2019a). In contrast, the Moroccan and Western Saharan phosphate rock can have Cd concentrations up to 507 mg kg^{-1} (Mar and Okazaki 2012).

Fertilizer application and wastewater are two segments of the cradle-to-grave phosphorus system. When phosphate fertilizers are applied to agricultural land, some of the phosphorus is taken up by the plant, some undergoes a mineralization process that fixes it to the soil, while some will leak into water bodies. Mekonnen and Hoekstra (2017) estimated that 38% of the freshwater basins experience pollution by phosphorus at higher rates than they can assimilate. This is mostly due to nutrient-rich runoff from agricultural lands, but also due to the discarding of untreated wastewater. Nutrient overload leads to a bloom in algae, which eventually die and sink at the bottom of rivers, lakes and coastal areas. The decomposition process uses the oxygen that would otherwise be used by the other living organisms present in the aquatic system. This process is called eutrophication. High rates of eutrophication can lead to the creation of the so-called “dead-zones”, where little or no marine life can be supported. The world distribution of dead zones is illustrated in Fig. 4.

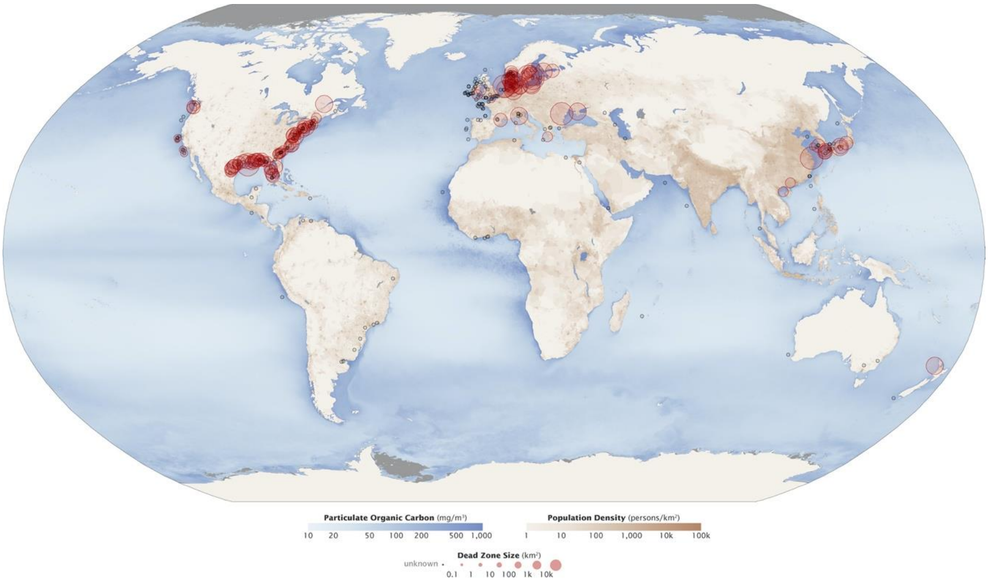

Figure 4. Map of dead-zones across the world for 2008. Dead-zones are areas that have experienced intense eutrophication processes. These processes have created an anoxic environment where little or no marine life can be supported (source: NASA 2010)

The International Resource Panel estimates that there are around 400 dead-zones worldwide, covering an area the size of UK (IRP 2019). Eutrophication and the creation of “dead zones” have not only a negative impact on the aquatic ecosystems. They can also decrease drinking water availability and negatively impact human activities such as fishing or tourism, posing a threat to livelihoods of the local population. Figure 4 also shows that eutrophication is unevenly distributed along coastal areas, thus acting in a localized manner and affecting some areas more than others.

There are three main factors characterizing areas where dead zones develop:

- highly inhabited areas, such as the eastern coast of the US, with intensive industrial activity and significant amounts of wastewater entering the coastal water bodies;
- areas with a large-scale intensive agricultural activities taking place near the coast, such as the Baltic Sea;
- areas located at the mouth of a nutrient-oversaturated river, such as the Mississippi Delta in the Gulf of Mexico;

The key role of phosphorus in the eutrophication process has been highlighted in the Planetary Boundaries studies (Rockström et al. 2009; Steffen at al. 2015). Planetary Boundaries (PB) are conceptualized as thresholds for nine main processes on which the stability and resilience of the Earth system depends. The thresholds are calculated based on the Holocene-like conditions, which have allowed humanity to develop and thrive during the past 10,000 years (Rockström et al. 2009). The biogeochemical flows of nitrogen and phosphorus constitute one of the PB processes and are considered to be in a zone of high risk, beyond the zone of uncertainty, which means they have the capacity to disrupt the Earth's ecological stability.

1.2.2 Geopolitics and social implications in phosphate exploitation

Significant PR resources are found in the disputed region of Western Sahara, which in 2016 accounted for almost a quarter of all PR exports of Morocco (OCP 2017). Western Sahara has been engaged in conflicts since 1975, when most of the region was occupied by Morocco, while the remaining part was claimed by the Polisario Front, which installed the Sahrawi Arab Democratic Republic or SADR (Saul 2015). Some international NGOs and academics have indicated that Morocco has engaged in violating the human rights of the Sahrawi people, indigenous to Western Sahara, as well as violating international law by exploiting resources from an occupied territory (Hopgood 2010; Cordell et al. 2015; Saul 2015).

Morocco's strong economic position and its emerging role as leader of a global P monopoly also means the North-African kingdom can use political leverage on the African continent. During a 20-day tour in Mali, Guinea, Ivory Coast and Gabon in 2014, King Mohammed of Morocco signed 80 bilateral agreements with African leaders, covering a wide range of sectors, from agriculture and trade to health and job training (The Economist 2014). Following the king's visit, all four West African countries changed their approach to the Western Saharan conflict, from supporting Western Saharan independence to supporting an autonomous Western Sahara under the sovereignty of Morocco (The Economist 2014). Morocco's political leverage can also be observed in the relationship with its Western allies, particularly the US, which has historically sided with Morocco, supplying the kingdom with weapons and aid (Miller 2013). In the EU, two rulings of the European Court of Justice in 2016 and 2018 decided that the Association and Liberalisation Agreements in agriculture and fisheries concluded between the EU and Morocco could not apply to Western Sahara, as the region has a separate and distinct status guaranteed under the Charter of the United Nations (CURIA 2018). However, the trade agreements between the EU and Morocco and Western Sahara were passed through the Parliament and Council in

2019, after the European Commission brought proof of consent from the local population, in compliance with the court ruling. The amendment was contested by SADR (European Parliament 2019b).

1.2.3 The multiple scales of the global phosphorus supply chain impacts

The phosphorus supply chain exhibits dynamics at multiple chains. The highly unequal distribution of phosphate resources combined with processing facilities all over the world are two global supply dimensions. It involves maritime and terrestrial transport between all inhabited regions of the world, as illustrated in Fig. 5. At the same time, greenhouse gas emissions and the air pollution associated in particular with PR mining and PR processing into phosphoric acid are also processes affecting the atmosphere at a global level (IRP 2019). Conservative estimates have shown that the production of fertilizers account for 1.5 - 2% of the total greenhouse gas emissions, which is similar to the emissions from aviation (IFA 2018). However, a recent study in the US found that emissions of methane from the fertilizing industry were 100 times higher than previously reported by the industry itself (Zhou et al. 2019).

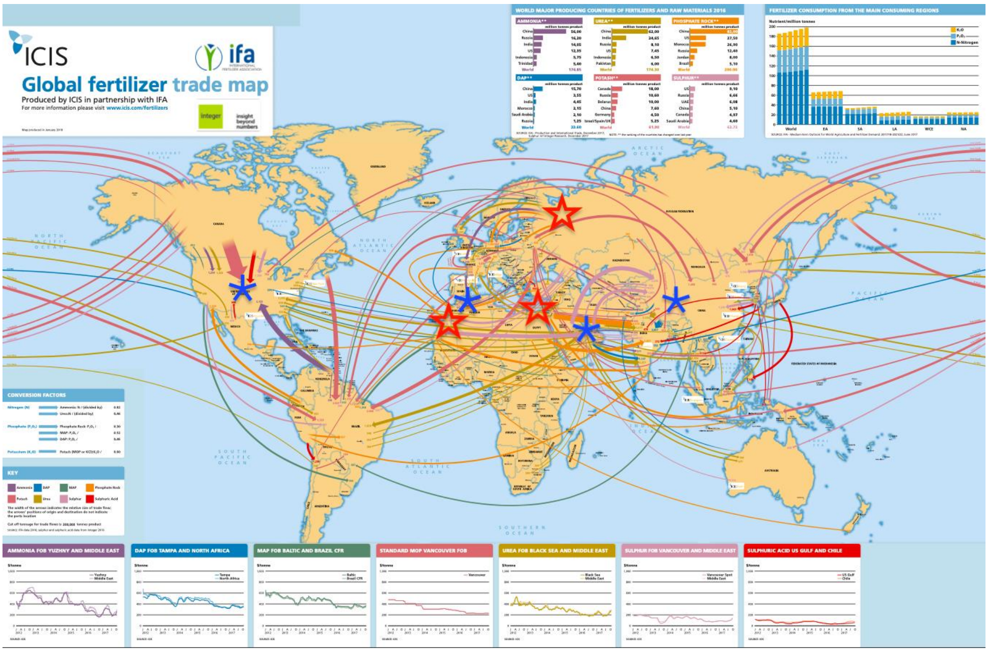

Figure 5. Global trade in fertilizers for 2016. Phosphate Rock flows are in orange, diammonium phosphate (DAP) flows are in blue. Red stars represent main phosphate rock exporting regions, while blue stars main DAP exporting regions (adapted from ICIS/IFA 2018)

Application of fertilizers happens at a national and local level, with direct impacts on food security at these levels. Runoff of nutrients from agricultural land does not only pollute local or national water bodies but it can affect entire regions. Examples in this sense are the Baltic Sea or the Gulf of Mexico (see Fig. 4). Moreover, if Cd concentration in crops is too high, food trade can enable such crops or processed food from these crops to transcend national borders. Similarly, pollution from untreated wastewater disposal in water bodies can transcend local and national boundaries, affecting regional marine ecosystems.

1.3 Gaps in the literature

With the series of social and environmental dynamics presented in the previous sections, it is of paramount importance to scrutinize the whole phosphorus supply chain. This would allow for more accurate and comprehensive analyses on the management of the supply chain and vulnerability to phosphorus criticality. It would also reduce the uncertainties that are present at the moment, especially in relation to the amount of reserves, the impact on the local population in exploiting countries or the losses recorded per supply segment. Such analyses are possible only if data along the supply chain is available, accessible, reliable and transparent. Despite calls for more data sharing, transparency and harmonization (see Van Vuuren 2010; Cordell and White 2011; Edixhoven et al. 2014), an analysis of the cradle-to-grave data access and quality has not yet been carried out. Assessments of data reliability, data availability, data ownership and data formatting needs are required in order to guide a more sustainable global governance of phosphorus as a key resource for food security (Wellmer and Scholz 2015; Rosemarin and Ekane 2016).

Methodologically, many of the P assessments are qualitative (see Cordell and Neset 2014; Cordell and White 2015), while quantified assessments are few and generally address the consumption-extraction aspects at the global level (see Mohr and Evans 2013; Sverdrup and Ragnarsdottir 2014; Nesme et al. 2016). Studies such as the Planetary Boundaries have called on sub-planetary levels of assessment for the biogeochemical flow of P, in order to better evaluate how the dynamics of sub-systems interact and impact Earth’s ecological stability (Rockström et al. 2009; Steffen et al. 2015). This is a timely challenge for the global P supply, where progress has been made on creating global system dynamics models, which can start integrating feedbacks, accumulations, non-linearities and delays in the P supply system (Ragnasdottir et al. 2011; Sverdrup and Ragnarsdottir 2011, 2014). However, regional models are missing and there is a need to integrate other dynamics in quantitative models, which can assess the connection between different planetary boundaries (Lade et al. 2020). In the perspective of the global P supply chain, such dynamics can build on the existing extraction-consumption models and assess connections that at the moment are considered externalities, such as pollution, eutrophication or climate change impact. Last but not least, there is a need for a better understanding of the implementation of end-of-pipeline solutions such as recycling. Despite concrete policy actions through the Circular Economy and a vast body of literature dedicated to recycling P from wastewater, an assessment of the drivers and obstacles in implementation is required as progress is insufficient. When considered in the context of a more systemic and dynamic assessment of the P supply chain, investigating P recycling can provide answers with regard to how efficient this solution is and whether CE actions can be used effectively in other parts of the P supply chain.

2 Aim and research questions

The aim of this thesis was thus to investigate the negative impacts of the global phosphorus supply chain at global and sub-global levels and propose theoretical and methodological tools to assess them. The thesis also critically investigated processes that occupy a vast part of the P literature, such as P recycling from wastewater. The main research questions guiding this study were:

- What are the general dynamics characterizing P recycling from urban wastewater and which are the main challenges in developing this sector?
- What are the key policy recommendations that can contribute to the development of the P recycling sector at a national level?
- What are the issues and potential solutions with reporting along the global P supply chain, as derived from the literature?
- How is the P reporting process connected to reporting on the implementation of global sustainability initiatives such as the UN Sustainable Development Goals (SDGs)?
- Which are the world regions, that are most affected by the current configuration and dynamics of the global phosphorus supply chain?
- Which of three scenarios targeting different stages of the P supply chain – namely agroecology, food loss reduction and recycling P from wastewater – is most effective in reducing the inorganic P requirement in industrializing regions to 2050?

3 Theoretical framework

The binding theory which guides this research is systems thinking. Systems thinking theory is based on the “thinking in systems” approach, with a system being “an interconnected set of things interconnected in such a way that they produce their own pattern of behavior over time” (Meadows and Wright 2009 p. 2). In this research, the system is the global phosphorus supply chain, from cradle to grave and the overall purpose of this system is to produce food for the global population. Nevertheless, what this research focuses on is the effects of the behavioral patterns of the global phosphorus supply chain and their implications for the people and our planet. While using systems thinking, the four papers in this thesis also integrate a number of concepts and frameworks that address the four sustainability dimensions of the cradle-to-grave global phosphorus chain: Social, economic, political, and environmental. Table 1 summarizes the concepts and frameworks used in the papers for assessing the sustainability dimensions of the phosphorus system. The most comprehensive research on the global phosphorus supply chain was done by Cordell and Neset (2014) and Cordell and White (2015), who developed a Phosphorus Vulnerability Framework (PVF). Their studies dealt with the vulnerability of national and regional food systems to phosphorus scarcity. It identified 26 stressors affecting vulnerability, ranging from global phosphate prices to national import dependency, access to alternative phosphorus resources and pollution of water bodies. The authors stress, however, that their research effort is only a first, theoretical step in elaborating a tool that would enable policy action to decrease phosphorus vulnerability. This research develops the PVF from Cordell and Neset (2014) by creating a regional dynamic phosphorus cradle-to-grave system that integrates feedbacks, delays, accumulations and non-linearities for some of the stressors identified in the vulnerability framework. The PVF approach to the P supply chain is evident in papers II, III and IV, while in paper I, the focus was on the concept of criticality understood as a function of economic importance and resource scarcity. When it comes to the environmental harm caused by the global phosphorus chain, this thesis builds on the Planetary Boundaries Framework, which indicate that the phosphorus biogeochemical flow is well beyond the safe-operating space, in a zone of high risk (Steffen et al. 2015). Planetary Boundaries (PBs) are “scientifically based levels of human perturbation of the Earth System beyond which Earth System functioning may be substantially altered” (Steffen et al. 2015, p. 1). The authors consider Holocene-like conditions as safe for humanity inhabitation and societal development, whereas the space outside PBs is an area of high-risk and uncertainty. The authors, as well as other academics, stressed that further work is needed to assess the impact of small-scale regime changes to global-level transitions (Hughes et al. 2013; Lenton and Williams 2013), while recognizing that processes such as the biogeochemical flow of phosphorus have different thresholds at different levels: global, continental or ocean basin (Steffen et al. 2015).

Table 1. Frameworks and concepts used in this thesis, with indications on the embedded sustainability dimensions of each framework. PVF stands for Phosphorus Vulnerability Framework, SDGs for the Sustainable Development Goals

SYSTEMS THINKING				
System: Cradle-to-grave global phosphorus supply chain				
Sustainability dimensions				
Social	***Economic***	***Political***	***Environmental***	***Concept/ Framework***
	X		X	Criticality
X	X	X	X	PVF
			X	Planetary Boundaries
	X	X	X	Circular Economy
X	X	X	X	Corporate Social Responsibility
X	X	X	X	Legal framework
X	X	X	X	Global governance, SDGs

The thesis also tackles the social, political and ethical aspects of the global phosphorus chain. From a socio-political perspective, the research briefly touches on the social impacts caused by phosphate exploitation in paper II. In that paper, an examination of the existing data sources available to assess the social and human rights impact of mining and processing of phosphate rock is carried out. In doing so, paper II highlights the means by which more light can be shed on the role of phosphate exploitation in conflict resolution, with a focus on Western Sahara. As such, the research brings into discussion the concept of corporate social responsibility in global supply chains (see Hamann 2003; Jenkins and Yakovleva 2006), stressing the need for more accountability in the phosphorus supply chain and more accountability in the ethics of sourcing. It also touches on the role of international law in providing guidelines for phosphate rock trade and exploitation, by examining rulings by the European Court of Justice on international trade agreements.

From a political perspective, the project investigates issues related to the management of P as a resource from the framework of global governance and the Sustainable Development Goals Agenda. It first builds on the idea advanced by Wellmer and Scholz (2015), who argue that due to P being a resource essential to food production, public knowledge on all aspects of the global P supply chain should be considered basic knowledge for a basic human right: Access to adequate food. It then connects the public knowledge idea of Wellmer and Scholz (2015) with a global governance framework of the P resource as proposed by Rosemarin and Ekane (2016). The authors build on global governance frameworks proposed for other minerals in order to bring the case for a similar approach to P, stressing the need for a Type 2 Multi-Level Governance (MLG). A Type 2 MLG is a form of governance with a flexible design, no limit of jurisdictional levels, intersecting memberships, task-specific jurisdictions and an ability to respond to specific demands for change in policies (Rosemarin and Ekane 2016). This type of global governance would enable the inclusion of the multiple stakeholders involved along the fragmented cradle-to-grave P system and across different scales: Global, national and local. Rosemarin and Ekane's (2016) idea is mirrored by Cordell et al. (2015), who stressed the need for interorganizational cooperation in the phosphorus supply chain, necessary to decrease vulnerability to supply disruptions. This, as the authors of the study point out, is even more relevant deeming phosphorus' non-substitutability for food production. As such, the immediate connection between the P supply chain and the SDG agenda would be through SDG 2 – Zero Hunger. However, paper II of this thesis explains the connection between the P supply chain and six other SDGs, developing on how reporting along the P supply chain affects reporting on these specific SDGs.

In addition to the concepts and frameworks summarized in table 1, the thesis incorporated the multi-scale aspect of the P supply chain impacts (see Fig. 6). An analysis of the literature reveals an overwhelming emphasis on end-of-pipeline solutions at local and national level, aimed at tackling the linearity of the phosphorus supply chain and its metamorphosis from a valuable resource into one of the biggest water pollutants (Mihelcic et al. 2011; Molinos-Senante 2011; Cordell and White 2014; Cardoso Chrispim et al. 2019). Increasingly, policy makers have also focused on end-of-pipeline solutions to solve perceived phosphorus criticality and phosphorus pollution, solutions which ae perceived as central to the Circular Economy. Germany and Switzerland recently adopted regulations stipulating the recovery of all phosphorus from wastewater treatment plants (European Commission 2016b; Swiss Federal Council 2015). In Sweden, the Environmental Protection Agency introduced targets for 40% phosphorus recovery from sewage at a national level, with recovery rates at 34% in 2016 (SCB 2018).

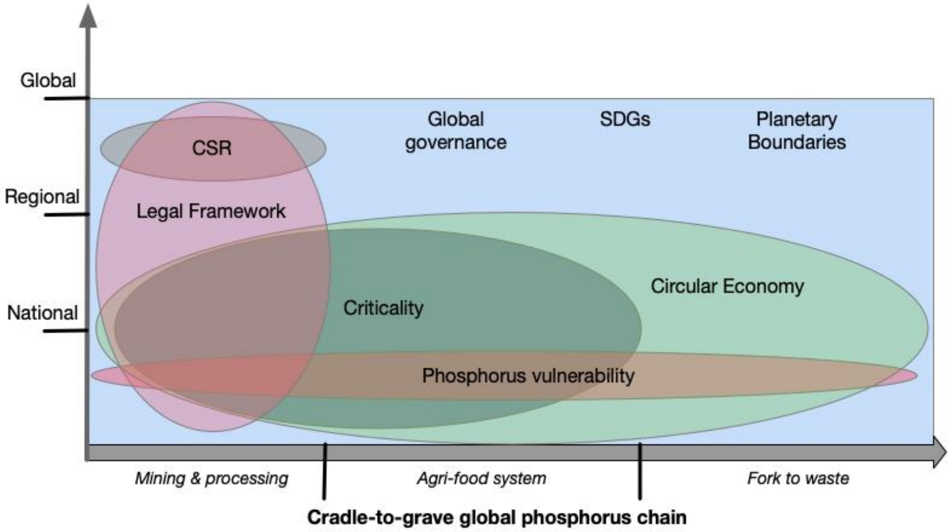

Figure 6. Illustration of the spatial scales of the concepts and frameworks, as used in this thesis. CSR stands for Corporate Social Responsibility, SDGs for Sustainable Development Goals

However, perspectives from the local and national levels are not sufficient if the aim is to design robust policies to make the entire P supply chain sustainable. This research analyses local and national level recycling measures, acknowledges the global impact of the cradle-to-grave phosphorus system, and assesses the impacts of the phosphorus chain at a regional level. In Fig. 6, the concept and frameworks used in the four papers are matched against the spatial scale at which they apply in this thesis. While a growing body of literature exists on the local, national and global levels of the P supply chain, this study's addition of a regional level focus is due to two main reasons. On the one hand, it is the dynamic between regional inequality in resource distribution for phosphate rock and very different regional population dynamics. This has implications for food security in regions experiencing high population growth rates but lacking in PR resources. On the other hand, phosphorus pollution can have disproportionate local environmental effects. First, the highly unequal distribution of phosphate rock resources means that resource rich regions will also experience the highest negative environmental impacts associated with mining and processing activities. Second, the linearity of the phosphorus chain entails that most of this resource eventually reaches water bodies and can cause eutrophication. The location of pollution sources is not necessarily the location where the negative environmental and economic impacts are felt, as P follows the route of moving water bodies.

4 Methodology

4.1 Literature review and terminology

In this thesis, the terms “global supply chain” and “cradle-to-grave” are used interchangeably when it comes to phosphorus. Both terms refer to the configuration of the phosphorus supply chain. The first sectors of the phosphorus supply chain – namely exploration, mining and processing, relate strictly to phosphate from phosphate rock. From the fertilizer market stage to wastewater level, phosphorus and phosphate refer to both phosphate from phosphate rock and recovered phosphorus, such as recycled phosphorus from wastewater or manure. Also, phosphorus (P) fertilizers and phosphate fertilizers are used interchangeably and they refer to all fertilizers containing phosphorus, including monoammonium phosphate (MAP), diammonium phosphate (DAP), compound fertilizers (NPK), single superphosphate (SSP) and phosphate rock (PR) that is directly applied to agricultural land for fertilizing purposes.

The initial methodological step in this research was the review of relevant literature on the phosphorus supply chain. Literature review resulted in three major findings:

- There is a focus on end-of-pipeline solutions to tackle P criticality and its role as both fertilizer and pollutant;
- There are significant research gaps when it comes to the sub-global dynamics of the P supply chain; and
- There are major challenges related to data availability, data reliability and data harmonization when it comes to reporting along the global P supply chain.

The next step was to employ additional methods, in order to acquire missing information. This was done through review of documents, other than scientific papers: Reports from a variety of government agencies both at national and international level; reports from NGOs; news articles; court cases; university reports for pilot projects and fieldwork.

4.2 Interviews

Further, in order to provide a better understanding of the cradle-to-grave P chain system dynamics, the research includes an analysis of semi-structured interviews, conducted with stakeholders in the phosphorus sector. Stakeholders were chosen and categorized following an initial stakeholder mapping and analysis, using an influence-power matrix design as proposed by Reed et al. (2009). The initial sample of stakeholders allowed for further targeted snowball sampling, which ultimately led to changes to the influence-power matrix as research progressed. The final influence-power matrix can be observed in Fig. 17. Interviews were conducted between May 2017 and May 2019. A summary of the type of stakeholders interviewed, as well as their numbers, is found in Table 2. Most of the stakeholders – 23 out of 26 – were interviewed for paper I.

Table 2. Interviewed stakeholders

Stakeholder	Number
Policy at national level	4
Policy at municipal level	1
Wastewater Treatment Plant administration	5
Private sector	5
Academia	6
Farmer association	2
Food industry	1
NGO	2
Total	26

4.3 Case study analyses

Next, as proposed by Flyvbjerg (2011) in multidisciplinary sciences, the research employed case study analysis in order to allow the testing of hypothesis and deepen the understanding of the complex P supply chain system. First, a comparative study between two European capitals – Budapest and Stockholm – explored the viability of end-of-pipeline solutions that are proposed for the phosphorus supply chain (see paper I). Second, an analysis of case studies was carried out on agroecology projects in industrializing world regions in order to assess the extent to which agroecology can reduce inorganic phosphate fertilizer requirement to 2050. This particular study, found in paper IV, allowed for the exploration of different scenarios aimed at curtailing the increase in inorganic phosphate fertilizer consumption and reducing import dependency for phosphate-scarce regions.

4.4 Systems analysis and system dynamics modelling

Due to the long, fragmented and complex nature of the phosphorus supply chain, this research has primarily relied on systems analysis to examine data from literature and document review, as well as from the stakeholder interviews. Systems analysis is a method of using systems thinking to unravel complexity and understand a system's behavior. By doing so, systems analysis is an adequate tool to increase policy effectiveness and enable evaluation designs that are sensitive to what each proposed intervention is intended to achieve (Shiell and Riley 2017).

System behavior dynamics were discussed by creating a causal loop diagram (CLD) from the literature review and the coding of semi-structured interviews, following Kim and Andersen's (2012) procedures of creating CLDs from purposeful text. A CLD helps to identify causal structures connecting dynamics created by the current linearity of cradle-to-grave phosphorus chain. The last methodological step was using system dynamics (SD) modelling, a tool originating from engineering as pioneered by Jay Write Forrester at the Massachusetts Institute of Technology (MIT) in Cambridge, Massachusetts. System dynamics modelling was used to replicate the behavior of the global phosphorus supply chain from mine to market and assess its impact on the world's regions. It built on previous SD modelling works on the global phosphorus chain by Ragnarsdóttir and Sverdrup (2011) and Sverdrup and Ragnarsdóttir (2011, 2014). System dynamics modelling allowed the transition from theory/conceptualization to a quantifiable evaluation of the interaction between feedbacks, delays, accumulations and non-linearities in the cradle-to-grave of phosphorus.

For the SD modelling stage in this thesis, an initial conceptualization of the main dynamics to be modelled was carried out, resulting in a stock and flow diagram and a causal loop diagram (CLD). The model operates at a global scale (Fig. 7) and at a regional level (Fig. 8), where the world was divided into eight regions: North America (NA), Latin America and the Caribbean (LAC), Europe and Central Asia (ECA), North Africa and Western Asia (NAWA), Sub-Saharan Africa (SSA), Southern Asia (SA), East and South-East Asia (ESEA) and Oceania (see Appendix A for more details on regional composition).

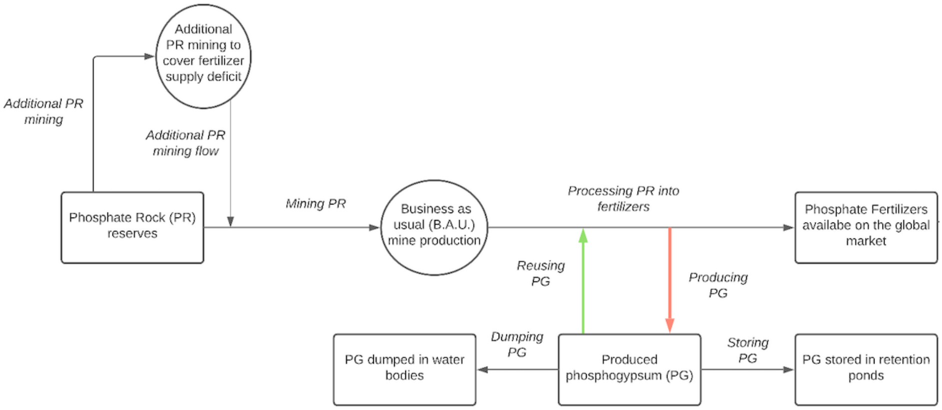

Figure 7. Stock and flow diagram of the global level in the SD model. Arrows are flows, rectangles are stocks, circles are also flows, but represented as temporary stocks in the model, in order to keep track of some important processes in the P supply

At the global scale, the model deals primarily with the production and processing of global phosphate rock into phosphate fertilizers available on the global market, calculating the amount of byproduct produced at this stage, namely phosphogypsum.

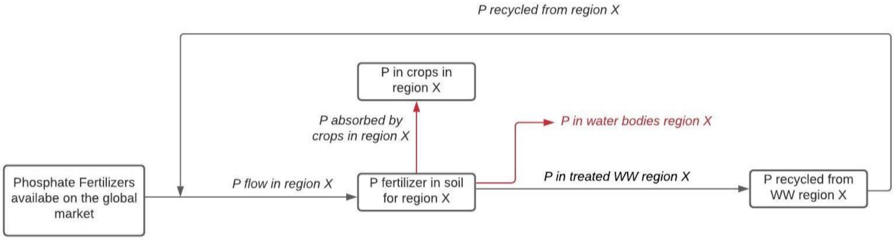

Figure 8. The regional level of the SD model. Arrows are flows (in red representing losses), rectangles are stocks

At a regional level, every region is allocated its own flow of phosphate fertilizer, depending on their specific P requirement tied to population and based on the availability of global phosphate fertilizers. Fig. 8 shows the simplified, reduced diagram for one region – in the model this is replicated eight times for the eight world regions considered. A full flowchart is available in Appendix A. While in Fig. 8 the flow chart shows P going into regional soil, from where some is absorbed in crops, this was not included in the model, where, for the sake of simplicity, P flowing into a region goes straight to runoff and into water bodies. A flowchart was also made for the global and regional population, including a migration flow between Latin America and the Caribbean and North America (see Fig. 9).

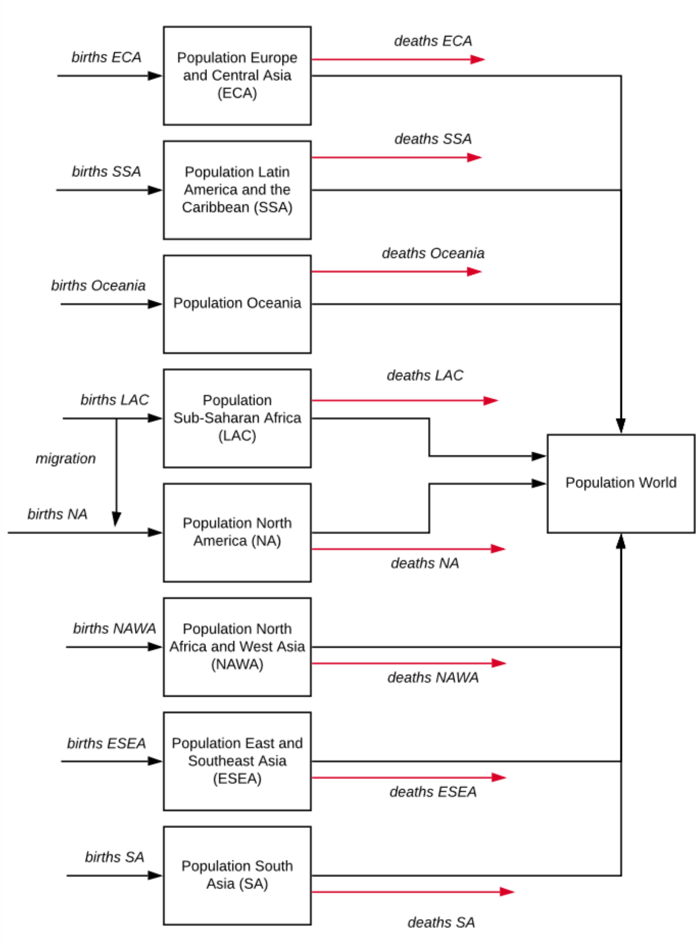

Figure 9. Population flowchart. Arrows are flows (in red representing losses), rectangles are stocks

The next step in the conceptualization stage was to create a CLD, the result of which can be seen in Fig. 10. One important factor impacting on the phosphorus requirement in this CLD is population, represented in loops R1 and B1. In the model, phosphorus requirement refers to phosphorus use as calculated from historical phosphate use rates and tied to population dynamics. The availability of phosphate fertilizers is determined by the mining and processing of phosphate rock, which is represented in loop B4, but also by the amount of phosphate recycled from wastewater, represented in loops B2 and R2.

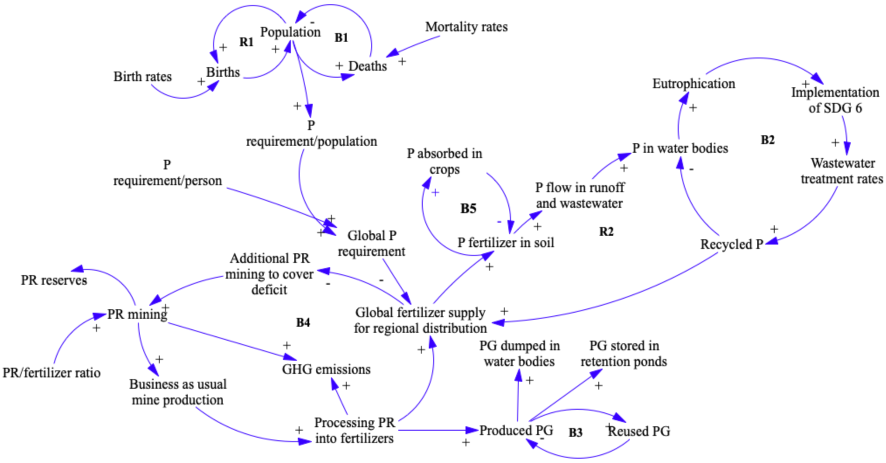

Figure 10. Causal Loop Diagram used for the initial conceptualization of the SD model. B stands for balancing, R for reinforcing, P for Phosphorus, PR for phosphate rock, PG for phosphogypsum, SDG for Sustainable Development Goal

The CLD highlights other important variables that are present in the model, such as the ratio of required units of phosphate rock to produce one unit of phosphate fertilizers (PR/fertilizer ratio) or the historical phosphate requirement tied to population (P requirement/person and P requirement/population). Moreover, it links the development of the P recycling sector from wastewater to the implementation of SDG 6 and the associated increase in wastewater treatment rates (loop B2, Fig. 10).

Finally, a system dynamics model was built using STELLA ARCHITECT, which followed the flowchart structure, with one global module and one regional module. All regional modules have the same structures and embed the same assumptions, apart from NA and LAC, where an immigration part was added. The model, model documentation and model data are open-access and available at https://adaptecon.com/publications/ in the “Models” section. More information on the main embedded assumptions in the model and its building methodology is available in Appendix A.

5 Results

The four papers of this thesis reflect a sequential progress. The first paper investigated already explored end-of-pipeline P recovery practices, focusing on municipal wastewater in two European capitals. The second paper examined the current availability, accessibility and reliability of data that can be used to report along the global P supply chain. It also explored the implications of reporting in terms of global governance of a resource vital for global food security. The third paper employed the use of SD modelling to determine regional impact of the global P supply chain and it projected historical behavior to 2050. Lastly, the fourth paper explored scenarios to 2050, of P requirement reduction at a regional level.

5.1 Phosphorus recycling from municipal wastewater in Europe (Paper I)

A significant body of literature has been dedicated to end-of-pipeline solutions for the linearity of the P supply chain and its cradle-to-grave transformation from waste to resource (see Mihelcic et al. 2011; Molinos-Senante et al. 2011; Cardoso Chrispim et al. 2019). This first paper aimed to investigate the status of these solutions in Europe, where P is already on the Critical Raw Materials List of the European Commission.

A comparative study on two European capitals – Stockholm and Budapest – was chosen. First, a review of the current situation was given for the two locations. Second, semi-structured interviews with 23 stakeholders in the P recycling sector were carried out to complement literature information and provide an insight into the current challenges and opportunities for the P recycling sector.

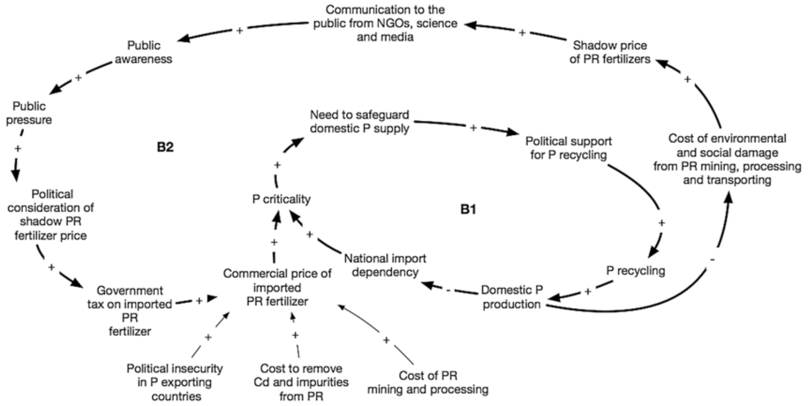

Figure 11. Causal Loop Diagram showing the impact of phosphorus criticality on phosphorus recycling. Arrows show a relation between variables, "+" and "-" show the type of relation, B1 and B2 stand for balancing loops 1 and 2 (source: Nedelciu et al. 2019)

Third, systems analysis was performed on data derived from the literature and interviews. The resulting causal loop diagrams (CLDs) were used to determine leverage points of intervention in the system, where policy action would be most effective. The study found that P criticality is the main driver for the P recycling sector (see Fig. 11). Phosphorus criticality is mostly understood – both in the literature and by the interviewees – as a function of national dependency on phosphate fertilizer imports and the commercial price of P on the global market. In turn, the national import dependency is connected to the amount of phosphate fertilizers produced domestically.

The global price of phosphate fertilizers is, however, a function of government tax on imported fertilizers, political insecurity in P exporting countries, the cost of removing Cd and other impurities as required by regulation and the cost of PR mining and processing. Balancing loop B1 in Fig. 11 continues with the rationale that high P criticality leads to awareness among lawmakers on the need to safeguard domestic P supply. This awareness materializes into political support for P recycling. For many of the stakeholders, political support translates into national binding targets for P recycling, similar to those already set in Germany and Switzerland. Such targets would increase the rate of domestic P recycling. Loop B1 is closed by an increase in domestic P production through higher P recycling rates. In this situation, P criticality decreases, which reduces the need for political support.

Loop B2 is supported by the literature. Mining, processing and transport of PR require considerable amounts of resources such as water, sulphur, energy, and materials to build new infrastructure. Mining of PR generates millions of tons of waste annually, including phosphate sludge, contributing to pollution of land and aquatic ecosystems (Cordell et al. 2015). There are also social costs to pay for PR mining, most notably community displacement and conflict. Thus, PR fertilizers are produced with a hidden cost of socio-environmental externalities (Cordell et al. 2015), which increases their shadow price and triggers loop B2. The higher the shadow price of PR fertilizers is, the more it fuels interest from NGOs, academia and media, which communicate it to the public. Increased public awareness leads to increased public pressure on lawmakers, who are thus likely to consider the shadow PR fertilizer prices. One way that governments can account for externalities is taxing. China imposed a tax on the export of PR in order to secure domestic supply (Scholz et al. 2014), thus reducing both import and export. With the exception of Finland, in Europe the tax could only apply to imported PR fertilizer. Such tax would increase the commercial price of PR fertilizer and in turn, increase P criticality (see Fig. 11). Phopshorus criticality emerges where loop B2 merges with loop B1 and eventually leads to higher domestic P production through P recycling. A higher domestic P production will decrease international P externalities.

A further CLD was constructed in order to examine which interventions are more likely to lead to a development of the P recycling sector (see Fig. 12). All stakeholders believed political support should materialize in investment subsidies for wastewater infrastructure, wastewater technology and training of staff from the wastewater sector. These subsidies can also be directed at public–private partnerships or financing entrepreneurs in the wastewater sector. In loop B1 (in red), this policy intervention results in decreased costs of the P recycling process and increased recycling profitability. It further enables an increased amount of recycled P to reach the market by intensifying the recycling process. More recycled P on the market decreases import dependency and the urgency of the government to decide on investing in the recycling sector, hence reducing investment subsidies.

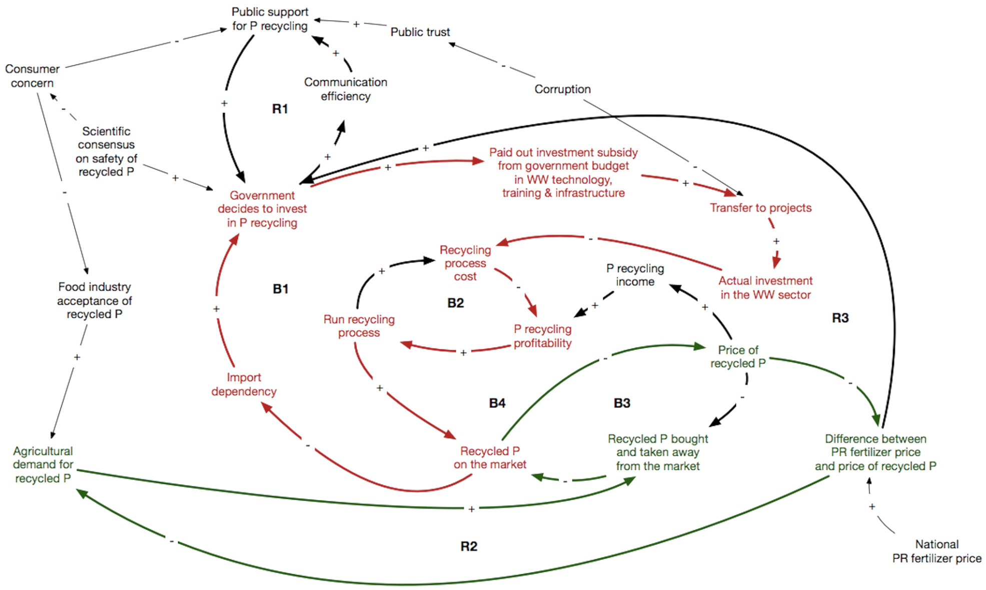

Figure 12. Causal loop diagram showing the main dynamics of P recycling implementation as identified from interviews and the literature. Red arrows are for the policy intervention in loop B1, green arrows are for the impact of the agriculture sector on recycled P (source: Nedelciu et al. 2019)

However, the aim of policy intervention is twofold. Market mechanisms in loops B2, B3, and B4 lower the price of recycled P by increasing the amount of recycled P on the market. Loop R2 shows that as the difference between PR fertilizer prices and price of recycled P decreases, agricultural demand for recycled P increases, taking away recycled P from the market. This means that P recycling costs can be covered more by market revenues and less by government subsidies. The system then sends a feedback to policy makers through loop R3, enabling them to decide on further investments whenever PR–RP fertilizer price difference increase.

Lastly, an influence-interest stakeholder matrix was constructed, allowing the identification of which stakeholders were key to the development of the recycling sector (see Fig. 13). Policy makers at a national and local level have the highest influence but lack somewhat in interest. This is due to perceived low P criticality, as global fertilizer prices are generally much lower than those of recovered P fertilizers. Also, avoiding conflict between stakeholders is another factor that keeps national and local policy makers reluctant in taking decisive action. Farmers associations have a relatively high influence through their lobby power and a high interest in recycling P. However, low fertilizer prices and lack of conclusive scientific consensus on recycled P safety prevents them from lobbying more for P recycling. The food industry has influence through its lobby power but less interest due to current low fertilizer prices and concerns about consumers and contamination scandals. To put it in the words of one of the interviewed food industry stakeholders “low P prices means safety [i.e. safety of the phosphate fertilizer that is being used] wins over recycling at the moment”.

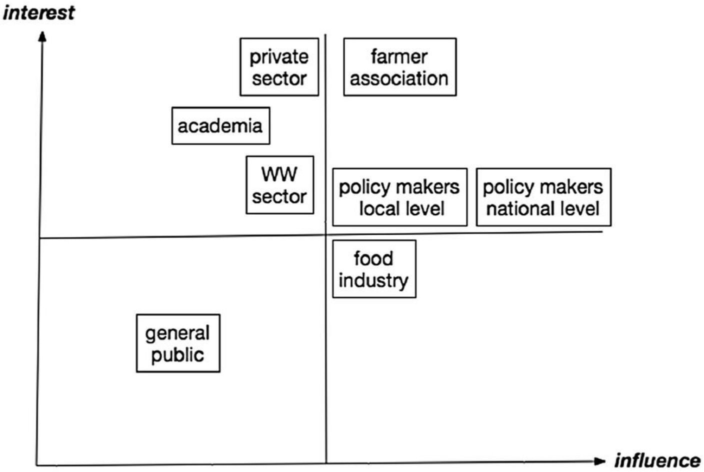

Figure 13. Interest-influence matrix of stakeholders in the P recycling sector for Stockholm and Budapest (source: Nedelciu et al. 2019)

Stakeholders in the academic and the private sector have a high interest in the topic but not enough influence—this is due to the perceived lack of urgency for P recycling by stakeholders with higher influence and the small scale of P recycling companies. The interest of wastewater sector stakeholders in Stockholm and Budapest is not that high because binding regulations to recycle P do not exist. The general public has in most cases low interest and low influence, unless in exceptional circumstances, such as contamination cases or widespread awareness raising campaigns.

5.2 The need for reporting on the global phosphorus supply chain (Paper II)

Assessing the social, economic and environmental impacts of the global phosphorus supply chain requires data. Because of the long, fragmented and very complex nature of the phosphorus cradle-to-grave chain, as well as due to the multitude of different stakeholders involved along the supply chain, accessing data can be challenging. In this second paper, a review of the current shortcomings arising from reporting along the phosphorus supply chain was carried out.

The study started from the idea that public knowledge on all aspects of the P supply chain should be basic knowledge for a basic right: Access to food (Wellmer and Scholz 2015). The human right to adequate food is embedded in the UN International Covenant on Economic, Social and Cultural rights and is defined as follows:

“The right to adequate food is realized when every man, woman and child, alone or in community with others, has the physical and economic access at all times to adequate food or means for its procurement (FAO 2012).”

A review of the current reporting practices was carried out. The study investigated five sectors of the P cradle-to-grave chain: Prospecting and exploration for phosphate rock reserves and resources; mining and initial processing; processing of phosphate rock into fertilizers; application of fertilizers on agricultural land; and post-harvest to consumer and eventually to waste.

The results indicate four main issues with P reporting. First, assessment of reserves and resources lacks reliability, transparency and consistency. At present, PR reporting—including for the only entity reporting publicly, the United States Geological Survey (USGS) — relies on country- or deposit-specific assessments. In undertaking these assessments, geological surveys or companies can use different terminologies and, in some cases, different methodologies. This assessment approach decreases the reliability of global PR reporting. A relevant example is the 2005 compilation of studies by the International Geological Correlation Programme (IGCP 2005). In this book, all currently identified phosphate deposits of the world are described, country by country. Each deposit is further divided into assessments of ore bodies. However, the methodologies and terminologies used to calculate PR reserves and resources vary from country to country and sometimes among ore bodies of the same deposits. Moreover, the characteristics of one deposit or ore body can be very vague, for instance, the 800 million tonnes Saudi deposit at Al Amud, which has an ore grade of "less than 20% P_2O_5" (Notholt et al. 2005), or the ore body at Constable Hill in the Western Cape Province of South Africa, which has 0.27 million tonnes at 27.5% P_2O_5 concentration, "with an additional several million tonnes of low-grade ore" (Notholt et al. 2005).

Access to accurate, up-to-date data is also restricted, not only to the public but also to reporting entities. This is in part due to the concept of proprietary data. In Australia, for instance, the International Fertilizer Development Center (IFDC 2010) noted that the state geological survey (Australian Geological Survey Organisation – AGSO) does not have a complete account of the country's PR reserves and production because mining and fertilizer companies are not obliged to provide this information. Disclosure of PR reserves, resources and production can be problematic when a state considers this information of national security. China, for instance, has in the past altered its reported reserves without explanation. Its reserves doubled over night when it joined the World Trade Organisation (WTO) in 2001 and decreased in 2007–2008, when the fertilizer spike in prices occurred (Cordell and White 2011). Therefore, reporting entities often need to estimate a country's resource.

Second, reporting on the losses along the P supply chain is incomplete. Although the literature shows that up to 90% can be lost from cradle to grave (Scholz and Wellmer 2015), studies investigating losses per sector have yielded inconclusive results. In Fig. 14, the prospecting and exploration processes at the initial stage of the value chain are subject to the limitations in deposit characterization and reporting. This poses challenges in determining the amount of ultimately recoverable resources (URR). Steiner et al. (2015) proposed solutions to increase the efficiency of exploration. These include improved geophysical methods, re-exploration of P in search of other resources such as uranium, and search strategy optimization. Actors involved at this stage would be geological surveys and mining companies.

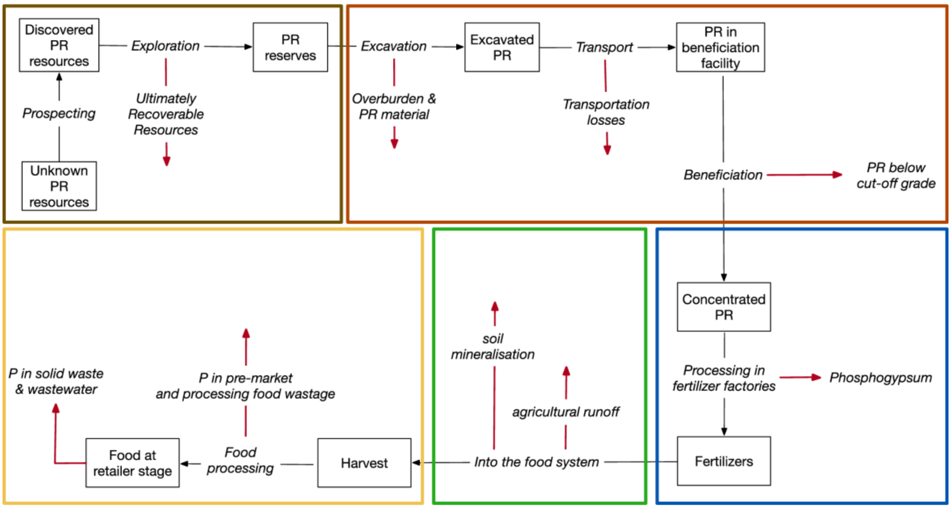

Figure 14. Losses along the phosphorus supply chain, in red arrows (source: Nedelciu et al. 2020a)

The next supply chain sector in Fig. 14 is mining and beneficiation. Data on how much P is lost in the overburden, during transport or during beneficiation, can be provided at the mine and beneficiation unit level. Actors involved here are the mining companies and the authorities responsible with the regulation of mining activities. Next is the processing of beneficiated concentrate to fertilizer. Fertilizer production is highly inefficient, as “between 30- and 50% of the P_2O_5 equivalents in the mined ore is unrecovered and is contained in waste ponds” (IFDC 2012). However, improving estimations would require an integrated reporting from the fertilizer producing companies. Proprietary data and lack of monitoring and reporting regulations make this difficult. In the green box from Fig. 14, phosphate fertilizers are spread on agricultural land and follow three paths: (1) absorption by crops, (2) accumulation in soil through mineralization, and (3) runoff or transport by subsurface drainage in water bodies (King et al. 2014). The amount of P in absorbed crops can be estimated by the harvested crop amounts. However, while some studies investigated mineralization of organic P in soil at a global level (Bunemann 2015), studies examining the extent and characteristics of inorganic P mineralization are limited to some soil types or some geographical regions (Achat et al. 2016). Similarly, literature on the amount of P runoff and subsurface drainage is also limited to region- or soil-specific studies (King et al. 2014). The next sector of the P chain is food production and consumption. Some recent studies investigate P losses specifically in this sector at a country level (e.g. Wang et al. 2018 for China). More studies investigated and reviewed the extent of post-harvest food wastage at the farm, manufacturer, retailer and transportation stages of the food supply chain (e.g. BCG 2018). The information could be used to calculate and quantify the extent of P losses. At the very end of this sector is the waste from food shops/supermarkets and consumers, which comes in the form of both food waste and wastewater. In some parts of the world, stricter water protection regulations have led to an increasing awareness of the double role of P as both a resource and a pollutant. In Europe, for instance, end of pipeline studies showed P from wastewater could supply up to 20% of the European demand (European Commission 2017). The earlier stages of the supply chain, however, remain largely unreported and thus their recovery potential remains untapped.

Third, what are now considered “externalities” of the P supply chain – such as forms of social and environmental harm – are only partially present in any reporting scheme, through reporting in other sectors (such as standalone reporting on water quality status or human rights abuse). A 2019 cradle-to-grave analysis of phosphorus fertilizers by UNEP’s International Resource Panel (IRP) revealed increasing negative impacts of PR mining, fertilizer production and application. Phosphoric acid production and PR mining are responsible for greenhouse gas emissions, largely through energy use. Ecotoxicity, human toxicity and eutrophication are caused by fertilizer application and, to a lesser extent, by PR mining. Finally, air pollution is mainly caused by phosphoric acid production and PR mining. In all cases, the negative impact of cradle-to-grave processes in phosphorus fertilizers has increased by 20% from 2000 to 2015 (IRP 2019). Reporting on the environmental impacts of phosphate mining is thus essential in protecting biodiversity, water and soil resources, and the climate. Ecosystems can be critically damaged by PR mining, with negative effects for the environment, society and economy.

From a socio-political standpoint, it is worth mentioning that significant PR resources are found in the disputed region of Western Sahara, which in 2016 accounted for almost a quarter of all PR exports of Morocco (OCP 2017). Western Sahara has been in a conflict since 1975, when most of the region was occupied by Morocco, while the remaining part was claimed by the Polisario Front, which installed the Sahrawi Arab Democratic Republic or SADR (Saul 2015). Morocco has repeatedly been accused of violating the human rights of the indigenous people of Western Sahara, as well as violating international law by exploiting resources from an occupied territory (Cordell 2015; Saul 2015; Amnesty International 2018). On the other hand, the Polisario Front has been accused of failing to hold to account those responsible of violating human rights in its camps during the 1970s and 1980s (Amnesty International 2018). Some fertilizer companies acted on the matter of phosphate originating from Western Sahara. For example, two of the three importing companies in Australia stopped purchasing PR originating from Western Sahara as of 2015, soon followed by fertilizer companies from Norway, Germany, the Netherlands, Belgium, Uruguay, Switzerland and the US (WSRW 2017). Two rulings of the European Court of Justice in 2016 and 2018 decided that the Association and Liberalisation Agreements in agriculture and fisheries concluded between the EU and Morocco did not apply to Western Sahara, as the region has a separate and distinct status guaranteed under the Charter of the United Nations (CURIA 2018). The Court highlighted that it was not apparent the people of the territory of Western Sahara consented to the EU-Morocco agreement, although they had the status of a third party (CURIA 2018). By ruling on the legality of PR exploitation, court decisions influence the activities of those involved in the P supply chain. At the same time, court rulings can indicate areas in the supply chain where more reporting and monitoring is needed.

Fourth, access to data is still one of the key obstacles to a comprehensive reporting along the P supply chain. Open access data have been advocated in the literature as a tool to improve governance, including governance of natural resources (Attard et al. 2015). Governments are usually seen as the entities that should provide open access to their data, to increase transparency but also to enable interested and affected stakeholders to reuse, redistribute and innovate on the data provided (Attard et al. 2015). Such transparency makes governments more accountable to their actions and enables citizens to actively participate in the governance process (Attard et al. 2015). However, companies can also provide access to their data. Carbonell (2016) has called for the use of big data by companies in big agriculture (large-scale farming actors) to evaluate and monitor externalities of the industrial agriculture system. The author argues that this would enable research on the designation of best agriculture models for the future of global food production. Open access to P reporting can not only assist in tracking vulnerability and impact of the value chain, but also help in tracking progress on broader indicators, in which P plays a significant role. For instance, despite the fact that P supply chain effects and has a central value in food production, P reporting is not an integral part of the reporting for the UN Sustainable Development Goals (SDGs). Table 3 shows the connection between reporting on achieving the SDGs as a global sustainability framework and reporting on the P supply chain.

Table 3. Connection between the Sustainable Development Goals and the reporting along the P supply chain (source: Nedelciu et al. 2020a)

Sustainable Development Goal	**How reporting on the P supply chain affects reporting on the fulfilment of the goal**
SDG1—Zero poverty SDG2—Zero hunger SDG3—Good health and well-being	- Poverty, hunger and health are related; people in less developed countries spend from 30 to 56% of their budget on food (WEF 2016) - Rural population in less developed countries is highly dependent on the productivity of their subsistence and semi-subsistence agriculture, and therefore P input can be essential - Eutrophication through P pollution can negatively affect the use of water for human purposes, including provision of drinking water. It can also negatively impact fishing, leading to decreased food availability and decreasing economic revenues
SDG6—Ensure availability and sustainable management of water and sanitation for all	- P pollution as runoff or wastewater effluent/sewage and its associated eutrophication
SDG12–Responsible Consumption and Production	- High rates of losses along the P supply chain
SDG14–Life under water	- Eutrophication and dead zones due to P pollution
SDG16—Peace, justice and strong institutions	- Oligopolistic phosphate market moving towards a monopoly with phosphate rock from conflict regions

In general, reporting on the P supply chain allows a better reporting on food security, pollution and human well-being (Cordell and White 2015) and all of these sectors are at the core of most of the SDGs. In turn, this can enable a better and more informed policy-making process in these areas but also an increased awareness among the public and other affected actors, such as farmers.

5.3 Global phosphorus supply chain dynamics: Assessing regional impact for the coming decades (Paper III)

The literature indicates that with population growth, food demand – and thus, fertilizer demand – will increase in the coming decades. This third paper aimed to develop a regionalized system dynamics (SD) 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 aimed to assess the regional and global environmental impact of the mined phosphate for the same period.

In answering the research question, the SD model ran for the 1961-2050 period for a world 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. Each region had a module, which included population, P requirement tied to population, amount of P reaching water bodies and amount of P that can be recycled from wastewater. A more detailed methodology of the model can be found in Appendix A. Sterman's (2000) modelling process was used for the SD model, following a five-stage process (see Fig.15). 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.

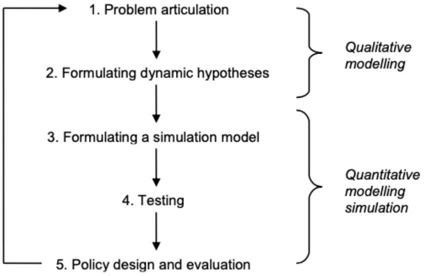

Figure 15. Process of system dynamics modelling (source: Sterman 2000)

The third stage is the formulation of a simulation model, which in this case is an SD model in STELLA ARCHITECT. The CLDs, flowchart, model and model documentation 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 1961-2019 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 relationship between PR mining and fertilizer production shows that the ratio of mined PR quantity and processed fertilizer is increasing. More PR will need 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 2050, 526 million tons of PR will need to be mined for 90.1 million tons 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 - 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).

Figure 16 shows phosphate fertilizer requirement tied to population per world region. 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 requirements, while in Europe and North America there will be little, or no requirement increase. It is worth noting that most of the population growth will occur in Sub-Saharan Africa, Asia and Latin America and the Caribbean. Figure 16 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.

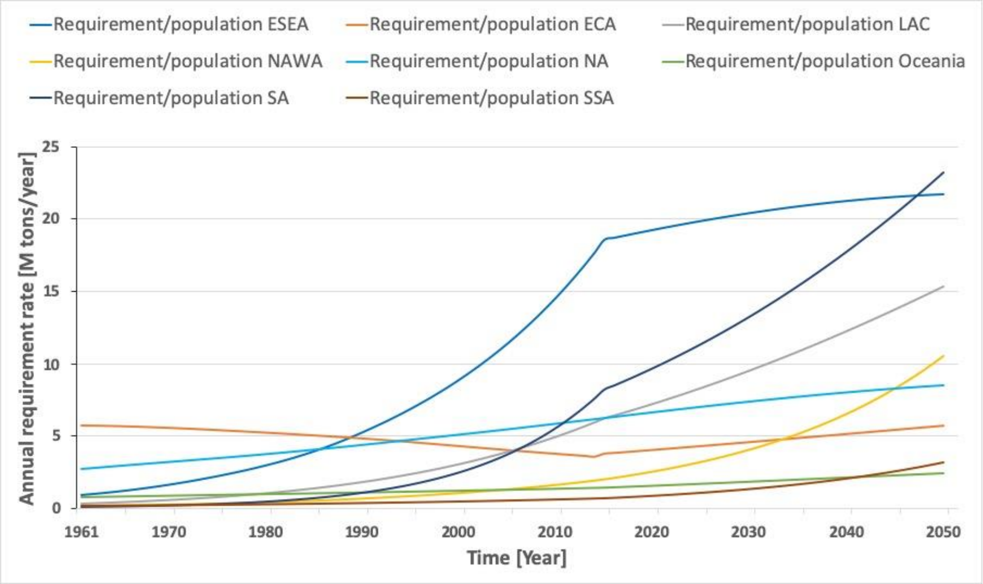

Figure 16. Phosphate requirement tied to population dynamics for the eight world regions in the SD model (source: Nedelciu et al. 2020b)

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. 17b). 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 prioritized 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. 17a). 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. 17b). A fully operational P recycling sector can only provide 10% of the total global supply by 2050. 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).

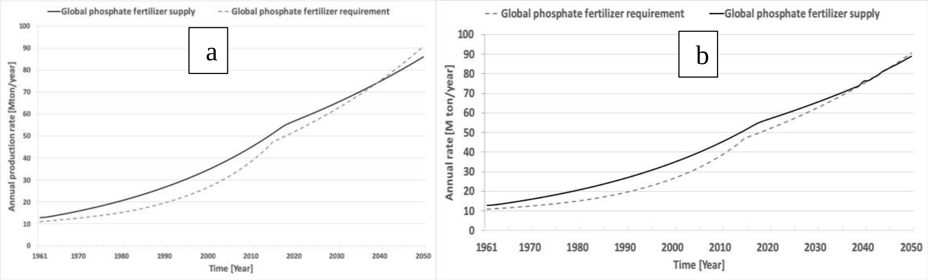

Figure 17. (a) Requirement-supply relationship in a business-as-usual scenario, (b), requirement-supply when more PR production and P recycling are activated (source Nedelciu et al. 2020b)

However, 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, with the highest P additions from ESEA and SA (Fig. 18). 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 Caribbean, 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 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.

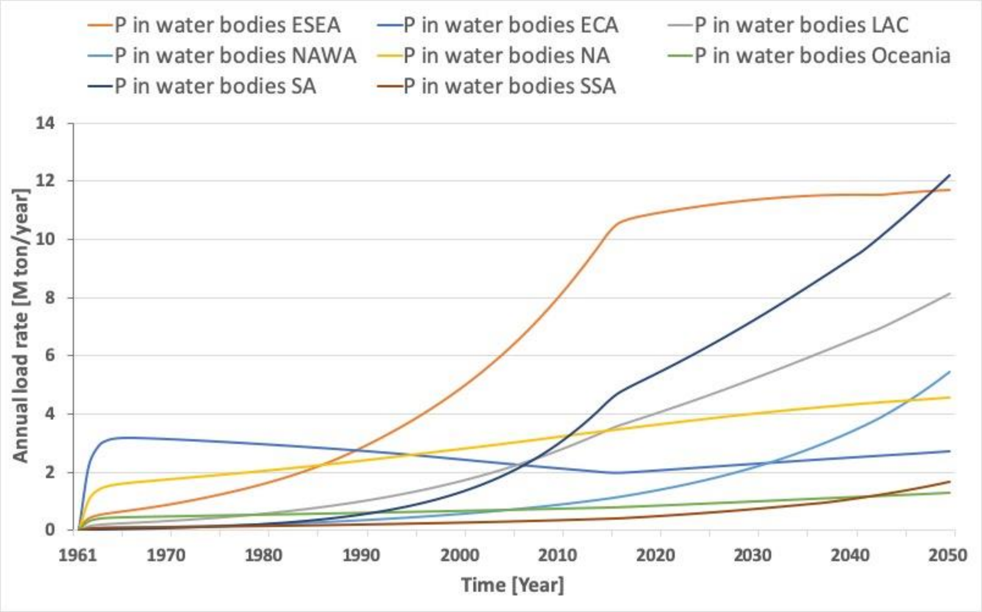

Figure 18. The amount of phosphorus entering water bodies in untreated wastewater and through agricultural runoff (source: Nedelciu et al. 2020b)

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. 19a), 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. 19b). The total stock of phosphogypsum stored in tailing ponds for the period between 1961-2050 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. 19c).

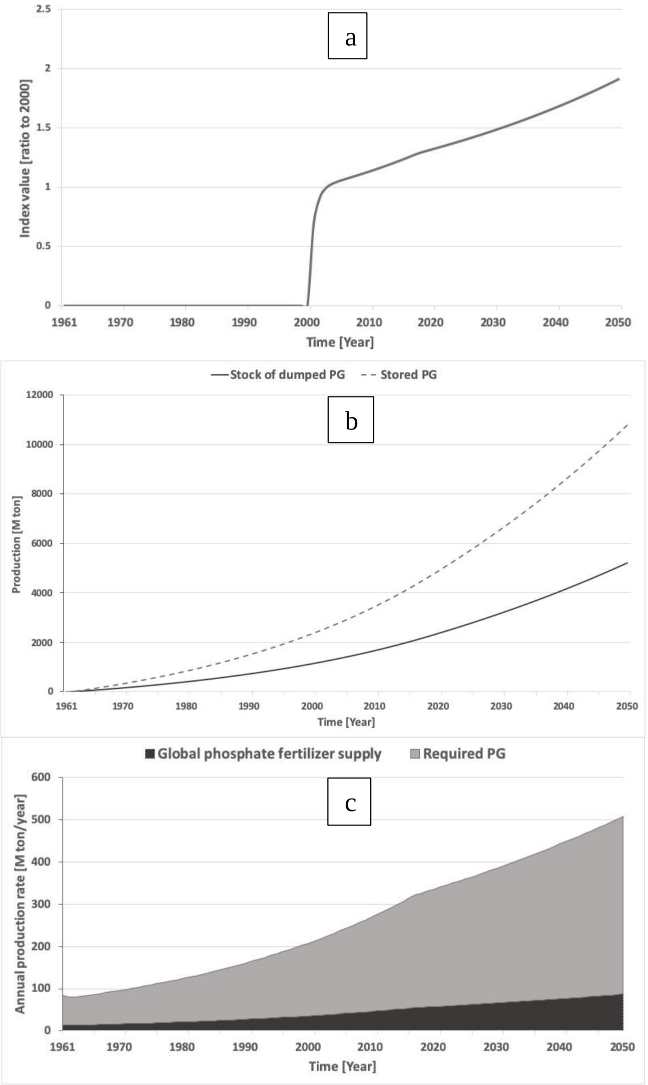

Figure 19. (a) Impact of PR mining and fertilizer production on GHG emissions indexed to 2000, (b) phosphogypsum (PG) production per year required to produce fertilizers and (c) the total stocks of stored and dumped phosphogypsum (source: Nedelciu et al. 2020b)

The numbers on phosphogypsum management, 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 (Canovas et al. 2018).

5.4 Regional scenarios for inorganic phosphate requirement decrease to 2050 (Paper IV)

The wastefulness of the linear supply chain of P, combined with increased import dependency of P-scarce region call for a more comprehensive approach to the P issue. The necessity for such an approach was highlighted during the current COVID-19 pandemic, as disruptions in global supply – including agro-chemical inputs – are a red flag for food security. As such, the purpose of this fourth and last paper was to explore four different scenarios envisaging a reduction in inorganic phosphate requirement to 2050: food loss reduction, recycling P from wastewater, agroecology and a combination of the three. In the geographical scope of the study were industrializing regions experiencing most population growth, namely Latin America and the Caribbean (LAC), Southern Asia (SA), East and South-East Asia (ESEA), North Africa and Western Asia (NAWA), and Sub-Saharan Africa (SSA).

The system dynamics model developed in paper III was used, building the four scenarios. The rate of recycling was kept from paper III, while for the food loss reduction scenario we used numbers from FAO (2019a). In order to calculate the potential decrease in the requirement for inorganic fertilizer due to agroecology, a case study analysis was carried out in each region. Several farming measures defined as “agroecological” in the literature were considered and the results from these studies were averaged to a regional number. Table 4 summarizes the results of the case study analysis.

Table 4. Results of the case study review on agroecological efficiency (SRI = System of Rice Intensification; OA = Organic Agriculture; AE = Agroecological; CA = Conservation Agriculture; SA = Sustainable Agriculture; IPM = Integrated Pest Management; SWI = System of Wheat Intensification; SSI = System of Sugarcane Intensification)

Region	**No. case studies**	**Type of AE measure (in %)**	**Average yield change**
Latin America and the Caribbean (LAC)	20	75% SRI, 20% OA, 5% general AE	+48%
Sub-Saharan Africa (SSA)	128	89% OA, 7% SRI, 1.5% CA, 1.5% SA, 1% IPM	+174%
North Africa and Western Asia (NAWA)	12	92% SRI, 8% SWI	+66%
Southern Asia (SA)	35	17% SA, 6% IPM, 77% SRI	+48%
East and South-East Asia (ESEA)	81	1% Aquaculture, 1% Contour Farming, 1% double cropping, 2.5% IPM, 3.7% SA, 90.8% SRI	+37%

The numbers used to build the four scenarios are summarized in Table 5. Food loss numbers show that East and South East Asia has the lowest post-harvest to distribution losses with 8%, while South Asia is at the opposite end of the scale, with 20.5%. In terms of efficiency in fertilizer use derived from the implementation of agroecological practices, the numbers follow the yield increases presented in Table 4.

Table 5. Numbers used in the model for each scenario, based on a BAU scenario and recycling rates from Nedelciu et al. 2020a as well as results from literature and case study review. In the food loss scenario, a 20% reduction of the food loss numbers presented in the table was applied

Region	**Business as usual (BAU) in 2050 (in m.t.)**	**P recycling (R) from WW (in %)**	**Food loss reduction (FLR) (post-harvest to distribution) (in %)**	**Agroecology (AE) (in increased efficiency ratio)**
LAC	15.4	-10%	-12%	1.48
SSA	3.2	-10%	-14%	2.74
NAWA	10.6	-10%	-11%	1.66
SA	23.2	-10%	-20.5%	1.48
ESEA	21.7	-10%	-8%	1.37

East and South-East Asia was the region experiencing the most significant changes in P requirement after scenario simulations (see Fig. 20). The Food Loss Reduction (FLR) scenario brought little change to phosphate requirement in the region compared to BAU, thus being the exception. This is because ESEA had the lowest food loss rate (see Table 5), of which only a 20% reduction is considered. Implementing a P recycling sector reduced the increase in requirement and kept it under 20 million tons yr^{-1} in 2050. Agroecology alone reduced the phosphate requirement in 2050 to 2012 levels, while a combination of food loss reduction, P recycling and agroecology further reduced phosphate requirement to 2007 levels. Thus, FLR had the lowest impact on phosphate requirement, while agroecology alone produced the highest change.

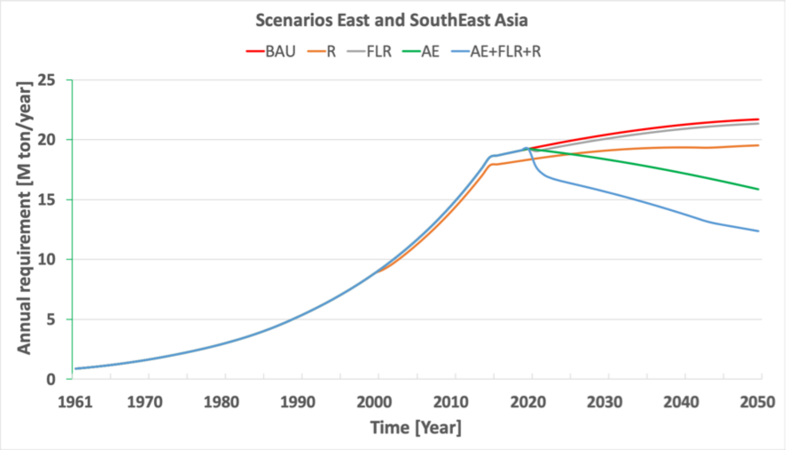

Figure 20. Simulation results for East and South East Asia. AE+FLR+R for a combination of the three scenarios

For the other regions, the results are summarized in Table 6 and show that by far, agroecology has the biggest impact in reducing the requirement for inorganic P. In East and South East Asia, agroecology leads to a decrease of P requirement to 2050 equivalent to the consumption rates recorded in 2012. In Sub-Saharan Africa, agroecology can flatten P requirement compared to a business-as-usual (BAU) scenario. In the other regions, agroecology cannot flatten or decrease BAU P requirement, but it considerably reduces BAU requirement increase. Food loss reduction was the least effective measure. This was because food loss and waste at retailer and consumer levels were not considered and for the post-harvest to manufacturer food loss rates, reducing a fifth of the loss was assumed to be feasible. More research is needed, however, on the national regional feasibility of food loss reduction strategies. When all industrializing regions are considered, food loss reduction was only able to account for a 3% decrease in phosphate requirement to 2050 (see Table 6). Recycling was responsible for a flat 10% decrease in phosphate requirement in all regions, which is reflected in the sum total. Agroecology enabled an aggregate reduction of 33%, while a combination of agroecology, food loss reduction and recycling would keep the total phosphate requirement increase in industrializing regions to only 5% in 2050 compared to 2020 levels (see Table 6).

Table 6. Results of the model simulations for all regions. Numbers are in million tons of phosphate fertilizer per year. BAU = business as usual; FLR = food loss reduction; R = Recycling AE = Agroecology

Region	*BAU 2020*	*BAU 2050*	*FLR 2050*	*R 2050*	*AE 2050*	*AE+FLR+R 2050*
ESEA	19.2	21.7	21.3	19.5	15.8	12.4
LAC	7.2	15.3	15	13.9	10.4	9
NAWA	2.5	10.6	10.3	9.6	6.4	5.6
SA	9.7	23.2	22.2	21	15.6	13.5
SSA	0.9	3.2	3.1	2.9	1.2	1
All	**39.5**	**74**	**71.9**	**66.9**	**49.4**	**41.5**

The results support information in the literature suggesting agroecology as an integrated, comprehensive farming system to support farmers and the environment (e.g. IFAD 2020). Not only did agroecology reduce the need for inorganic fertilizer input – and thus fertilizer cost - but it also increased yields. As such, agroecology can reduce the size of an unsustainable, linear, inorganic P supply chain while at the same time decreasing farmer vulnerability to supply disruptions and increasing farmers' income through increased production.

6 Discussion

The results of this research reinforce the global aspect of today's broader sustainability problems and the need to weld together fragmented supply chains in order to see the bigger picture and provide meaningful, high-impact actions. The study highlighted the importance of getting access to reliable and relevant data and argued for open access for the public. Phosphorus is vital for food production and food is a basic human right, thus information about P management should be public and transparent. Also, P is one of the main water pollutants, affecting human health, fish and marine life stocks, fishing activities, recreational activities and drinking water availability. Better reporting along the phosphorus cradle-to-grave can allow an integrated and improved monitoring of pollution. But perhaps the most important message that comes out of this project is the urgent need to radically change the current configuration of our system. Even ambitious plans to close the P loop and make the global P supply circular are not enough. The system as it runs now would still require more phosphate mining, more phosphate processing and more phosphate application in the coming decades. It is very likely that a solution originating from the structures of a consumption-based system will only encourage more consumption and create problems in other areas. Research needs to be directed at changing the narrative of the system and at tackling the real problem at hand: The mindset of unnecessary consumption of resources and the chase for eternal growth at the expense of the environment.

6.1 The scale and role of circularity

Undoubtedly the most researched measure to tackle P criticality is recycling it from wastewater or other waste sources, which is often regarded as the main Circular Economy intervention in the P supply chain, particularly in Europe (Hukari et al. 2016; Jedelhauser and Binder 2018). This was also the starting point of the present research, with an entire paper dedicated to recycling P from municipal wastewater in Europe (paper I). The results from paper I show that despite proven feasibility of recycling technologies (Molinos-Senante 2011) and an already established understanding of how critical of a resource P is at both academic and policy levels (Cordell et al. 2009; European Parliament 2019a), implementing end-of-pipeline circularity solutions in P-scarce areas is encountering a series of socio-economic and political barriers. Robust interventions are required in order to accelerate circularity deployment in P recycling, which will necessarily involve tradeoffs. For instance, more expensive technologies might be implemented instead of cost-effective ones, because they are deemed safer by most stakeholders, or at least by those stakeholders, who are key to implementing the recycling strategy. Moreover, recycling infrastructure also requires careful, holistic planning – this was evident in the case of Stockholm from paper I, where urban planners were collaborating with residential developers, academics and the waste management sector in order to implement an integrated waste system that would include P recycling. The need for an integrated approach to end-of-pipeline solutions is usually overlooked by the literature addressing P recycling within the broader context of P supply management, where integrated approaches are assigned across two or more sectors of the P supply chain (Cordell and White 2015; Neset and Withers 2016). However, the results support previous studies (see Hukari et al. 2016), which identified fragmented decision making as an impediment to P recycling deployment. Thus, implementing a seemingly straightforward solution is nonetheless complex and requires cooperation between administration departments, stakeholders and economic sectors. Scaling up or working across supply chain sectors naturally increases this complexity and the interactions that need to be considered.

Demand for phosphate fertilizers is expected to globally increase following food demand for a growing population, a result from paper III that is supported by existing literature (Van Vuuren 2010; Sverdrup and Ragnarsdottir 2014). Nonetheless, a key result from paper III is that the demand of phosphate fertilizers will increase differently across world regions, with the highest increase rates expected in industrializing regions. The quantitative results from this research, coupled with the qualitative P vulnerability frameworks and indicators developed in the literature (see Cordell and Neset 2014; Cordell and White 2015) can act as a guidance for key decision makers, who can design strategies better tailored for the needs and possibilities of their regions. For instance, P recycling from wastewater is mandatory in Germany and Switzerland. However, in industrializing nations wastewater treatment levels vary from 8-38% (see paper III and Appendix A), which means that in these regions, P recycling from wastewater can be a rather unrealistic, costly solution.

Another key result from paper III is that a fully operational global recycling sector would account for a minor part of the total global demand for P, as a result of a highly inefficient and loss-prone P supply chain. This result is supported by literature, where studies have shown that most of the mined P that is lost in mining and processing waste, ends in agricultural run-off or is mineralized in soils (Scholz and Wellmer 2015; Steffen et al. 2015; IRP 2019). Thus, while a potentially viable solution at a local or national level – particularly in areas with well-developed wastewater treatment infrastructure – recycling alone is not enough to satisfy increasing demand or halt the increase of P load in water bodies. Moreover, paper III shows that – even with a fully operational recycling sector – pollution from the mining and processing of phosphate rock will increase dramatically, while the GHG emissions from the same sectors will double by 2050. In order words, the implementation of what is now regarded as circular economy in the P sector is not sufficient to decouple the “environmental bads” from “economic goods” in the P supply chain. This result supports conclusions from Zink and Geyer (2017) that CE measures do not always deliver the expected result of reduced consumption and supports the assessment of Vaden et al. (2020) that so far, empirical evidence of absolute decoupling is missing.

It is for this reason that paper IV explored various scenarios of reduced inorganic P consumption, at different stages of the P supply chain. The agroecology scenario for paper IV shows that in industrializing countries, implementation of agroecological measures can flatten the phosphate requirement to 2050 at present-day levels. The results from paper IV underscore the efficiency of systemic, high-impact measures holistically tackling biophysical resource use (agroecology) compared to those measures applied at the end of the supply chain (food waste reduction or recycling). As such, paper IV provides evidence in support of interventions aimed at decreasing resource consumption, identifying them as uniquely positioned to contribute to the sustainability of the P supply chain. In the context of literature signaling a lack of absolute decoupling between economic growth and environmental pressures (Parrique et al. 2019; Vaden et al 2020), paper IV advances a credible solution for achieving this much needed decoupling in the P supply chain.

6.2 Stakeholders and Accountability

The issue of stakeholder responsibility has also been central to this research. The first two papers show how the length and complexity of the P supply chain translates into a large number of stakeholders involved in different processes, from mining phosphate rock to producing the fertilizers, to trading them, applying them on land, regulating their use, tracking their supply and supply ethics, regulating water pollution and others. With such a complex web of stakeholders, accountability on issues from pollution to ethical sourcing can be challenging to envision.

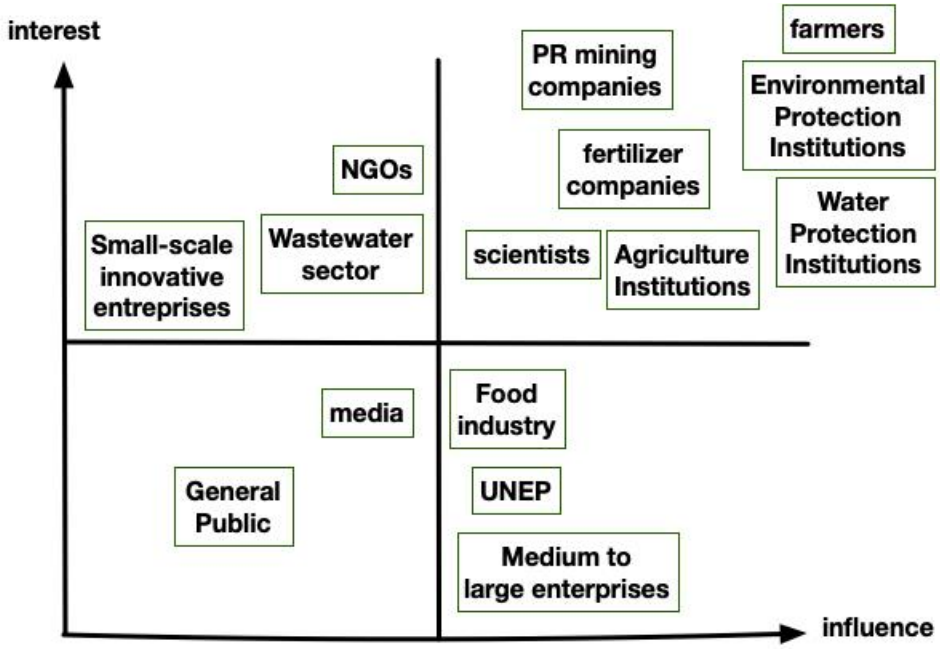

Figure 21. Interest-Influence matrix of stakeholders in the global phosphorus supply chain

Figure 21 shows the interest-influence matrix of the global phosphorus supply chain as understood at the end of this project. This matrix is different from the one in Paper I, which was plotting national-level stakeholders involved in the P recycling sector from municipal wastewater. The figure further shows the multi-scale complexity of the P supply chain and how influence-interest changes with scale and supply chain sector. The matrix can – and should – also change depending on how various actors behave.

The 2007-2008 price spike led by PR mining companies and fertilizer companies prompted an increase in academic interest and moved scientists from the lower-interest to the higher-interest quadrant. It can be assumed that, for instance, more work from the academia can increase both the interest of media and their influence through awareness-raising.

What the interest-influence matrixes from Fig. 21 and paper I also show is that any integrated approach to make the global P supply more sustainable – such as implementing circular economy measures – is challenging at any level. At a local and national level, an integrated, participatory approach is needed in order to find the optimal implementation strategy. While overcoming fragmented decision making is necessary (Hukari et al. 2016), it is not enough. Trade-offs between conflicting stakeholder interests can be essential to the success or failure of such strategy. At a global level, more leadership from UNEP in ensuring a sustainable global governance of P, as proposed by Rosemarin and Ekane (2016), could move the institution into the top right quadrant, on equal footing with PR mining and fertilizer companies. UNEP could thus play a central role in supervising global P supply management and could potentially provide a more reliable and robust set of data for P processes, enabling more quantitative empirical research and contributing to Wellmer and Scholz's "right to know" (2015).

6.3 Oligo- to monopoly of supply and inequalities

Another recurring aspect throughout the study was the dynamic of the global phosphate market, which is heading towards a monopoly by Morocco. This process is likely to be increasingly central for research and policy on the global P supply chain. Paper I showed that end-of-pipeline solutions to closing the P loop are not only challenging, but not enough. Paper III shows that P requirement will dramatically increase by 2050, mostly in world regions that are highly dependent on phosphate fertilizer imports and where population will also record significant growth. In the context of results from the literature, these trends are posing the risk of dangerous reinforcing loops. For instance, greater dependence on Moroccan phosphate (Mohr and Evans 2013; Rosemarin and Ekane 2016) can lead to less scrutiny for the Western Sahara situation and a consolidating oligo- to monopoly market. From this perspective, the call for more reporting along the P supply chain from paper II is even more relevant for the coming decades and reinforces the "right to know" about P governance, as advocated by Wellmer and Scholz (2015). The oligopolistic character of the market draws parallels to a characteristic that has, as of late, has been a defining thread for our world: Inequality. It is first and foremost the inequality of phosphate resource distribution and its geography that reinforces all other inequalities in the P supply chain. Paper I showed that significant investments are needed in order to recycle P from municipal wastewater, which begs the question of who will afford it and who will not. Paper II dealt in detail with access, reliability and availability of data, which is another inequality: Between those who possess the data and those who do not. Paper III showed that regions experiencing the bulk of population growth and increase in P requirement are also phosphate-scarce and largely dependent on imports. The research also showed a different kind of inequality: Environmental inequality. Water pollution from the phosphate runoff from agricultural land or from untreated wastewater discharge is causing damage to the economy and the biodiversity in hotspots that are usually far away from the source, confirming latest research on eutrophication (IRP 2019). Assessing environmental inequality and the negative environmental impact at regional level from paper III is a much-needed contribution to the literature, as highlighted by the Planetary Boundaries studies (Rockström et al. 2009; Steffen et al. 2015; Lade et al. 2020).

6.4 Methodological reflections

In paper I, the conceptualization of P recycling from wastewater using systems thinking was done in a purely qualitative manner, which allowed the identification of the main drivers of success for policy action but did not permit a quantification of the costs or social tradeoffs deriving from different policy strategies. Nonetheless, understanding the intensity of the main system dynamics, leverage points and their impact on the recycling sector, particularly from a participatory perspective, is a valuable addition to the literature on P recycling in particular and sustainable development in general (Abson et al. 2017).

On the other hand, the need to tackle the complexity of the global P supply chain was addressed by using quantitative tools such as system dynamics modelling. Very few studies follow this route (see Wallman et al. 2005; Malek et al. 2012; Sverdrup and Ragnarsdottir 2014) and they address the issue either at a local or a global level. The results from papers III and IV show the benefits of using system dynamics modelling to address complex interactions at regional level, making it an appropriate tool to assess the sustainability of the P supply chain and to contribute to the ongoing assessment efforts in the Planetary Boundaries studies (Rockström et al. 2009; Steffen et al. 2015; Lade et al. 2020). Because of its ability to capture complexity and cross-sectoral interactions, system dynamics modelling could also be used to evaluate trade-offs resulting from implementing, for instance, circular economy strategies in the P supply chain, as discussed in the previous sections. However, system dynamics models have their inherent strengths and weaknesses. One such weakness is that SD models oversimplify real world issues and can lack accuracy in their results (Featherston and Doolan 2012). In papers III and IV, this was done, for instance, through a number of assumptions, including tying phosphate consumption to population dynamics and not to a free market. Nonetheless, this limitation was addressed by validating model results against historical trends and the results of studies using other types of modeling tools, such as trade and production model (Van Vuuren et al. 2010) or demand-production interaction resource model (Mohr and Evans 2013). The validation process confirmed that the model can replicate P resource dynamics legitimately. Sensitivity analysis also showed that the model is responding well to the main variable drivers, such as population (also a main driver in Sverdrup and Ragnarsdottir 2014), PR/fertilizer production ratios or recycling rates. The regional P model used in papers III and IV is, however, simple with regard to the number of interactions considered, when compared to other, more complex global SD models (see Sverdrup and Ragnarsdottir 2014). It is expected that the uncertainty of results would increase with the addition of further interactions (Featherson and Doolan 2012). From that perspective, combining quantitative modeling with qualitative methods, such as those used in paper I, can improve the robustness and reliability of the model and its capacity to reasonably capture system behavior.

Another aspect of this research that raised methodological questions is the way in which agroecology was defined in paper IV- not as holistic as in the FAO's latest definition of 10 elements (FAO 2019b) but broader and encompassing less socio-economic aspects (Altieri and Nicholls 2012). This is due to three main reasons. First, regional data on many of the social, economic and environmental indicators for agroecology is lacking, particularly in industrializing regions, making it hard to quantify its benefits (IPES-Food 2020). Second, despite FAO's initiative to better define agroecology, the concept is still relatively vague in theory and practice (IPES-Food 2020). Third, quantifying the social benefits is generally challenging in SD modelling (Hirsch et al. 2007) and even more with agroecology in particular, as some of the benefits (e.g. resilience) are based on self-assessment (FAO 2019a). A combination of proxy indicators for quantification and stakeholder engagement for calibration could benefit the SD modelling technique.

7 Conclusions

This thesis has shown that end-of-pipeline solutions – on which a robust body of literature is focusing – can only minimally address the wasteful and inefficient configuration of the P supply chain. More research is required in other sectors of the P supply chain, such as mining and processing of PR or application of fertilizers on land. These sectors account for major losses along the supply chain, yet for now, they are mostly ignored by policies such as those directed at Circular Economy implementation. Recycling P from wastewater is needed, however it can be an expensive and difficult process and its implementation requires not only an integrated, participatory approach, but also existing infrastructure, which can make its deployment in certain areas of the world unfeasible. Political support and legally binding targets to recycle P are a prerequisite for the success of the recycling sector. However, the form in which political support is provided needs to involve a consensus among the main stakeholders in the sector, which can result in tradeoffs.

More focus on integrated solutions to reduce waste along the supply chain are needed, framed by an aspect iteratively present in this thesis: “limits”. There are limits to: Access and availability of data on P reporting; P reserves and resources at global, regional and national level; the capacity of a country’s agricultural system to produce food, as related to P input; the extent of P-load in water bodies before eutrophication intensifies (Planetary Boundaries); and business-as-usual exploitation in conflict territories. The growth in future P demand associated to global and regional food security for the coming decades will need to face these limits.

As such, a mix of qualitative and quantitative research methods are needed in order to provide an integrated assessment of these limits and propose coherent, systemic solutions. This is one of the characteristics of this thesis, where stakeholder mapping and engagement, qualitative systems analysis and SD modelling were some of the main research methods used. The results of the four papers show that this choice of methods can provide valuable additions to the literature that seeks to address the systemic nature of P processes, such as the Planetary Boundaries or the Phosphorus Vulnerability Framework. It can also be used to analyze the robustness of models other than SD that have been developed. Nonetheless, all methods have their weaknesses. Results from the SD modelling process should not be taken as predictions but as a general representation of system behavior, which can indicate where the system is heading under different scenarios. Moreover, certain dimensions – particularly the social and political ones – require additional methods to complement SD modelling and address lack of data or evaluation of aspects that are difficult to quantify. Involving stakeholders can be a key approach to improve this shortcoming.

For countries experiencing high rates of population growth and with little or no P resources, supply of P will be a critical challenge and a big obstacle in achieving food security. This thesis is published at a time when the COVID-19 pandemic has been highlighting the vulnerabilities of global supply chains of all sorts: Resources, assembly parts, medical and sanitary supplies, and food – to name just a few. A wider implementation of low-input farming systems such as agroecology is required, with the triple benefit of reducing P consumption, improving environmental conditions and soil productivity, and making farmers more resilient to price shocks and disruptions in fertilizer supply. This is a preemptive approach, which would have the biggest contribution in reducing the losses along the P supply chain and decreasing environmental pressures. As shown in this thesis, low-input farming systems does not necessarily translate into less food being produced. These systems can be a winning strategy for farmers to produce more, while maintaining the productivity of their soils and farmlands and decreasing their vulnerability to future crises.

Nonetheless, in the current socio-economic and political context, a world where all the food is produced by means of agroecological farming is subject to a number of obstacles and lock-ins. As such, global governance of phosphorus as a vital resource for food production needs to be strengthened. Reporting along the P supply chain is required in order to allow for predictability when planning food supply and production strategies. In turn, reporting needs available, accessible, reliable and harmonized data on different aspects of the P supply chain, from phosphate rock reserves to the amount of food wastage at retailer stage. Undoubtedly, this is a field in need of much improvement and will require collaboration that transcends national borders, social sectors, political views and economic interests.

8 Future research

There are two complementary research directions that I see as important following the work on this thesis. The first one would be aimed at exploring scenarios and opportunities to achieve improved circularity along the entire P supply chain. An important research question would be *"What are the main dynamics that can transform the linear cradle-to-grave phosphorus chain into a circular cradle-to-cradle system?".* Further work should include research on circular economy solutions upstream of the P supply chain and their contribution to reducing the significant losses that currently characterize the cradle-to-grave P system. System dynamics modelling would be an adequate tool to assess the efficiency gains that can be achieved in the mining and processing stages of the P supply chain, as well as quantifying gains from potential recycling avenues (e.g. phosphogypsum). At the same, further work could be done in using SD modeling to quantify the negative environmental impacts from the P supply chain and compare this to results that are starting to come out of the Planetary Boundaries studies.

The second research direction has to do with the integration of the P supply chain into the discourse on rural resilience and rural wellbeing. A radical paradigm shift is needed in order to make farmers – and in particular poor rural communities – resilient to future social, health, economic and environmental crises. Phosphate fertilizers can be challenging to procure, due to price or availability, and they cause environmental problems such as eutrophication, which can affect the livelihoods of affected communities. Reducing the requirement for P fertilizers through low-input farming systems while retaining or increasing agricultural productivity is key to strengthening farmer resilience. An important research question here would be "*How can low-input farming systems contribute to increased resilience and wellbeing in rural communities?".* A starting point in this direction would be to use SD modelling to not only integrate FAO's 10 agroecology elements, but also to provide an integrated tool that can measure the Tools for Agroecology Performance Evaluation (TAPE) indicators. The two research directions are complementary: the integration of a circular cradle-to-cradle phosphorus system can be key to progress on rural resilience and wellbeing.

However, a broader research question that I ask myself while finishing this five-year research project is why is agroecology – or any of the several lower-input and improved-yield farming systems – not a widespread phenomenon in our food production system? As I write this, the world is still farming large-scale, high-input monocultures. A recent study by IPES-Food (2020) identified eight obstacles and eight "lock-ins" to the implementation of agroecology in West Africa. This is a good starting point in assessing to which extent these lock-ins and obstacles can be overcome at a regional level. At the same time, it is an opportunity to further regionalize the model developed in this thesis and increase the resolution of the analysis, as the model now considers the whole of Sub-Saharan Africa as one region. Building on the regionalization aspect of the modelling process, further research is needed on the industrialized regions, which were not considered in paper IV. It will be worth exploring whether the same scenarios can be applied to industrialized regions as industrializing nations or whether other, more relevant strategies should be assessed, which would align to existing policies and infrastructure in specific regions (e.g. the Circular Economy Package in Europe) or emerging ones (Green New Deal in the US, European Green Deal in the EU).

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Paper I

From waste to resource: A systems dynamics and stakeholder analysis of phosphorus recycling from municipal wastewater in Europe

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RESEARCH ARTICLE

From waste to resource: A systems dynamics and stakeholder analysis of phosphorus recycling from municipal wastewater in Europe

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Abstract Recycling Phosphorus (P) from urban wastewater can secure part of domestic agricultural P supply and contribute to a circular P supply chain. In this paper, we use literature review, stakeholder interviews and analysis, and systems dynamics for the capital cities of Stockholm and Budapest as case studies. We find that political support is a prerequisite for developing the P recycling sector, and policy makers are the most influential stakeholders. P criticality is the main driver for political support. P externalities from mining to sludge disposal should be considered when evaluating P criticality and recycling profitability. We conclude with policy recommendations for the development of the P recycling sector, arguing for legally binding P recycling targets and prioritization of the safest technological solutions available. Our analysis identifies three policy action indicators and five policy interventions in the recycling system.

Keywords Case study · Phosphorus · Recycling · System dynamics · Stakeholder analysis · Wastewater

INTRODUCTION

Phosphorus (P) is an essential macronutrient needed for plant growth. In agriculture, more than 85% of the P fertilizer comes from mined phosphate rock (PR) (Cordell et al. 2009). PR is mined from a very limited number of countries, most notably Morocco, China, and the United States of America (USA). According to the latest report of the United States Geological Survey (USGS), close to 74% of the world's reserves of PR are found in Morocco and Western Sahara (USGS 2018). The European Union's import dependency on PR was estimated at 92% in 2011 (EU Commission 2013), prompting the European Commission to include P in the list of Critical Raw Materials (CRMs) in 2014. This means that PR is now considered a high supply-risk and high economic value raw mineral. P fertilizer prices were also a determining factor for this decision. In 2007–2008 a 400% increase in P fertilizer prices sent a shockwave to the world market and attracted increased attention from the media, scientific community, and policy makers (Cordell et al. 2009; The Guardian 2010; Cordell and White 2014). The main factors for the price spike are many and include decreased P fertilizer production in the US; an increased export tax on P fertilizer, especially from China; increased oil and energy prices; disproportionate fertilizer demand for biofuel production; and disproportionate supply–demand relation (Scholz et al. 2014).

There are also differences in the heavy metal concentration—in particular cadmium (Cd)—between different deposits of PR. Purity of sedimentary PR, which accounts for almost 95% of the world resources, is much lower than that of magmatic deposits. The former usually exceed $60\ \mathrm{mg\ Cd\ kg^{-1}}$ PR and the latter are around or less than $10\ \mathrm{mg\ Cd\ kg^{-1}}$ PR (GTK 2017). Concentrations of Cd in soil depend on Cd deposition as well as Cd concentration of fertilizers and their application rates. Increasing Cd concentrations in soil have been shown to lead to increased Cd concentration in crops (Roberts 2014). Cd in food can have an adverse effect on human health, especially in the form of kidney disease, but harmful effects on the musculoskeletal system are also documented (Roberts 2014). A 2013 report of the Swedish Chemicals Agency estimates

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the economic cost of bone fractures caused by dietary Cd exposure in Sweden at 4.2 billion SEK (app. 420 million euros) a year (KEMI 2013). At present, Europe is importing most of its PR from Morocco and Algeria, both of which have sedimentary reserves (EU Commission 2013).

P is following a linear path from mining sites to wastewater effluent or disposal as some form of solid waste (Fig. 1). This means that the P input in the agricultural/food system is to a large extent not recovered and it causes a considerable harm to the environment. P is one of the main causes of eutrophication and the creation of "dead zones" in coastal areas (Chowdhury et al. 2017). Thus, P starts its life cycle as a natural resource retrieved at great environmental costs and ends as pollutant.

One solution to solve the P issue is to transform the P cycle into a circular rather than linear process (Ragnarsdottir et al. 2011). A leverage point identified in the literature is the wastewater (WW) stream (Mihelcic et al. 2011; Cordell and White 2014) from which P can be recovered and then recycled. In Fig. 1, P recycling from urban wastewater is shown in red arrows: from sewer, P is recovered from raw sludge and processed into fertilizer. It is then used in farm systems for food production. Part of the food ultimately reaches the sewers through human waste disposal and the process starts again. Studies show that up to 20% of the European P demand could be supplied by recycling P from municipal wastewater (EU Commission 2017a). Countries like Germany and Switzerland have recently introduced legally binding targets to recycle P from wastewater (EU Commission 2016; Swiss Federal Council 2015). Following Circular Economy Package (CEP) principles, the new EU Fertilizer Regulation Revision also aims to boost large-scale production of fertilizer from domestic organic or secondary raw materials. At the same time, it is expected to impose lower EU-wide limits on heavy metal concentration in fertilizers (EU Commission 2017b).

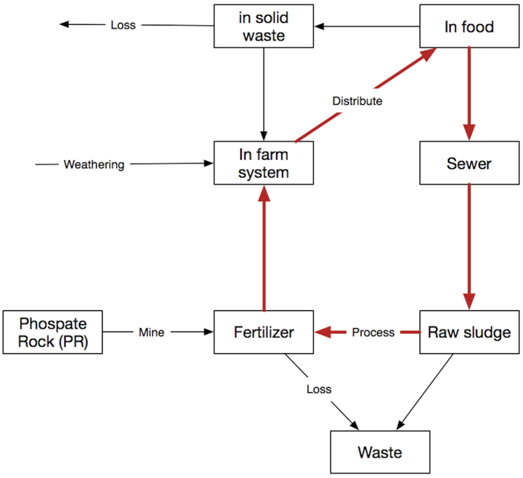

Fig. 1 Flowchart of the phosphorus (P) supply chain. Boxes refer to P stocks, while arrows refer to P flows. P recycling from urban wastewater is in red

The aim of this study is (1) to analyze the dynamics of P recycling from urban wastewater, using two European capitals as case studies, and (2) to provide policy recommendations at the national level that can contribute to the development of wastewater P recycling sector.

THEORETICAL FRAMEWORK

Case studies allow the testing of hypotheses, while being an appropriate method in understanding dynamics in multidisciplinary sciences (Flyvbjerg 2011). We gathered data from 23 stakeholders, using semi-structured interviews. In deciding on the interviewee sample, we adopted the method proposed by Malterud and Guassora (2016), using the concept of "information power" to guide our sample size and representation. Because of the very specific nature and restricted size of the P recycling sector we focused on the quality and relevance of information rather than on the quantity of interviewees. We used stakeholder analysis (Brugha and Varvasovszky 2000) based on an influence-interest matrix of stakeholders in the decision-making process as perceived in the literature. The final version of this matrix (Fig. 5) emerged after analyzing interview data. Stakeholder sample and size were completed using a combination of insider information provided by interviewees and by applying targeted snowball sampling method (Heckathorn and Cameron 2017). The difference in sample composition between Budapest and Stockholm is due to the different stages of development of P recycling in the two locations. For example, in Budapest there was no sludge spreading or P recycling from municipal wastewater. Moreover, there was no involvement or interest on behalf of farmer associations or the food industry. Therefore, these stakeholders are not represented. We examined P recycling using systems thinking and systems dynamics. Systems dynamics is a method "of dealing with questions about the dynamic tendencies of a complex system, that is, the behavioral patterns they generate over time" (Meadows 1970).

MATERIALS AND METHODS

Study area

We chose Stockholm and Budapest as case studies for three reasons: (1) they reflect to a satisfying extent the differences in how the wastewater (WW) sector is approached across European Member States in the North and West on one hand and Central Eastern Europe (CEE), respectively; (2) both capitals are comparable in size: 1.5 million people in the urban area of Stockholm and 1.8 million people in the urban area of Budapest; and (3) they are places where a relevant sample of stakeholders was approachable by us as researchers.

Stockholm, Sweden

Based on the P flow dynamics in Sweden (Linderholm and Mattsson 2013) and the total P discharge in municipal wastewater (SCB 2018), P from sewage sludge could secure 20–22% of the total P needed for food production in the country. The Swedish Environmental Protection Agency (SEPA) has proposed a milestone target to the Swedish Government to recycle 40% of the P and 10% of the N from sewage onto agricultural land, by 2018. By 2016, 34% of the P from wastewater was recycled on farmland through sludge spreading (SCB 2018). The Swedish Water and Wastewater Association, The Federation of Swedish Farmers (LRF, also referred in this study as "farmer association"), The Swedish Food Federation, the Swedish Food Retailers Federation and SEPA as co-opted member developed a certification system for wastewater treatment plants (WWTPs) referred to as REVAQ. REVAQ aims to reduce the flow of dangerous substances reaching WWTPs, in order to provide for a sludge quality that is acceptable for agricultural use and thereby to obtain acceptance for spreading sludge on arable land. Digested sludge at REVAQ certified WWTPs needs to have concentrations of certain contaminants such as Cd at levels deemed safe. Cd in fertilizers is of particular importance in Sweden, where the limit of 44 mg Cd kg^{-1} P_2O_5 and 100 mg Cd kg^{-1} P is stricter than in the EU due to environmental and human health concerns (Roberts 2014). Sweden made considerable efforts in the past decades to tackle high heavy metal loads in sludge; concentrations for cadmium, silver, copper, zinc, mercury, and lead decreased by up to 90% since 1970s (Kirchmann et al. 2017). Currently, SEPA's position is that recycling P has to be made by imposing much stricter concentration levels for certain heavy metals and organic contaminants, in order to avoid adverse effects on ecosystems and human health (Naturvårdsverket 2013).

Budapest, Hungary

In Hungary, the focus in Budapest and other major cities across the country is to remove the pollutants from urban wastewater and ensure that the effluent released in water bodies is in accordance with nationally agreed targets. The sludge produced in the process is removed and managed by contracted companies. There is no certification system for using sludge in agriculture. Forty-two percent of the sludge produced in the country is used in landscaping projects, a process referred to as "recultivation" but which has no links to agricultural production. A quarter of the sludge is mixed with other compost and used in landscaping, while approximately 17% is disposed on fields, which are not used for agricultural production (Garai, pers. comm. 2017). At present, there are no municipal or national targets to recycle P from sludge. There is no legislation or guidelines with regard to pharmaceuticals and other chemicals. The closest initiatives to P recycling are limited to pilot projects of nutrient capture in biomass in the form of plant and tree greenhouses in South Pest WWTP (Organica 2018) or algae at in North Pest WWTP (MAB 2018).

Research process

We used qualitative research methods and systems thinking to shape our research process in four stages. First, we gathered data through literature review and 23 semi-structured interviews. Second, we used systems dynamics to analyze the data. We chose to illustrate our results using causal loop diagrams (CLD), in which each causal link has a polarity—this is the direction of effect that the influencing variable has on the influenced variable. The polarity of each feedback loop is essential in understanding system's behavior. The perturbation of a loop may result in the magnification of the original effect (a reinforcing loop, R) or into an equilibrating response (a balancing loop, B). Third, we made a normative stakeholder analysis for the P recycling sector, using the influence-power matrix design as described by Reed et al. (2009). Fourth, we identify policy action indicators and policy interventions in our "Discussion" section.

Table 1 Sample of stakeholders selected for semi-structured interviews. Numbers indicate the number of stakeholders interviewed, m stands for male and f for female. The interviews comprised 23 persons, 11 in Hungary, 12 in Sweden, 7 were women, 16 were men

Stakeholder	Stockholm	Budapest
Policy at national level	0	1 m
Policy at municipal level	1 f	0
WWTP administration	1 m, 1 f	3 m
Private sector	1 m	4 m
Academia	2 f, 3 m	1 f
Farmers association	2 m	0
Food industry	1 f	0
NGO	0	1 f, 1 m

The final stakeholder sample reflects key sectors impacting P recycling at the two locations (see Table 1). The guiding questions addressed during the semi-structured interviews revolved around four main topics: (1) P criticality; (2) Feasibility of P recycling; (3) Policy aspects of P recycling; and (4) Social and safety aspects of P recycling. The set of guiding questions can be found in Electronic Supplementary Material. Interviews lasted for an hour on average.

Throughout the paper, we refer to P removal as P capture in sludge. We refer to P recovery as the process of extracting P from sludge for further use in any branch of the industry but agriculture and food production, and we refer to P recycling as the extraction of P from sludge and its return to farmland, or as the spreading of sludge on farmland. Also, in our analysis, discussion and conclusion "stakeholders" refer strictly to the interviewed stakeholders, unless otherwise specified.

RESULTS

Systems synthesis of literature and interviews

P recycling on policy agenda

All stakeholders in Budapest and Stockholm think that recycling P should be higher up on policy agendas. They believe that policy action is triggered by a high perceived P supply risk for the national agricultural sector. Throughout interviews "critical" or "criticality" are terms often mentioned. In the literature, criticality is seen as a matrix function of two axes: supply risk and vulnerability. Supply risk refers to the probability of disruption in the supply of a resource, while vulnerability is the impact of supply risk (Habib and Wenzel 2016). The European Commission also considers high supply risk, high environmental risk and high economic importance as key factors in identifying critical raw materials (EU Commission 2013). Thus, P criticality depends on a number of variables, but two are particularly significant: commercial price of PR fertilizer and national import dependency. These two variables start driving balancing loop B1 in Fig. 2.

Stakeholders identify three variables influencing commercial price of PR fertilizer (Fig. 2, non-bold arrows). First, they identify political insecurity in P exporting countries. Recurring examples given during interviews were the situation in PR-rich disputed territory of Western Sahara, the Arab Spring and the Syrian Civil War. In the literature, Cordell et al. (2015) and Allan (2016) also discuss the problematic of Western Sahara-Morocco conflict for the global P fertilizer supply. Second, they identify the cost of removing Cd and other heavy metals from PR. This particular aspect is important in the light of the new EU Fertilizer Regulation Revision (EU Commission 2017b). The Revision is likely to set ambitious low-level targets for Cd in phosphate fertilizers. Third, it is the cost of PR mining and processing. Specifically, stakeholders refer to costs for infrastructure development to increase production capacity and costs of other resources needed for PR processing. Scholz et al. (2014) also attributed the price spike in 2007–2008 partially to production capacity constraints and an increase in oil and energy prices. A fourth factor impacting commercial price of PR fertilizer derived from literature is government tax on PR fertilizer (Fig. 2, bold arrow). It is discussed as part of loop B2 below.

Stakeholders from the farmer association, national policy-making, private sector and academia believe that higher commercial price of PR fertilizer means higher food prices. They claim higher food prices are "political suicide" through loss of electorate if not civil unrest. In the literature, Bellemare (2015) finds that increase in food prices has led to increased social unrest across the world in the last few decades. All stakeholders in Stockholm and Budapest also argue that higher national import dependency makes farmers more vulnerable to global market price fluctuations, such as the ones in 2007–2008. They believe that higher national import dependency can jeopardize the delivery of optimal P supply for the domestic agricultural sector.

The balancing loop B1 in Fig. 2 continues with the rationale that high P criticality leads to awareness among lawmakers on the need to safeguard domestic P supply. This awareness materializes into political support for P recycling. For many of the stakeholders, political support translates into national binding targets for P recycling, similar to those already set in Germany and Switzerland. Such targets would increase the rate of domestic P recycling. Loop B1 is closed by an increase in domestic P production through higher P recycling rates. In this situation, P criticality decreases, which decreases the need for political support.

In Hungary, all stakeholders highlight the lack of a long-term vision on resource management by policy makers. In the words of a former lawmaker, the political establishment thinks, that "future generation problems need to be solved by future generations." However, transition from political support for P recycling to optimal P recycling rates takes time. Interviewees estimate this interval to be one generation (20–25 years), while recent targets implemented in Germany and Switzerland indicate 10–15 years. Therefore, support for P recycling needs to be prepared and set in a timely manner.

Loop B2 in Fig. 2 is supported by the literature. Mining, processing and transport of PR require considerable amounts of resources such as water, Sulphur, energy, and

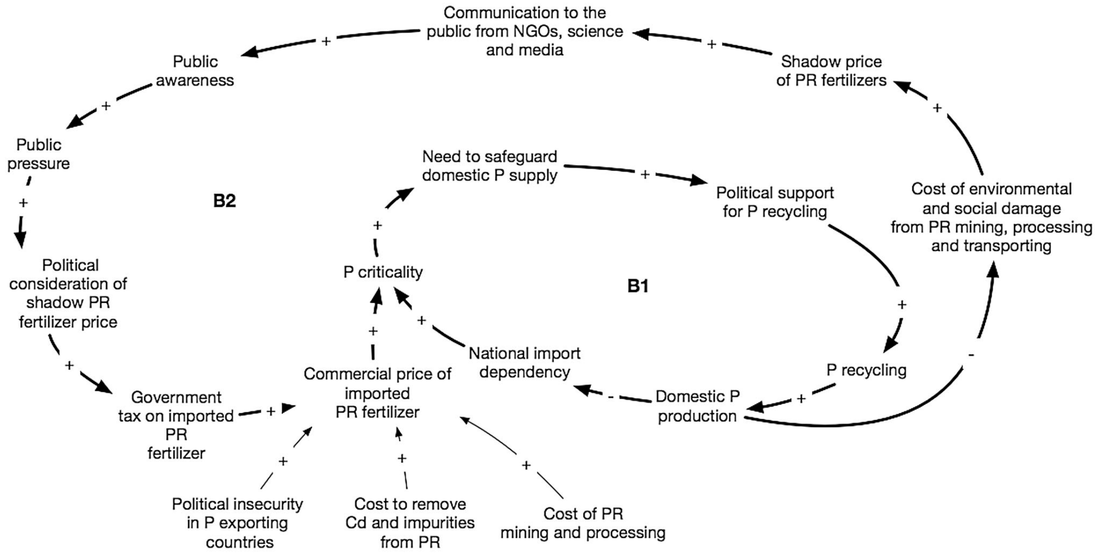

Fig. 2 Causal loop diagram with two balancing loops (B1 and B2) showing how P recycling can get higher on policy agenda

materials to build new infrastructure. Mining of PR generates millions of tons of waste annually, including phosphate sludge, contributing to pollution of land and aquatic ecosystems (Cordell et al. 2015). There are also social costs to pay for PR mining, most notably community displacement and conflict. Thus, PR fertilizers are produced with a hidden cost of socio-environmental externalities (Cordell et al. 2015), which increases their shadow price and triggers loop B2. The higher the shadow price of PR fertilizers is, the more it fuels interest from NGOs, academia and media, who communicate it to the public. Increased public awareness leads to increased public pressure on lawmakers, who are thus likely to consider the shadow PR fertilizer prices. One way that governments can account for externalities is taxing. China imposed a tax on the export of PR in order to secure domestic supply (Scholz et al. 2014), thus reducing both import and export. Except in Finland, in Europe the tax could only apply to imported PR fertilizer. Such tax would increase the commercial price of PR fertilizer and in turn, increase P criticality (see Fig. 2). P criticality is where loop B2 merges with loop B1 and eventually leads to higher domestic P production through P recycling. A higher domestic P production will decrease international P externalities.

Developing P recycling from urban wastewater at a national level

Figure 3 shows the main dynamics for P recycling development at national level. Assumptions taken for this CLD are that (1) political support exists and there is sufficient available budget; and (2) WWTPs are operational. The first assumption stems from political support being a prerequisite of P recycling as shown in Fig. 2 and the understanding of stakeholders that state investment is essential to the overall development of the recycling sector. The second assumption stems from stakeholders' assumptions.

All stakeholders believe political support should materialize in investment subsidies for wastewater infrastructure, wastewater technology and training of staff from the wastewater sector. These subsidies can also be directed at public–private partnerships or financing entrepreneurs in the wastewater sector. In loop B1 (in red), we show that this policy intervention results in decreased costs of the P recycling process and increased recycling profitability. It further enables an increased amount of recycled P to reach the market by intensifying the recycling process. More recycled P on the market decreases import dependency and the urgency of the government to decide on investing in the recycling sector, hence reducing investment subsidies.

However, the aim of policy intervention is twofold. Market mechanisms in loops B2, B3, and B4 lower the price of recycled P by increasing the amount of recycled P on the market. Loop R2 shows that as the difference between PR fertilizer prices and price of recycled P decreases, agricultural demand for recycled P increases, taking away recycled P from the market. This means that P recycling costs can be covered more by market revenues and less by government subsidies. The system then sends a feedback to policy makers through loop R3, enabling them

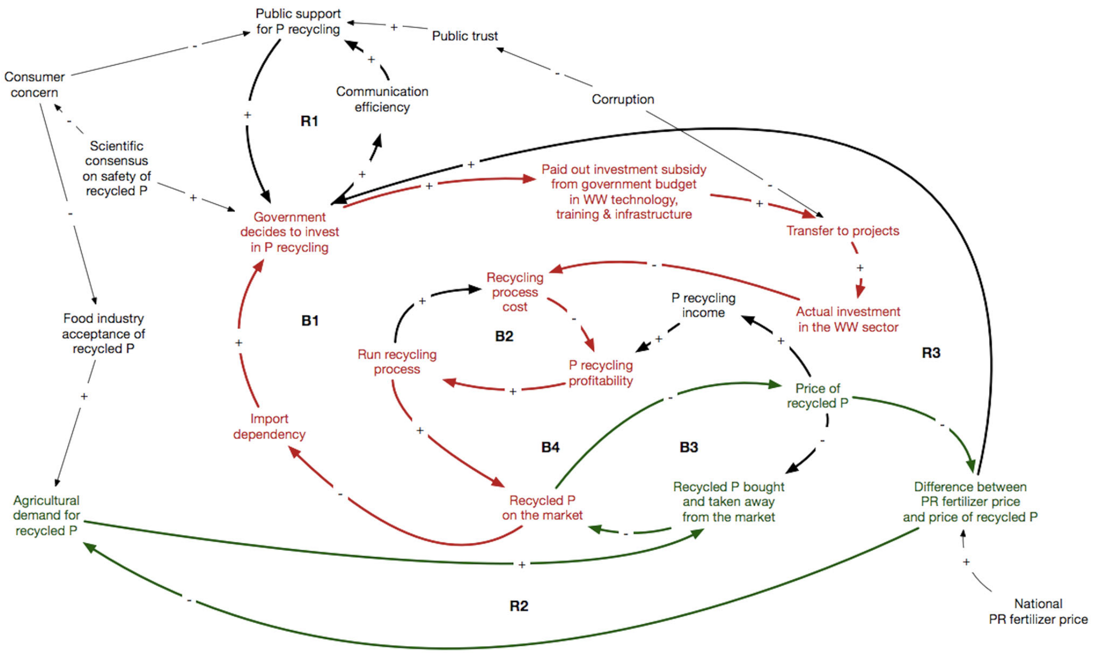

Fig. 3 Causal loop diagram showing the main dynamics of P recycling implementation as identified from interviews and the literature. Red arrows are for the policy intervention in loop B1, green arrows are for the impact of the agriculture sector on recycled P market

to decide on further investments whenever PR–RP fertilizer price difference increase.

All stakeholders in Budapest and Stockholm believe that increasing initial price of WW treatment in order to enable P recycling is a delicate issue for policy makers. A Swedish farmer association stakeholder explained it differently: “the P-REX project (EU Commission 2017a) concludes that to go from the sludge treatment [we have] today to new technology where we can recover phosphorus, the cost increase [per person] would be roughly 3% of the cost for handling the sewage water […] so if you increase the cost by 3% in Stockholm, you end up with 12 SEK [app. 1.2 euros/month] and that is not even half a cup of coffee”. Therefore, public support for P recycling can also be increased by a more efficient communication on behalf of policy makers (loop R1 in black). Higher public support would give legitimacy to the government to allocate taxpayer money for P recycling. The national-level policy maker interviewee from Hungary as well as the Hungarian NGOs stressed the role of corruption in the system. They believe corruption erodes public trust in the government and decreases available funds for investment. The literature supports this and states that democratic governance and a fair competition are a deficit in the majority of Hungarian public sector organizations that carry out public procurement (Fazekas and Toth 2016). In Fig. 3, corruption decreases public support for P recycling through breach of trust. It also decreases paid out investment subsidies to P recycling projects through graft.

Another factor impacting public support is scientific consensus on sludge spreading safety, which is currently the cheapest form of P recycling. This was a divergent topic for stakeholders in both locations. Stakeholders from academia and the wastewater sector were overwhelmingly supporting sludge spreading, arguing that there is no proof of contamination. On the other hand, one stakeholder from the Swedish farmer association and all stakeholders from the private sector, food industry and the policy-making sectors were either neutral or against sludge spreading, using the argument of the precautionary principle. The food industry representative in Stockholm stated that voluntary initiatives in Sweden such as REVAQ have not yet convinced the industry that sludge spreading is safe. One stakeholder from the Swedish farmer association agreed, stressing that REVAQ only guarantees safe levels for some, but not all heavy metals and pollutants. The Federation of Swedish Farmers now considers the option of withdrawing from REVAQ in 2018 and voted in 2017 to recommend to its farmers not to spread sludge on their land (Land Lantbruk 2017). In 1999, the farmers association recommended that their members stop spreading sludge due to safety concerns (Naturvårdsverket 2011). LRF’s

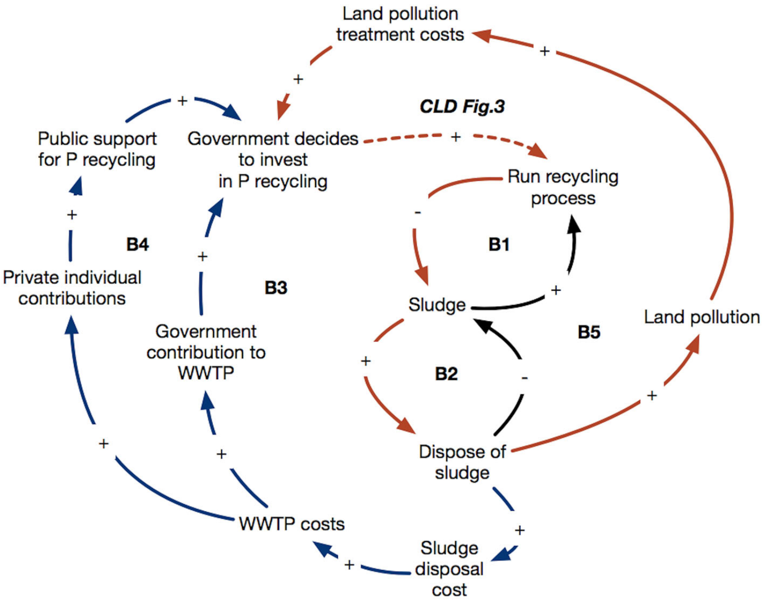

Fig. 4 Causal loop diagram on domestic externalities of sludge disposal. Blue arrows are for loops B3 and B4, which show the impact of sludge costs on public support and political support via investment in P recycling. The red arrow is for loop B5, which shows the impact of land pollution of political support via government investment

decision at the time, combined with anti-sludge spreading on farmland campaigns from consumer associations has had the effect of most food companies opposing sludge spreading in their supply chain (Bengtsson and Tillman 2004). Moreover, the Swedish Government has recently launched an inquiry into proposing a ban on sewage sludge spreading on agricultural land in July 2018 (Regeringskansliet 2018). One private sector stakeholder from Budapest summarized the safety dilemma with the following: “it’s a question of who will take technical, juridical and political responsibility if contamination takes places”. With a high sensitivity to consumer concern, neither the food industry nor the policy makers are willing to take such responsibility. In Sweden, the achievement of phosphorus recycling targets has up until now been reliant on sludge spreading. Latest statistics for 2016 placed the number at 34%, closer to the proposed 2018 target of 40% (SCB 2018). If sludge spreading is banned, achieving the new P recycling targets now implies a rapid optimization of the wastewater system towards P recycling technologies deemed safe. Higher scientific and stakeholder consensus on the safety of recycled P would decrease consumer concern and thus allow the food industry to loosen regulations on the use of recycled P in its supply chain. By doing so, the food industry would positively impact agricultural demand for recycled P and influence the dynamics in loop R2 in Fig. 3. It also gives legitimacy to lawmakers to implement P recycling strategies.

Molinos-Senante et al. (2011) concluded that P recovery is economically feasible if environmental benefits are considered. The authors looked at 20 WWTPs in Spain and calculated environmental benefits amounting to an average of 42.74 euros for each ton of phosphorus that is not released in the environment. On average, the mean value of environmental benefits was 301 785 euros per WWTP (Molinos-Senante et al. 2011). In Fig. 4 we show the externalities of sludge disposal, with two driving loops: B1 and B2. In B1, P recycling takes out P from sludge and decreases sludge amount. In B2, a lower sludge amount leads to less sludge disposal. Most stakeholders in both Stockholm and Budapest mention that sludge disposal is costly and harmful for the environment. By decreasing the amount of sludge disposal, WWTPs pay less for disposal and lower their overall costs. Lower WWTP costs decrease the price private customers need to pay for wastewater treatment and in turn increases public support for P recycling (loop B4 in blue). As a result, the government also needs to contribute less for wastewater treatment (loop B3 in blue) and pay less for depollution of sludge disposal sites in the future (loop B5 in red).

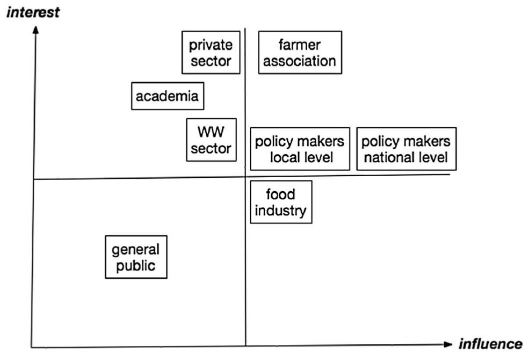

Fig. 5 Interest-influence matrix of stakeholders in the P recycling sector

Stakeholder analysis

Based on the synthesis presented here, we analyze stakeholders' role in Stockholm and Budapest in an interest-influence matrix shown in Fig. 5. Policy makers at a national and local level have the highest influence but lack somewhat in interest. This is due to perceived low P criticality, as global fertilizer prices are generally much lower than those of recovered P fertilizers. Also, avoiding conflict between stakeholders is another factor that keeps national and local policy makers reluctant in taking decisive action. Farmers associations have a relatively high influence through their lobby power and a high interest in recycling P.

However, low fertilizer prices and lack of conclusive scientific consensus on recycled P safety prevents them from lobbying more for P recycling. The food industry has influence through its lobby power but less interest due to current low fertilizer prices and concerns about consumers and contamination scandals. To put it in the words of one of the interviewed food industry stakeholders "low P prices means safety wins over recycling at the moment". Stakeholders in the academic and the private sector have a high interest in the topic but not enough influence—this is due to the perceived lack of urgency for P recycling by stakeholders with higher influence and the small scale of P recycling companies. The interest of wastewater sector stakeholders in Stockholm and Budapest is not that high because binding regulations to recycle P do not exist. General public has in most cases low interest and low influence, unless in exceptional circumstances, such as contamination cases or widespread awareness raising campaigns.

DISCUSSION

Political support by implementing legally binding P recycling targets is key to developing the P recycling sector. Policy makers are also the most influential stakeholders. Their support for P recycling increases as P criticality

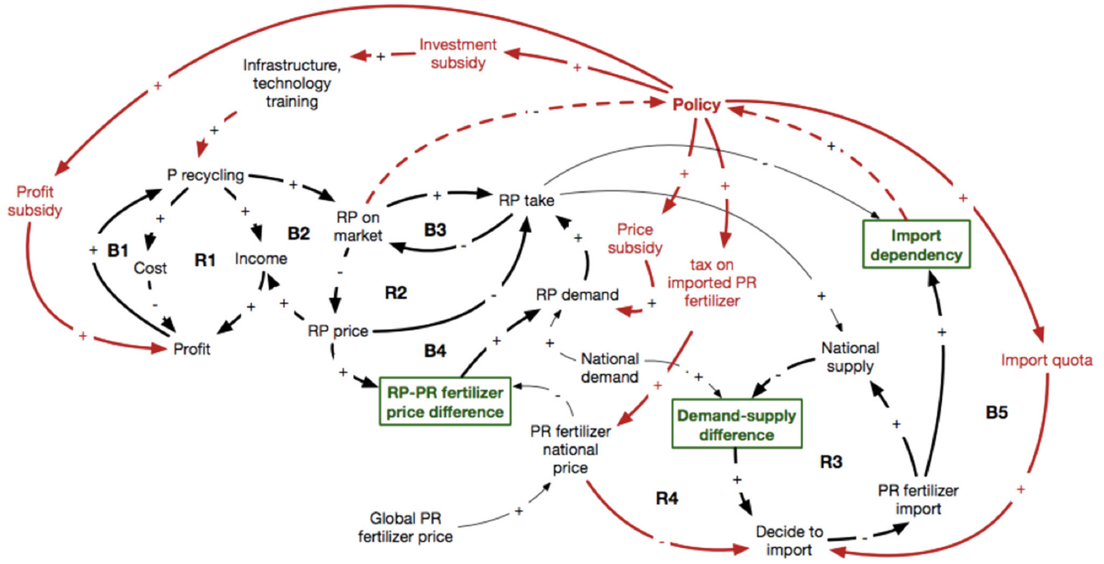

Fig. 6 Causal loop diagram showing policy interventions in the P recycling sector (red), their feedback (dashed red) and policy action indicators (green boxes)

increases, which in our analysis has two components: national import dependency and price of imported PR fertilizer (see Fig. 2). Both stakeholders and the literature overwhelmingly point at the economics of P recycling as a sector challenge: the claim is that recycled P price is too high to make recycling profitable.

We argue that policy makers need to consider more than recycled P fertilizer price. In Fig. 6 we show three indicators for policy action in green bold boxes. First, it is the difference between the price of phosphate rock (PR fertilizer price) and the price of recycled P (RP fertilizer price), which was also presented in Fig. 2. A small or negative difference is an indicator for a profitable P recycling sector. Second, it is the difference between demand and supply. A small or negative difference is a red flag for suboptimal supply of P to the national agricultural sector. Third, it is import dependency, which was presented in Figs. 2 and 3.

In terms of policy interventions, most suggestions from both stakeholders and the literature favor government-lead investment in the wastewater sector. The aim of policy interventions as it emerges from the literature and interviews, is to lower the RP-PR fertilizer price differences. We thus propose four additional entry points in the market system where the state can intervene by setting policies (Fig. 6 in red). First, profit subsidies can intervene in loops R1, B1, and B2 and increase RP on the market by keeping the P recycling sector profitable. Second, price subsidies can increase RP demand by decreasing PR-RP fertilizer price difference (loops R2 and B4). The difference can further be lowered by a third intervention, namely tax on imported PR fertilizer. Lastly, the amount of imported PR fertilizer can be regulated through import quotas. Import quotas will also regulate the share of RP on the market out of the total P fertilizer.

CONCLUSION

P is a limited natural resource and an essential macronutrient in agriculture. Its finite resource availability, combined with global supply insecurity, makes it a critical mineral in Europe. Literature shows that recycling P from urban wastewater can secure 20% of the domestic P supply in Europe. Currently, P recycling from urban wastewater is undertaken on a voluntary and small-scale basis in some parts of Europe. Our stakeholder analysis indicates that legally binding targets to recycle P, similar to those in Germany and Switzerland, are needed to improve performance and scale. Previous research showed that such targets can be affordable if P criticality is high. In determining P criticality, we suggest a shadow P fertilizer price to be calculated, taking into account externalities from mine to sludge disposal. According to both the literature and our stakeholder analysis, national import dependency is another key aspect of criticality that policy makers should account for. Policy interventions need to account for high initial costs to establish recycling and the delay in the system to reach recycling profitability. P recycling strategies need to sufficiently address public concerns on health and safety, costs and the reasoning behind P recycling. Past experience in Sweden showed that the decades long sewage sludge debate caused significant delay in implementing a P recycling strategy. Our interviews suggest that scientific and stakeholder consensus on P recycling safety is required when designing such a strategy. Improving P recycling in Europe will support the circular economy EU regulation from 2015 and expand the circular economy action plan of 2018.

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Paper II

Opening access to the black box: The need for reporting on the global phosphorus supply chain

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PERSPECTIVE

Opening access to the black box: The need for reporting on the global phosphorus supply chain

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Abstract Phosphorus (P) is an essential macronutrient in agriculture; however, lack of reporting makes its supply chain a black box. By using literature synthesis on the P challenge, we identify four areas where the reporting process is problematic: P reserves and resources; P losses along the supply chain; P externalities; and access to data. We find that in these areas, the reporting system is inconsistent, inaccurate, incomplete, fragmented and non-transparent. We use systems analysis to discuss implications of reporting on the sustainability of the P supply chain. We find that reporting is essential for the achievement of global P governance and the human right to adequate food. It can also inform decision makers and other impacted stakeholders on policies on agriculture, food security, pollution and international conflict. An improved P reporting process also allows a better evaluation of global sustainability commitments such as the United Nations Sustainable Development Goals.

Keywords Global governance · Open access data · Phosphorus · Supply chain · Systems analysis

INTRODUCTION

Phosphorus (P) is an essential macronutrient needed for food production and human life, yet it has no substitute (Cordell et al. 2009). Because P a main limiting factor to plant growth, access to industrially produced inorganic P fertilizers has been indispensable for the Green Revolution and the contemporary large-scale, high-productivity agriculture (Cordell and White 2014). Estimates from the UN point towards over 9 billion people by 2050 and a correlated food demand increase of 60% (FAO 2013) for the same period, which would in turn trigger an increase in global P demand.

More than 85% of the P in agriculture comes from processing mined phosphate rock (PR) (Cordell et al. 2009). Phosphate rock is a finite natural resource globally, distributed in a limited number of countries. According to the latest data of the United States Geological Survey (USGS), most PR reserves are found in Morocco and Western Sahara (71.5%), China (4.6%) and Algeria (3%) (USGS 2019). At present, production is led by China (52%), Morocco and Western Sahara (12%), USA (10%) and Russia (5%) (USGS 2019).

In 2007–2008, an 800% increase in P fertilizer prices sent a shockwave to the world market and food price soared (Cordell and White 2011). The event led to the emergence of a "phosphorus challenge" (ESPP 2013) and the concept of "peak phosphorus" (e.g. Ragnarsdottir et al. 2011), which called for action in sustainably managing a scarce resource. A controversial revision of world PR reserves by USGS from 16 GT in 2010 to 65 GT in 2011 led to a more moderate peak phosphorus discourse, but raised questions concerning the methodology behind PR resource reporting (Edixhoven et al. 2014). Subsequently, accessibility to affordable P became more visible on policy agendas. In the European Union (EU), P was included in the list of Critical Raw Materials in 2014 (European Commission 2014). The most recent report of the Food and Agriculture Organisation (FAO) with regard to fertilizer trends and outlook for 2020 (FAO 2017) also shows that a number of regions have a negative phosphate balance (reported as P_2O_5): Oceania, Central and Western Europe, South Asia and Latin America, and the Caribbean. The gap between supply and total demand is expected to further widen by 2020.

Table 1 Researched databases and search strings used for literature review and snowballing

Researched databases	Search string in databases
• Stockholm University Library e-resources	• Phosphorus/phosphate resources
• Scopus	• Phosphorus/phosphate reserves
• Science Direct	• Phosphorus/phosphate deposits
• SciFinder	• Phosphorus/phosphate/fertilizer reporting
• SpringerLink	• Phosphorus challenge
• National and University of Iceland Library e-resources	• Peak phosphorus
• Google Scholar	• Phosphorus/phosphate/fertilizer losses
• Food and Agriculture Organisation Statistics	• Phosphorus/phosphate supply chain
• World Bank Open Data	• Phosphorus/phosphate/fertilizer externalities
• United States Geological Survey—Commodities	• Phosphorus/phosphate/fertilizer pollution
	• Phosphorus/phosphate + Western Sahara
	• Phosphorus/phosphate + conflict
	• Phosphorus/phosphate/fertilizer data
	• Phosphorus/phosphate governance
	• Eutrophication + phosphate/phosphorus
	• Eutrophication + fertilizers
	• Eutrophication + global, food waste/wastage
	• Food waste/wastage + global

Other aspects of the phosphorus challenge were brought into discussion following the 2007–2008 price soaring event. It was acknowledged that the phosphorus supply chain demonstrates an unsustainable and linear use, with large fractions of waste at each stage, from mine to fork (Scholz and Wellmer 2015). P is also one of the main causes for eutrophication of water bodies across the world. Fertilizers entering the ocean are responsible for the creation of 400 coastal dead zones, totalling more than 245 000 km^2 (UN 2019). Thus currently, P is both angel and demon: it is vital for agricultural productivity, yet it is one of the most widespread water pollutants, causing ecosystem devastation.

In the literature, academics have called for policy leadership and global governance for P, with a preferably UN-related institution to overlook reporting (Rosemarin and Ekane 2016). They argue that the reporting process could benefit from more harmonization of terminologies and methodologies, as well as become more transparent. It could also provide additional data and allow for a more thorough examination of the impacts along the supply chain.

The aim of this study is to frame P reporting in terms of sustainable global management of an essential global resource. Our objective is to review the current shortcomings of reporting along the global P supply chain, from exploration and mining of PR, to fork and waste. The research questions we ask are as follows: (1) "What are the issues and potential solutions with reporting along the global P supply chain, as derived from the literature?" and (2) "How is the P reporting process connected to reporting on the implementation of global sustainability initiatives such as the UN Sustainable Development Goals (SDGs)?"

MATERIALS AND METHODS

We analyse the literature in detail and identify the shortcomings of the current supply chain reporting. We started from the search string and databases shown in Table 1 and we subsequently used snowballing to access other studies that were not immediately visible. Overall, in our results we used 18 academic journals and books, nine documents from reporting entities, five reports from Non-Governmental Organisations and one legal document.

For P resources and reserves, the study addresses exclusively P derived from phosphate rock. For the other parts of the supply chain, we refer to all P input, including non-PR sources. The study starts from the idea that public knowledge on all aspects of the P supply chain should be basic knowledge for a basic right: access to food (Wellmer and Scholz 2015). The human right to adequate food is embedded in the UN International Covenant on Economic, Social and Cultural rights and is defined as follows:

> The right to adequate food is realized when every man, woman and child, alone or in community with others, has the physical and economic access at all

Table 2 Most common reporting terminology for P as a resource

Preporting terminology	Definition
Phosphate rock (PR); also phosphorite	Rock with a high concentration of phosphates in nodular or compact masses. Here, phosphates can include any of the 200 recognized species of phosphate minerals (Britannica 2006)
Phosphate rock mineral deposits	A mineral occurrence of PR, sufficient size and grade that it might, under the most favourable of circumstances, be considered to have economic potential (USGS 1996)
Ultimately recoverable resource	The amount of resource that is eventually extractable—including high grade, medium grade, low grade (Sverdrup and Ragnarsdottir 2014); Resources that can be extracted with future technologies, with either lower extraction costs or an increase in the potentially producible quantities (Speirs et al. 2015)
Phosphate rock ore deposit	A mineral deposit of PR that has been tested and is known to be of sufficient size, grade and accessibility to be producible to yield a profit (USGS 1996)
Phosphate rock reserves, ante-2010 USGS definition	That portion of an identified resource from which a usable mineral or energy commodity can be economically and legally extracted at the time of determination (USGS 1980)
Phosphate rock reserves, post-2010 USGS definition	That part of the reserve base, which could be economically extracted or produced at the time of determination. The term reserves need not signify that extraction facilities are in place and operative. Reserves include only recoverable materials; thus, terms such as "extractable reserves" and "recoverable reserves" are redundant and are not a part of this classification system (USGS 2010)
Phosphate rock ore grades (in P_2O_5 as % of PR)	The concentration of PR within the ore. Grade may exhibit considerable variation throughout the deposit (Britannica 2007)
Cut-off grade	Grade below which is not profitable to mine PR even though P_2O_5 is present in the ore (Britannica 2007)
Phosphate rock Concentrate	Crushed PR after beneficiation (increased P_2O_5 concentrations)

> times to adequate food or means for its procurement (FAO 2012).

Our conceptualization of the P supply chain relies on the use of systems analysis and systems thinking to frame our results. Systems thinking is an approach that "embraces the nature and organization of coupled human and natural components, actors and relationships" (Bunch et al. 2018). In particular, we use one of systems thinking conceptual tools, a flowchart (Morecroft 1982), to better illustrate the linear yet complex aspects of the global P supply chain and differentiate between its main sectors. This tool is needed due to the cross-sectoral and multi-actor characteristics of the global P supply chain. In Discussion section, we use systems thinking to build our arguments about the implications and relevance of reporting on the global P supply chain in terms of global sustainability and global food security.

RESULTS

We identified four major issues in P reporting in the literature synthesis: (1) reporting P as a resource; (2) reporting inefficiencies and losses along the global P supply chain; (3) the extent of global P supply externalities and their monitoring; and (4) the implications of a lack of open access to data.

Deposits, resources and reserves

A number of studies advanced the concept of peak phosphorus following the 2008 price crisis, most notably Cordell et al. (2009) and Ragnarsdottir et al. (2011). In 2010, the USGS reported a nine-fold increase in Moroccan reserves, from 5.7 to 51 billion tonnes (USGS 2011). The change occurred due to USGS adopting a 2010 reporting methodology proposed by the International Fertilizer Development Centre (IFDC) with the scope of ending the "peak phosphorus" debate (IFDC 2010). As expected, the event prompted critics to indicate that peak phosphorus had been based on static, unchanging estimates by USGS on PR reserves and reserves base (see Table 2), a method not suitable to assess the longevity of PR world deposits (Scholz and Wellmer 2013). However, Edixhoven et al. (2014) criticized the new IFDC methodology, highlighting that the new reporting methodology renders the PR reporting inaccurate, by allowing "deposits to be termed reserves or resources which could not be recognized as such under leading mineral resource classifications" (Edixhoven et al. 2014). The post-2010 definition of "reserve" according to USGS was also modified by removing the legal aspect of an ongoing or potential resource extraction (see Table 2). In sect. "Socio-political externalities", we show how this can have implications for some PR deposits, such as the ones in the contested Western Sahara region. Of note is that publicly available data are scarce when it comes to global PR reserves and resources.

At present, USGS is the only agency publicly reporting on a yearly basis on global PR reserves and resources.

Table 2 summarizes the significant differences between currently used terminologies. At present, PR reporting—including for the USGS—relies on country- or deposit-specific assessments. In undertaking these assessments, geological surveys or companies can use different terminologies and, in some cases, different methodologies. This assessment approach decreases the reliability of global PR reporting. A relevant example is the 2005 compilation of studies by the International Geological Correlation Programme (IGCP). In this book, all currently identified phosphate deposits of the world are described, country by country. Each deposit is further divided into assessments of ore bodies. However, the methodologies and terminologies used to calculate PR reserves and resources vary from country to country and sometimes among ore bodies of the same deposits.

Moreover, the characteristics of one deposit or ore body can be very vague, for instance, the 800 million tonnes Saudi deposit at Al Amud, which has an ore grade of “less than 20% P_2O_5” (Notholt et al. 2005), or the ore body at Constable Hill in the Western Cape Province of South Africa, which has 0.27 million tonnes at 27.5% P_2O_5 concentration, “with an additional several million tonnes of low-grade ore” (Notholt et al. 2005).

Access to accurate, up-to-date data is also restricted, not only to the public but also to reporting entities. This is in part due to the concept of proprietary data. In Australia, for instance, IFDC (2010) noted that the state geological survey does not have a complete account of the country’s PR reserves and production because mining and fertilizer companies are not obliged to provide this information. Disclosure of PR reserves, resources and production can be problematic when a state considers this information of national security. China, for instance, has in the past altered its reported reserves without explanation. Its reserves doubled over night when it joined the World Trade Organisation (WTO) in 2001 and decreased in 2007–2008, when the fertilizer spike in prices occurred (Cordell and White 2011). Therefore, reporting entities often need to estimate a country’s resource.

Rosemarin and Ekane (2016) have identified this lack of transparency and best practices in terms of PR reporting and highlighted the need for more global governance and more involvement from the UN when it comes to reporting of P resources. Their perspective is that UN oversight can work towards more cooperation and trust between reporting parties and improve the accuracy of global PR reporting. These authors propose a Global Phosphorus Facility (GPF), under the lead of UN Environment Programme (UNEP) to “provide clarity on the geological knowledge base as well as on best practices along the entire value chain” (Rosemarin and Ekane 2016). Similarly, they argue that other supra-national institutions can increase the transparency and reliability of global PR reporting by establishing their own reporting mechanisms. Cordell and White (2011) also argue that reliance on USGS reporting does not allow for triangulation of results with other sources and there is a need for other entities to conduct their own reporting to allow for comparison.

Table 3 summarizes the PR reporting issues, its effects and possible solutions, based on existing literature. In general, more leadership by the UN as the ultimate global partnership platform can lead to a more transparent and accountable reporting. The International Resource Panel of UNEP for instance uses reporting data from USGS when discussing P (UNEP 2019). Other global reporting entities are also essential in strengthening global governance of P by following a unified and responsible, transparent and

Table 3 PR reporting issues, their effects and proposed solutions

Preporting issue	Effects	Solution	Actors
Different definitions of reserves and resources	Non-reliability of reserve/resource estimates and incompatibility between reports of different reporting entities	Harmonization of terminology	Reporting entities
No differentiation between mineral ore and phosphate concentrate	Can lead to overestimation of reserves/resources	Specification of which of the two is being reported	Reporting entities
Lack of reporting due to proprietary data or national security concerns	Non-reliability of reserve/resource estimates	Global governance in reporting for a more transparent reporting	UN, other supra-national institution, global reporting entities
Dependence on one publicly available, open access source of annual reporting	Lack of transparency and accuracy of what is being reported and who reports to the reporting entity, non-reliability of data	Open access annual reporting from a number of reporting entities to allow triangulation of results	UN, other supra-national institution, global reporting entities

reliable reporting process (Rosemarin and Ekane 2016). National geological surveys, mining and fertilizer companies, the IFDC or IFAD should aim to harmonize their terminologies and definitions when reporting. In this way, global resources can more accurately be estimated and researchers, policy makers and the private sector can make more informed decisions and carry out research with a lower degree of uncertainty.

Losses and inefficiencies along the supply chain

Reporting along the P supply chain could also help in increasing P use efficiency, while at the same time considerably reducing P losses. Scholz and Wellmer (2015) estimate that only 10% of the phosphorus used for agro-food production is digested by humans. Cordell et al. (2009) also suggested that as much as 80% of the P is wasted from mine to fork, but due to lack of reliable and accurate data, it is difficult to quantify losses at each step of the value chain.

Figure 1 shows a flowchart of the P supply chain, from resource exploration to waste, with its associated losses along each supply chain step, as derived from the literature. In the dark brown box, the prospecting and exploration processes at the initial stage of the value chain are subject to the limitations in deposit characterization and reporting. This poses challenges in determining the amount of ultimately recoverable resources (URR). Steiner et al. (2015) proposed solutions to increase the efficiency of exploration. These include improved geophysical methods, re-exploration of P in search of other resources such as uranium, and search strategy optimization. Actors involved at this stage would be geological surveys and mining companies.

The next supply chain sector (Fig. 1) is mining and beneficiation, in light brown. Data on how much P is lost in the overburden, during transport or during beneficiation, can be provided at the mine and beneficiation unit level. Actors involved here are the mining companies and the authorities responsible with the regulation of mining activities.

Next, the blue box (Fig. 1) covers the processing of beneficiated concentrate to fertilizer. Fertilizer production is highly inefficient, as “between 30 and 50% of the P_2O_5 equivalents in the mined ore is unrecovered and is contained in waste ponds” (IFDC 2012). However, improving estimations would require an integrated reporting from the fertilizer producing companies. Proprietary data and lack of monitoring and reporting regulations make this difficult.

In the green box (Fig. 1), phosphate fertilizers are spread on agricultural land and follow three paths: (1) absorption by crops, (2) accumulation in soil through mineralization, and (3) runoff or transport by subsurface drainage in water bodies (King et al. 2014). The amount of P in absorbed crops can be estimated by the harvested crop amounts. However, while some studies investigated mineralization of organic P in soil at a global level (Bunemann 2015),

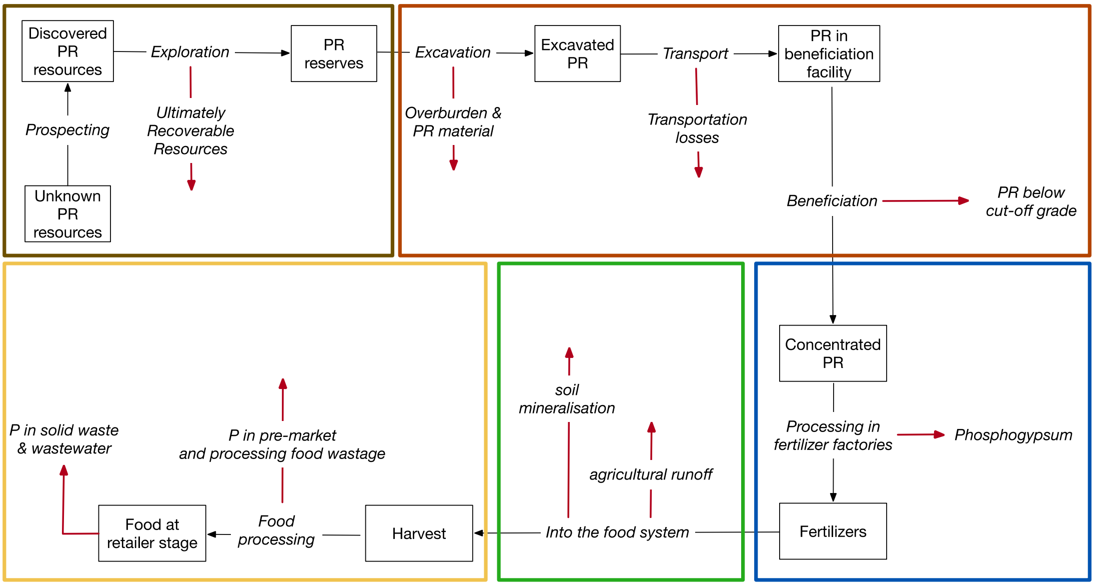

Fig. 1 Flowchart of the global P supply chain with P losses along the chain. Red arrows represent losses, and coloured squares represent different sectors of the P chain

Table 4 Reporting issues, solutions and involved actors for the global P supply chain sectors

P supply chain sector	Reporting issue	Solutions	Actors
Prospecting and exploration	Lack of data, different geological exploration methodologies	Improvement and harmonization of exploration methodology, sharing data	Mining companies, geological surveys, state authorities/departments responsible for the mining industry
Mining/excavation and beneficiation	Lack of data, considered proprietary data or sensitive information at state level	Sharing data on mining and beneficiation	Mining companies, state authorities/departments responsible for the mining industry
Fertilizer processing	Lack of data, considered proprietary data or sensitive information at state level	Sharing data on fertilizer processing and the composition processing by-products	Fertilizer producing companies, national environment agencies
Agricultural application	No reporting on the extent of P runoff from agricultural land to water bodies or of P mineralization in soil	Implementation of a P runoff monitoring programme on agricultural lands and reporting on estimates of P mineralization in soil	Farmers, state departments/authorities responsible for agriculture, national environment agencies
Post-harvest	Lack of data—in many cases considered proprietary data—on the extent of post-harvest food wastage; no reporting on the extent of P in solid municipal waste	Sharing of post-harvest food wastage data; estimates of the P in solid municipal waste	Food processing companies, retailers, food agencies at state level, municipal authorities responsible for waste, national environment agencies

studies examining the extent and characteristics of inorganic P mineralization are limited to some soil types or some geographical regions (see Achat et al. 2016). Similarly, literature on the amount of P runoff and subsurface drainage is also limited to region- or soil-specific studies (see King et al. 2014).

The yellow sector (Fig. 1) of the P chain is food production and consumption. Some recent studies investigate P losses specifically in this sector at a country level (e.g. Wang et al. 2018 for China). More studies investigated and reviewed the extent of post-harvest food wastage at the farm, manufacturer, retailer and transportation stages of the food supply chain (e.g. BCG 2018). The information could be used to calculate and quantify the extent of P losses. At the very end of the yellow block is the waste from food shops/supermarkets and consumers, which comes in the form of both food waste and wastewater. In some parts of the world, stricter water protection regulations have led to an increasing awareness of the double role of P as both a resource and a pollutant. In Europe, for instance, end of pipeline studies showed P from wastewater could supply up to 20% of the European demand (European Commission 2017). The earlier stages of the supply chain, however, remain largely unreported and thus their recovery potential remains untapped.

Table 4 summarizes the reporting issues for each of the P supply chain sectors, proposed solutions and actors responsible for their implementation, as derived from the literature. In general, reporting on P management can be implemented and monitored by a range of actors, from both the public and private sector. This includes companies involved in mining PR deposits, the food industry, fertilizer companies, state departments, environment agencies, municipal authorities but also "consumers", such as farmer associations or wastewater treatment plants. The wide range of actors involved in the supply chain highlights the need of working across silos for an integrated reporting process.

Mine to waste externalities

Environmental externalities

A 2019 cradle-to-grave analysis of phosphorus fertilizers by UNEP's International Resource Panel (IRP) revealed increasing negative impacts of PR mining, fertilizer production and application. Phosphoric acid production and PR mining are responsible for greenhouse gas emissions, largely through energy use. Ecotoxicity, human toxicity and eutrophication are caused by fertilizer application and, to a lesser extent, by PR mining. Finally, air pollution is mainly caused by phosphoric acid production and PR mining. In all cases, the negative impact of cradle-to-grave processes in phosphorus fertilizers have increased by 20% from 2000 to 2015 (IRP 2019). Reporting on the environmental impacts of phosphate mining is thus essential in protecting biodiversity, water and soil resources, and the climate. Ecosystems can be critically damaged by PR mining, with negative effects for the environment, society and economy.

P is also responsible for alarming rates of worldwide eutrophication. Freshwater basins covering 38% of the global land cover have P water pollution levels higher than those basins can assimilate (Mekonnen and Hoekstra 2017). Eutrophication leads to the creation of so-called "dead zones" by enabling overgrowth of algae, which block the inflow of oxygen into the water. Eutrophication can also negatively affect the use of water for human purposes, including provision of drinking water and economic activities such as fishing.

Socio-political externalities

Significant PR resources are found in the disputed region of Western Sahara, which in 2016 accounted for almost a quarter of all PR exports of Morocco (OCP 2017). Western Sahara has been in a conflict since 1975, when most of the region was occupied by Morocco, while the remaining part was claimed by the Polisario Front, which installed the Sahrawi Arab Democratic Republic or SADR (Saul 2015).

Morocco has repeatedly been accused of violating the human rights of the Sahrawi people, indigenous to Western Sahara, as well as violating international law by exploiting resources from an occupied territory (Cordell 2015; Saul 2015; Amnesty International 2018). Western Sahara Resource Watch (WSRW) reported that the number of Sahrawis employed at the Bou Craa complex decreased from 1600 jobs in 1968 to only 200 in 2011 and that Sahrawis are discriminated against Moroccans (WSRW 2011). On the other hand, the Polisario Front has been accused of failing to hold to account those responsible of violating human rights in its camps during the 1970s and 1980s (Amnesty International 2018). Two rulings of the European Court of Justice in 2016 and 2018 decided that the Association and Liberalisation Agreements in agriculture and fisheries concluded between the EU and Morocco did not apply to Western Sahara, as the region has a separate and distinct status guaranteed under the Charter of the United Nations. The Court highlighted that it was not apparent the people of the territory of Western Sahara consented to the EU-Morocco agreement, although they had the status of a third party (CURIA 2018). Some fertilizer companies also acted on the matter of phosphate originating from Western Sahara. For example, two of the three importing companies in Australia stopped purchasing PR originating from Western Sahara as of 2015, soon followed by fertilizer companies from Norway, Germany, the Netherlands, Belgium, Uruguay, Switzerland and the US (WSRW 2017).

Court rulings and reports from organizations such as WSRW and Amnesty International are examples of how reporting on the socio-political impact of PR mining can influence the behaviour of various actors in reducing these impacts. Monitoring programmes and periodical reports of the two NGOs informed governments, companies and investment funds about the Western Saharan origin of PR and allowed them to make informed ethical decisions. By ruling on the legality of PR exploitation, court decisions also influence the activities of those involved in the P supply chain. At the same time, court rulings can indicate areas in the supply chain where more reporting and monitoring is needed.

Most of the PR-rich countries score low to very low in the Corruption Perception Index. The index ranks countries from 1 to 176 with 1 being the least corrupt. China is ranked 77th, Morocco 81st, Algeria 112th, Egypt 117th and Russia is at 135th (Transparency International 2019). When it comes to the World Bank's Worldwide Governance Indicators, all the above countries score low or very low on the control of corruption, rule of law, political stability/no violence and the voice and accountability indicators (World Bank 2019). These indexes and indicators can thus indirectly inform the underlying ethics of P-procurement decisions by government, companies, consumers or the general public.

Open access to data

Open access data have been advocated in the literature as a tool to improve governance, including governance of natural resources (see Attard et al. 2015). Governments are usually seen as the entities that should provide open access to their data, to increase transparency but also to enable interested and affected stakeholders to reuse, redistribute and innovate on the data provided (Attard et al. 2015). Such transparency makes governments more accountable to their actions and enables citizens to actively participate in the governance process (Attard et al. 2015). However, companies can also provide access to their data. Carbonell (2016) has called for the use of big data by companies in big agriculture to evaluate and monitor externalities of the industrial agriculture system. The author argues that this would enable research on the designation of best agriculture models for the future of global food production.

With a similar scope, Cordell and Neset (2014) advanced the Phosphorus Vulnerability Assessment Framework, through which they identified and integrated 26 phosphorus-related biophysical, technical, geopolitical, socio-economic and institutional factors that can lead to food system vulnerability. In a later paper, Cordell and White (2015) addressed global phosphorus vulnerability indicators in the global food system and suggested a number of publicly existing databases to track progress on these indicators. Their sources are in general international reporting entities, such as the World Bank, the International Fertilizer Association (IFA), the Food and

Table 5 Connection between SDGs and reporting on the P supply chain

Sustainable Development Goal	How reporting on the P supply chain affects reporting on the fulfilment of the goal
SDG1—Zero poverty SDG2—Zero hunger SDG3—Good health and well-being	- Poverty, hunger and health are related; people in less developed countries spend from 30 to 56% of their budget on food (WEF 2016) - Rural population in less developed countries is highly dependent on the productivity of their subsistence and semi-subsistence agriculture, and therefore P input can be essential - Eutrophication through P pollution can negatively affect the use of water for human purposes, including provision of drinking water. It can also negatively impact fishing, leading to decreased food availability and decreasing economic revenues
SDG6—Ensure availability and sustainable management of water and sanitation for all	- P pollution as runoff or wastewater effluent/sewage and its associated eutrophication (see section "Environmental externalities")
SDG12–Responsible Consumption and Production	- High rates of losses along the P supply chain (see section "Losses and inefficiencies along the supply chain")
SDG14–Life under water	- Eutrophication and dead zones due to P pollution (see Sect. 3.3.1)
SDG16—Peace, justice and strong institutions	- Oligopolistic phosphate market moving towards a monopoly with phosphate rock from conflict regions (see sect. "Socio-political externalities")

Agriculture Organisation (FAO), but also "domestic sources" (Cordell and White 2015).

Wellmer and Scholz (2015) brought into discussion the population's "right to know". In formulating their argument, the authors cite population's right to know as a "basic regulatory rule in the frame of democratic and free market-based societies" (Wellmer and Scholz 2015). As such, public knowledge about phosphorus, which is an essential fertilizer, should be basic knowledge for the basic right of access to food.

However, open access to data does not in itself guarantee such benefits. Jansse et al. (2012) warned about the barriers of benefitting from open data, such as task complexity in processing the data. The authors stress that "open data has no value in itself; it only becomes valuable when it is used". Transforming open access public data into some form of public value has been researched to an insufficient extent (Jansse et al. 2012).

Open access to P reporting can not only assist in tracking vulnerability and impact of the value chain, but also help in tracking progress on broader indicators, in which P plays a significant role. For instance, despite the fact that P supply chain effects and has a central value in food production, P reporting is not an integral part of the reporting for the UN Sustainable Development Goals (SDGs). In Table 5, we make the connection between reporting on achieving the SDGs as a global sustainability framework and reporting on the P supply chain.

In general, reporting on the P supply chain allows a better reporting on food security, pollution and human well-being (Cordell and White 2015) and all of these sectors are at the core of most of the SDGs. In turn, this can enable a better and more informed policy-making process in these areas but also an increased awareness among the public and other affected actors, such as farmers.

DISCUSSION

In Results section, we showed that reporting on the global P supply chain has a number of critical flaws. This virtually makes the supply chain a black box, the contents of which are difficult to predict or analyse. The different terminologies used to report on P deposits means that current estimates on the actual P resources are inaccurate. Moreover, lack of global, public reporting entities with the exception of the USGS do not allow for triangulation of results. Sudden changes in methodologies can have serious repercussions on the global P market, influencing the price of phosphate rock and P fertilizers. It also poses serious challenges in the evaluation of global P scarcity and raises questions as to how critical a material P actually is. A clear example in this sense is the 2010 overnight change in the reserves of Morocco and Western Sahara by IFDC, which had previously been considered potential resources.

Reporting on losses along the P supply chain is one of the most important processes that can allow for an increase in efficiency in the way P is being mined, processed, applied and recovered. It is also one of the most challenging reporting processes because it would require a wide range of actors from across sectors, local, national and supra-national, to monitor and publish their data. Perhaps an even greater challenge is to harmonize and integrate all data once it has been collected and made available. The benefits, however, would also be substantial, considering that 80–90% of the mined P is lost before reaching human consumption through food.

Although P has an extensive supply and value chain, there have been very few attempts at investigating this chain's externalities, both environmental and social. We discussed the externalities in sect. "Open access to data", with a particular focus on Morocco. The North-African kingdom is emerging as a key player on the phosphate market and because of its vast reported phosphate reserves, its importance will only increase in the future. Access to reports on externalities in PR-exporting countries such as Morocco can allow not only governments, fertilizer companies, farmers but also investment companies and/or banks to make ethical, socio-environmental sound decisions when buying phosphate or investing in PR mining companies.

Last but not least, we discussed the open access aspect of global P reporting. At the moment, the scarce information on the P supply chain is not publicly available, being mostly treated as proprietary data by mining and processing companies. Public knowledge on the P supply chain is needed because of the essential role of P in food production, global food security and the human right to food. But P reporting is also needed for other global goals, such as the SDGs. We directly linked the global P supply chain to seven SDGs, showing the interlinkages between the different impacts of the P chain and food security, pollution, environmental status, management of water resources as well as peace and justice. Reporting on the SDGs could improve through reporting on P, a natural resource that is key for seven of the 17 SDGs. Open access data on P reporting and the form publicly available data take are also important. Available data should be relevant and easy to analyse, which would make it valuable from a governance perspective. Access to relevant, easy to use data is essential to academia and civil society in their endeavour to complement the work of governments and other governance entities.

CONCLUSION

Phosphorous is an essential resource for food production, but its supply chain has far reaching impacts on environment, society and economy. This study showed that when it comes to reporting on P reserves and resources, the information is not harmonized, unreliable, fragmented and non-transparent. This intransparency poses a fundamental threat to food security worldwide, influencing the price of P fertilizers and the ability of those in the food production system to sustainably plan for the future. The global P supply chain induces a number of environmental and socio-political externalities, which are poorly documented. Improving reporting on these aspects can assist policy makers, farmers, fertilizer companies, investment banks and the public to make informed, ethical decisions on the procurement of phosphate rock or P fertilizers.

Global leadership in P reporting can lead to a more integrated and transparent approach to the P supply chain. Working towards quantification of P losses and inefficiencies in the supply chain can lead to more sustainable production and consumption. It can also raise awareness about the importance of improved agricultural practices. Exposing P losses can not only translate into more accountability by all stakeholders involved in the chain, but it can also better inform policy makers across a variety of sectors, from agriculture, to waste management, innovation, pollution control and human rights protection.

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Paper III

Global phosphorus supply chain dynamics: Assessing regional impact to 2050

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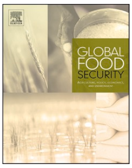

Global phosphorus supply chain dynamics: Assessing regional impact to 2050

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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

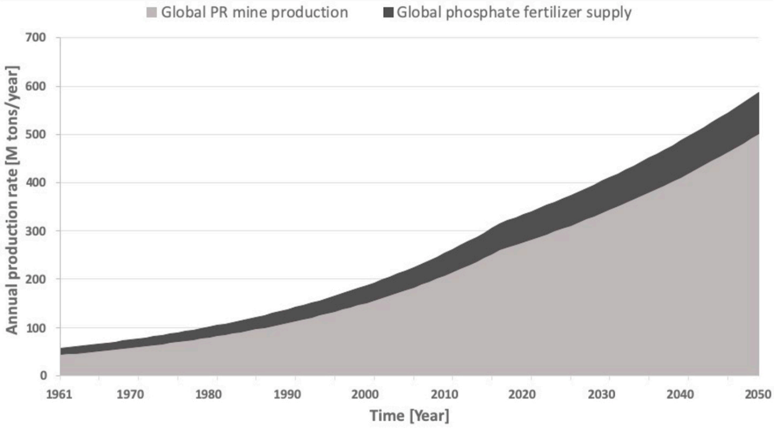

Fig. 1. Business-*as*-usual simulation of global PR mining and global phosphate fertilizer supply (M tons/year) using historical trends and FAO's current CAGR predictions.

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

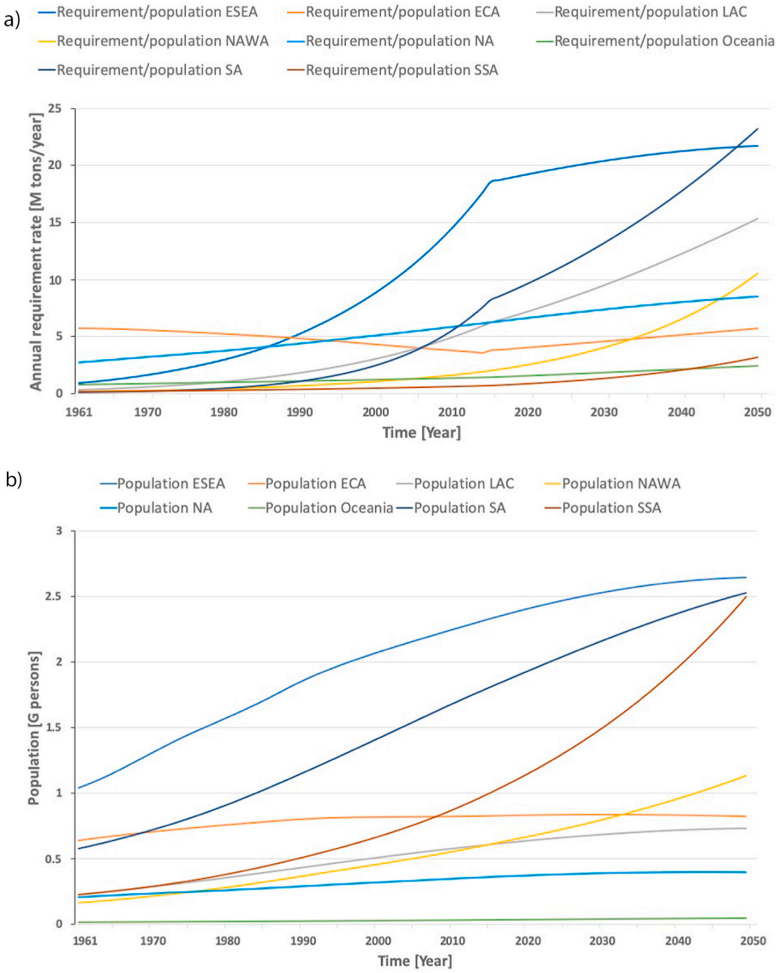

Fig. 2. (a) Business-*as*-usual model simulation of fertilizer requirement tied to regional population, and (b) a simulation of regional population development.

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

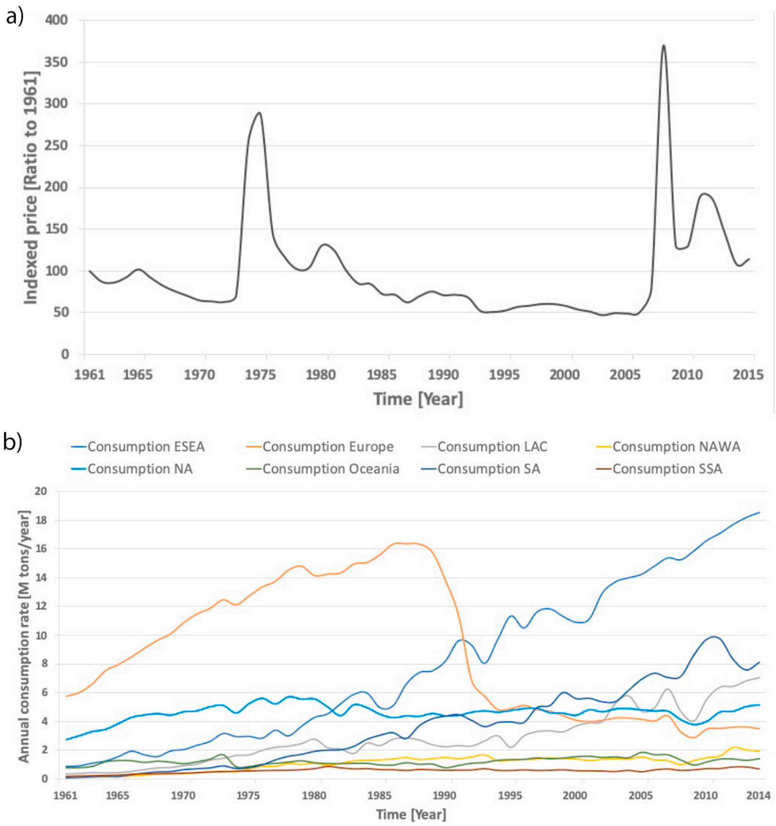

Fig. 3. (a) Phosphate fertilizer in US dollar prices indexed to 1961 and (b) Consumption of phosphate fertilizers by region for the period of 1961–2014 (data compiled from Our World in Data, 2014).

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

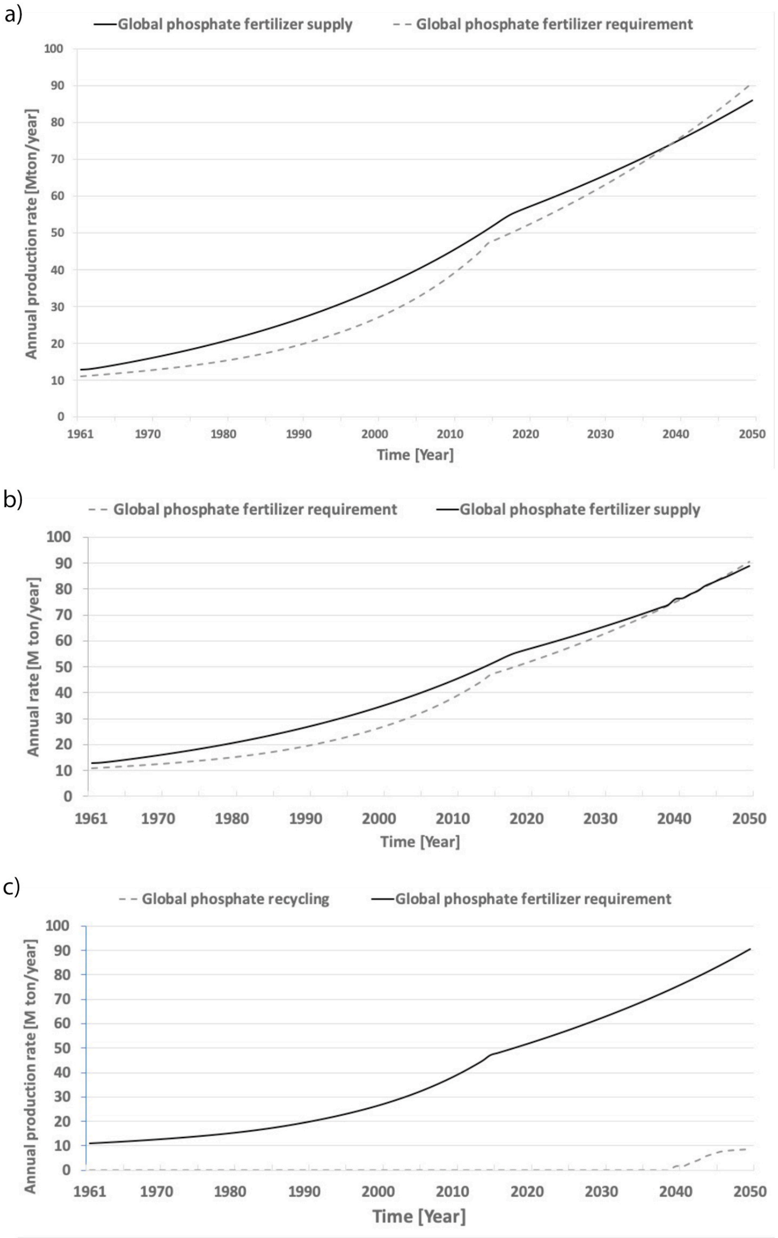

Fig. 4. (a) Requirement-supply relationship in a business-*as*-usual scenario, (b), requirement-supply when more PR production and P recycling are activated and (c) the share of recycled P in the total global phosphate fertilizer supply.

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).

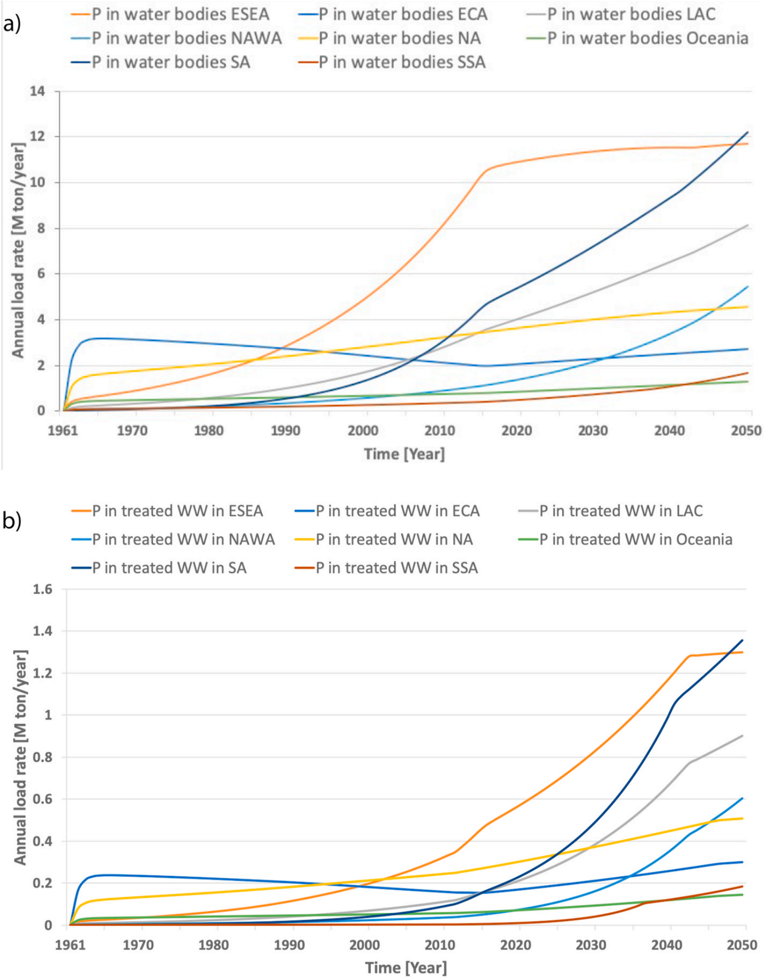

Fig. 5. (a) Phosphorus load in water bodies due to runoff and untreated water and (b) Phosphorus load in treated wastewater.

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

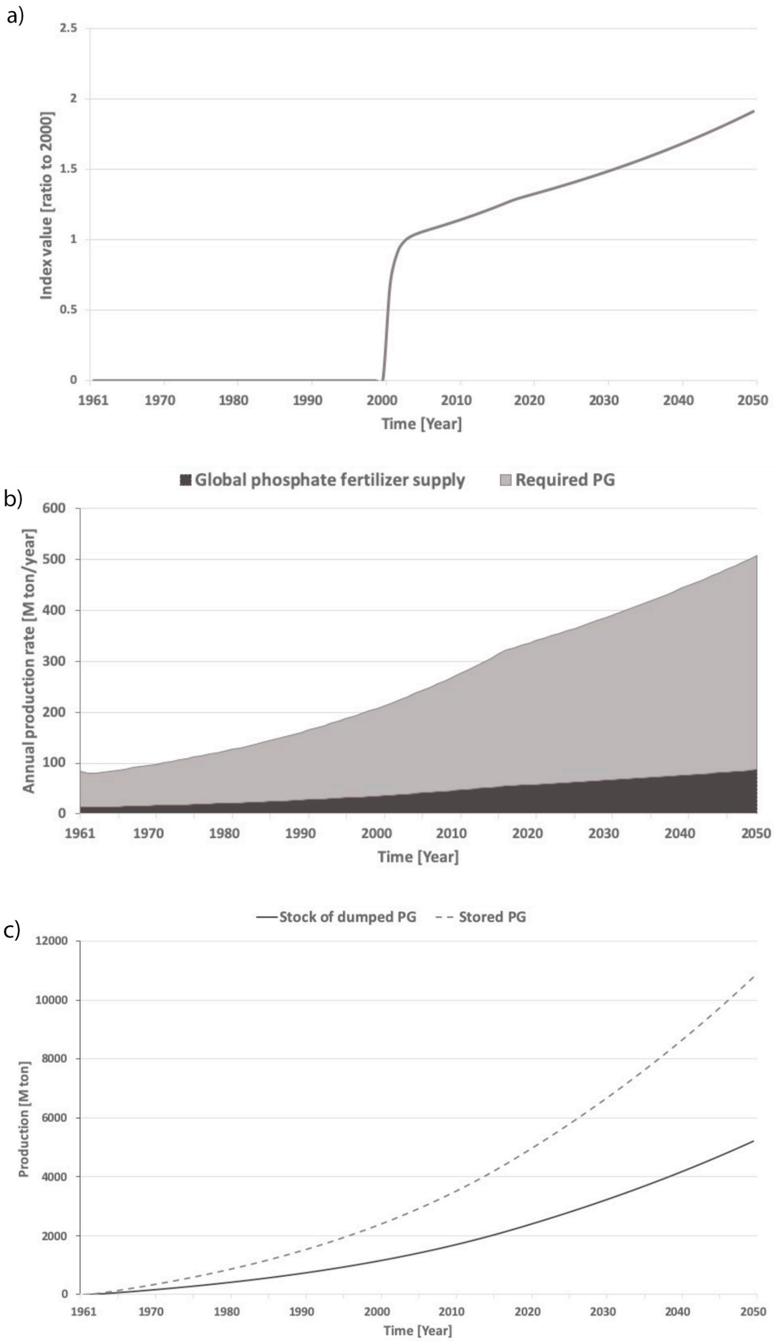

Fig. 6. (a) Impact of PR mining and fertilizer production on GHG emissions indexed to 2000, (b) phosphogypsum (PG) production per year required to produce fertilizers and (c) the total stocks of stored and dumped phosphogypsum.

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

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gfs.2020.100426.

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Paper IV

Regional scenarios for inorganic phosphate requirement decrease in industrializing regions to 2050

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Abstract

The current pandemic has highlighted the vulnerabilities of our food production system. An overwhelming number of studies and reports warn that in a business-as-usual scenario, the global food system will be increasingly challenged to secure food for a growing population. In its current configuration, the food system reinforces social and economic inequalities, and negatively impacts the environment. At the same time, farmers are increasingly dependent on imported agricultural inputs, such as phosphate fertilizers, which makes them vulnerable to major supply disruptions or price spikes. In this study, we used system dynamics modelling to assess several scenarios for decreased regional inorganic phosphate requirement to 2050 in industrializing regions with a growing population. Four scenarios illustrate the policy options of reducing phosphorous demand through i) recycling of phosphorus (P) from municipal wastewater, ii) food loss reduction, iii) a shift to agroecological farming practices; and iv) a combination of the three measures. We found that food loss reduction has the lowest potential in reducing P requirement, while the implementation of agroecological farming practices results in significant decreases in P requirement. East and South East Asia and Sub-Saharan Africa were two regions where scenarios indicated a decrease or a near flattening of P requirement to 2050 compared to 2020. In North Africa and Western Asia, Southern Asia and Latin America and the Caribbean, scenario simulations show increases in P requirement, albeit at much lower rates than in a business-as-usual case.

Keywords: phosphorus; food loss reduction; phosphorus recycling; agroecology; system dynamics

1. Introduction

The latest median variant estimate for population growth by the UN places the world population at close to 10 billion by 2050 (UN 2019), although the most recent study on global demographics points to a population peak at 9.73 billion people in 2064 (Vollset et al. 2020). An associated estimate of the increase in food demand has been calculated in the literature at between 50-98% compared to 2005 levels (Valin et al. 2013; FAO 2017a). However, the population is not growing at the same rate in all regions. Africa, Latin America and the Caribbean, and most of the Asian countries will account for the bulk of this growth (UN 2019). Thus, an increase in the number of people, combined with changing diets of the industrializing nations in these regions as well as the ongoing efforts to eradicate hunger through the Sustainable Development Goals (SDGs) are making these regions hotspots of increased food demand (WRI 2019). These are also regions where sustainable intensification is perceived as an optimal solution owing to the fact that suitable land resources are not at hand to meet the increase in regional food demand (Pastor et al. 2019). The ongoing COVID-19 pandemic highlights the vulnerabilities of the food production system, especially through exacerbated hunger in vulnerable areas. The World Food Programme have estimated 135 million more people facing hunger in addition to the already existing 821 million undernourished. That figure has now been doubled to 265 million people as a result of the COVID-19 pandemic (WFP 2020). The International Panel of Experts on Sustainable Food Systems (IPES-Food) highlighted that our global food system had already been on the edge –

from children a meal-away from hunger to farmers a failed harvest away from bankruptcy. In addition, the industrial agriculture so prevalent in the world has been driving habitat loss and established conditions for viruses to emerge and spread (IPES-Food 2020). The Executive Director of the World Food Programme has warned that disruptions in trade and a lack of ensuring the necessary inputs can lead to famine of "biblical proportions" (WFP 2020).

Against this background, the requirement for fertilizers to match an increase in food demand and the intensification of agriculture is set to increase. Phosphorus (P) in particular has been of great interest, since it is a mined non-renewable and non-replaceable element. While central to the "peak phosphorus" debate triggered by the 800% spike in phosphate rock prices in 2007-2008 (Cordell et al. 2009; Scholz and Wellmer 2013), the finite aspect of global phosphorous reserve (PR) resources is only one of many issues associated with the global phosphate supply chain. A regional deficit of phosphate supply has been signaled by the FAO (2017b) in most of Europe, Oceania, Latin America and South Asia. While the FAO study claims that Africa does not exhibit any deficit, that is owing to North Africa and Sub-Saharan Africa not being analyzed as separate units. Almost three quarters of the global PR resources are in Morocco and Western Sahara (USGS 2020), while apart from South Africa, there are no significant resources in Sub-Saharan Africa. Similarly, Russia and China account for the positive phosphate balance in Eastern Europe and Central Asia, and East Asia, respectively. So far, the literature on phosphorus has largely focused on depletion rates for PR and ways to close the loop either through recycling P from wastewater or tackling losses and inefficiencies along the supply chain (see Van Vuuren et al. 2010; Mihelcic et al. 2011; Sverdrup and Ragnarsdottir 2014; Scholz and Wellmer 2015). However, less attention has been paid to reducing the consumption of inorganic phosphate fertilizers and decreasing the national and regional import dependency to PR-originating phosphate. There are only a few regional studies in the phosphate literature (Mohr and Evans 2013; Nesme et al. 2018), although the relevance of regional assessments in the evaluation of global processes has been highlighted by, for example, the Planetary Boundaries Framework (Steffen et al. 2015) and the latest report of the International Resource Panel (IRP 2019).

The World Economic Forum (WEF) have stressed the need to focus on tackling overconsumption, food wastage and currently unsustainable diets as a means to tackle food security (WEF 2020). Indeed, food wastage – which comprises both food loss and food waste – accounts for 30-50% of the total food produced in the world (FAO 2019). The measures required to reduce food wastage, however, differ by country and region. While wastage of fruits and vegetables are widespread, FAO found that Sub-Saharan Africa and Central and Southern Asia have higher degrees of wastage compared to other developing regions (FAO 2019). The same report highlights that while some food waste reduction can be cost-effective, more reduction of food loss comes at increasing higher costs. Thus, food wastage strategies need to be tailored for national and regional specifics and exhibit cost-optimization. Indeed, the FAO report points to only 20% of the food loss as feasibly reduceable from post-harvest to processor stage, although this is a number from a US perspective (FAO 2019).

The Covid-19 crisis illustrates the central role that trade plays during crisis times and how disruptions in trade also translate into disruptions in supply, including fertilizers.

The World Trade Organisation (WTO) estimated a decline in trade for 2020 between 13% in the most optimistic scenario and 32% in the pessimistic scenario (WTO 2020a). While some similarities can be traced back to the economic crisis in 2008-2009, in the current situation restrictions on labor supply and transport mean that the pandemic disruptions will have wider implications (WTO 2020).

While trade is certainly a necessity in times of crisis, an increased reliance on trade also increases the vulnerability of import-dependent countries to secure food for their population. Additionally, the global food system and food security is highly dependent on a limited number of systems critical chokepoints functioning without serious disruptions (Bailey and Wellesley 2017). The International Fund for Agricultural Development (IFAD) stressed the need to invest in agriculture as a sector that is two to three times more efficient in tackling poverty and food insecurity than other sectors (IFAD 2020). Trade is also responsible for around 27% of the global phosphate fertilizer movement in the world by means of trade in human food, animal feed and crops for other uses (Nesme et al. 2018). The authors conclude that phosphorus exporters are thus vulnerable to the volatility of the global phosphate fertilizer market. The main P-in-food exporting regions were North America and South America. While South Asia did not account for a significant quantity of P-exports, it was nevertheless a net P exporter, which is surprising deeming the region's dependency on P imports. Africa, while also accounting to small quantities of P exports and import, appeared to be highly dependent on P-imports from other regions. Low-input farming systems such as agroecology have often been cited in the literature as means to decrease agro-chemical inputs, increase soil health and productivity, and increase farmer income (see Altieri and Nicholls 2012; FAO 2019). Moreover, agroecology is seen as a wider process of increased resilience and wellbeing for farmer communities (FAO 2019).

Extensive literature also exists on recycling P from wastewater as a means to reduce reliance on imports, close part of the P loop and increase resilience to price shocks on the global phosphate fertilizer market (see Hukari et al. 2016; Chrispim et al. 2019), although some authors have questioned the sustainability of the recycling process (Golroudbary et al. 2019).

Countries like Switzerland and Germany recently implemented legislation to enable recovery of P from wastewater treatment plants (EU Commission 2016; Swiss Fedeal Council 2015), while the European Union (EU) adopted a revised Fertilizer Regulation to boost phosphate fertilizer recycling in the community block (EU Parliament 2019). Recycling in industrializing nations is still challenging, however, considering that only 8-38% of the wastewater is treated in low- to upper-middle income countries (UN-Water 2017).

1.1 Aim

The Aim of this study is to analyse regional phosphate dynamics and assess inorganic phosphate use reduction scenarios. The aim is also to determine which of three solutions proposed in the literature – namely food loss reduction, recycling P from wastewater and agroecology – is likely to decrease requirement for inorganic phosphate fertilizers in industrializing regions experiencing high rates of population growth.

2. Methodology

The methods used in this paper can be divided into two main parts: the use of a system dynamics model to build scenarios of phosphate requirement reduction to 2050 and a case study review of agroecology practices. The latter was used in order to quantify the regional impact of the agroecological scenarios.

2.1 System Dynamics Model

A regional system dynamics model developed by Nedelciu et. al (2020) was used for scenario-building. The studied regions are Latin America and the Caribbean (LAC), North Africa and Western Asia (NAWA), Sub-Saharan Africa (SSA), Southern Asia (SA) and East and South-East Asia (ESEA). The model ties inorganic phosphate requirement to population growth in the world regions and simulated requirement and supply behaviour to 2050. The scenarios assesses *"to what extent can inorganic fertilizer requirement be decreased in industrializing regions with high rates of population growth?".*

In the model from Nedelciu et al. (2020), recycling of P from wastewater and increased PR mining for additional fertilizer production are both triggered by a fall of phosphate supply under the requirement. The scenarios in this paper are built under a different assumption. For the recycling scenario, a 10-year exponential growth of the recycling sector starting 2021 is built in; it means that by 2031 the recycling sector is fully operational. There is no increase in PR mining, as the purpose was to show how different scenarios aimed at reducing inorganic phosphate requirement position themselves in relation to the Business-as-Usual (BAU) scenario. In the Food Loss Reduction (FLR) scenario, food loss refers to losses in the food supply chain from post-harvest and up to, but not including, the retailers and consumers. The model assumes a 20% reduction in food loss starting 2021. The food loss numbers are taken from FAO (2019), as is the assumption that a 20% reduction in food loss reduction is feasible. It should be noted, however, that the 20% number results from a study in North America; regional specific numbers could not be obtained due to lack of data.

2.2 Case study review on agroecological practices

The numbers for the Agroecology (AE) scenario are based on a review of case studies from developing regions (see Table 1). Case studies were assessed in terms of the yield increase per each agroecology measure applied. Studies were collected from the literature, NGO reports, reports of international institutions, government reports, and various documents published by universities. It was then assumed that an increase in yield would correspond to an increase in the efficiency use of inorganic fertilizer. For instance, for SSA, the yield increase was of 174%, which translates into an efficiency ratio for inorganic fertilizer of 2.74. In other words, 1 ton of inorganic fertilizer under AE practices is – in the model – equivalent to 2.74 tons of inorganic fertilizer under conventional practices. Thus, a farmer from SSA can produce 2.74 times more with the same amount of inorganic fertilizer when using agroecological practices as opposed to conventional methods.

The numbers for each region were obtained by averaging the yield increase from all case studies in that particular region and converting it to an efficiency ratio. With a high degree of certainty, it can be said that this is a significant underestimation of the decrease in the requirement for inorganic fertilizer, as AE practices such as organic agriculture (OA) preclude the use of inorganic fertilizers. Similarly, the system of rice intensification (SRI) generally requires little input of inorganic fertilizer. However, the model runs under the above-mentioned efficiency ratio assumption due to lack of data on the extent of inorganic fertilizer reduction that is associated with the implementation of AE practices. Although most case studies in, for instance, SSA are based on OA practices, these practices are described as "organic or near organic" (UNEP/UNCTAD 2008), which means a zero inorganic fertilizer use assumption is not possible.

In the AE scenario, it is assumed that a full implementation is executed from 2021-2050. Annual compound growth rates are used to express the speed of implementation. The term "agroecological measures" is used vaguely in this study. It includes the seven farming systems shown in Table 1 (See section 3.1), which in the analysed literature are placed under the agroecology umbrella. Nevertheless, these seven farming systems are not necessarily agroecological following the ten FAO agroecological elements (FAO 2019). For instance, one of FAO's ten agroecological elements is "diversity", which refers to a diversity of species and genetic resources in the farming system. The system of rice intensification (SRI), the system of wheat intensification (SWI), and the system of sugarcane intensification (SSG) do not necessarily have a diversity component. Nonetheless, these systems are also considered agroecological in the literature (Altieri 2012). Moreover, it was not possible to assess the compliance of all case studies to other FAO agroecological elements, in particular "responsible governance", "human and social values", and "circular and solidarity economy". Most of the analysed data referred predominantly to increased productivity with less or no agro-chemical inputs.

Table 1 summarizes the findings of the agroecological case-study review. With the exception of Sub-Saharan Africa (SSA), the calculated regional average yield change was between +37% and +66%. The average yield increase for SSA was substantially higher, at +174%. This can be explained by the historically low rates of fertilizer use in the region, combined with average yields far below the world average (Tian and Yu 2019). As such, while a +174% increase in yields is significant, it would still place SSA under the world average of yield productivity.

Table 1. Results of the case study review on agroecological efficiency (SRI = System of Rice Intensification; OA = Organic Agriculture; AE = Agroecological; CA = Conservation Agriculture; SA = Sustainable Agriculture; IPM = Integrated Pest Management; SWI = System of Wheat Intensification; SSI = System of Sugarcane Intensification)

Region	**No. of case studies**	**Type of AE measure (in %)**	**Average yield change**
LAC	20	75% SRI, 20% OA, 5% general AE	+48%
SSA	128	89% OA, 7% SRI, 1.5% CA, 1.5% SA, 1% IPM	+174%
NAWA	12	92% SRI, 8% SWI	+66%
SA	35	17% SA, 6% IPM, 77% SRI	+48%
ESEA	81	1% Aquaculture, 1% Contour Farming, 1% double cropping, 2.5% IPM, 3.7% SA, 90.8% SRI	+37%

The numbers used to build the four scenarios are summarized in table 2. Food loss numbers show that East and South East Asia (ESEA) have the lowest post-harvest to distribution losses with 8%, while South Asia (SA) is at the opposite end of the scale, with 20.5%. In terms of efficiency in fertilizer use derived from the implementation of agroecological practices, the numbers follow the yield increases presented in Table 1.

Table 2. Numbers used in the model for each scenario, based on a BAU scenario and recycling rates from Nedelciu et al. 2020 as well as results from the literature and case study review. In the food loss scenario, a 20% reduction of the food loss numbers presented in this table was applied

Region	**Business as usual in 2050 (in m.t.)**	**P recycling from WW (in %)**	**Food loss (post-harvest to distribution) (in %)**	**Agroecology (in increased efficiency ratio)**
LAC	15.4	-10%	-12%	1.48
SSA	3.2	-10%	-14%	2.74
NAWA	10.6	-10%	-11%	1.66
SA	23.2	-10%	-20.5%	1.48
ESEA	21.7	-10%	-8%	1.37

3. Results

The SD model simulated four scenarios for each region, which were then compared to the business-as-usual run. For ESEA (Fig. 1), the FLR scenario brought little change to phosphate requirement. This is because ESEA had the lowest food loss rate (see Table 2). Implementing a P recycling sector reduced the increase in requirement and kept it under 20 million tons yr^{-1} in 2050. Agroecology alone reduced the phosphate requirement in 2050 to 2012 levels, while a combination of food loss reduction, P recycling and agroecology further reduced phosphate requirement to 2007 levels. Thus, FLR had the lowest impact on phosphate requirement, while agroecology alone produced the highest change.

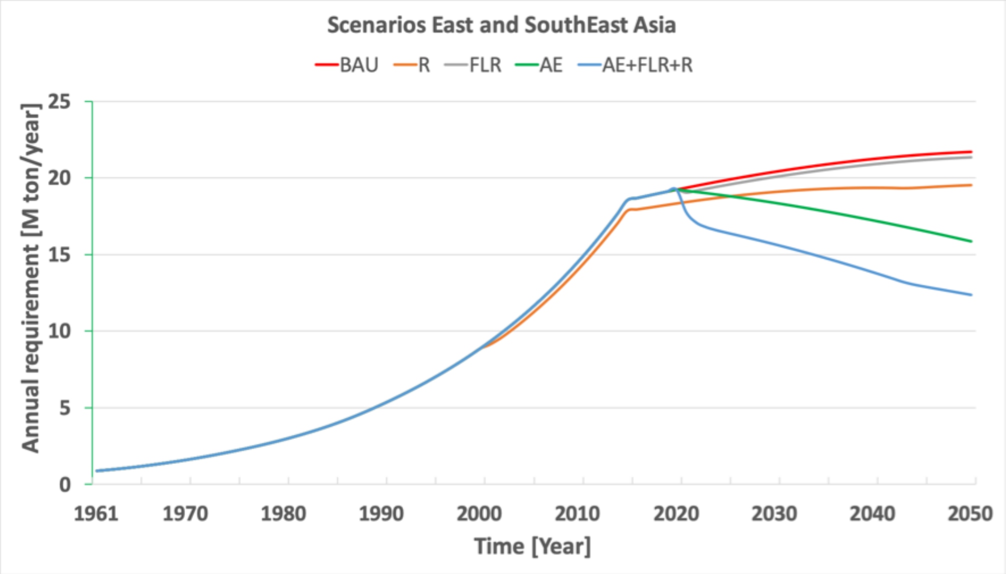

Figure 22. Simulation results for East and South East Asia (ESEA). BAU stands for business-as-usual, R for recycling, FLR for Food Loss Reduction, AE for agroecology and AE+FLR+R for a combination of the three scenarios

In LAC, the model simulation yielded different results. Phosphate requirement increased in all scenarios (see Fig. 2). The FLR and R scenarios followed BAU's high rate of increase. On the other hand, AE and the combination of all recycling, food loss reduction and agroecology substantially decreased the rate of phosphate requirement increase to 2050. Similarly to the simulation in ESEA, food loss reduction had the lowest impact, while agroecology alone brought the most significant changes.

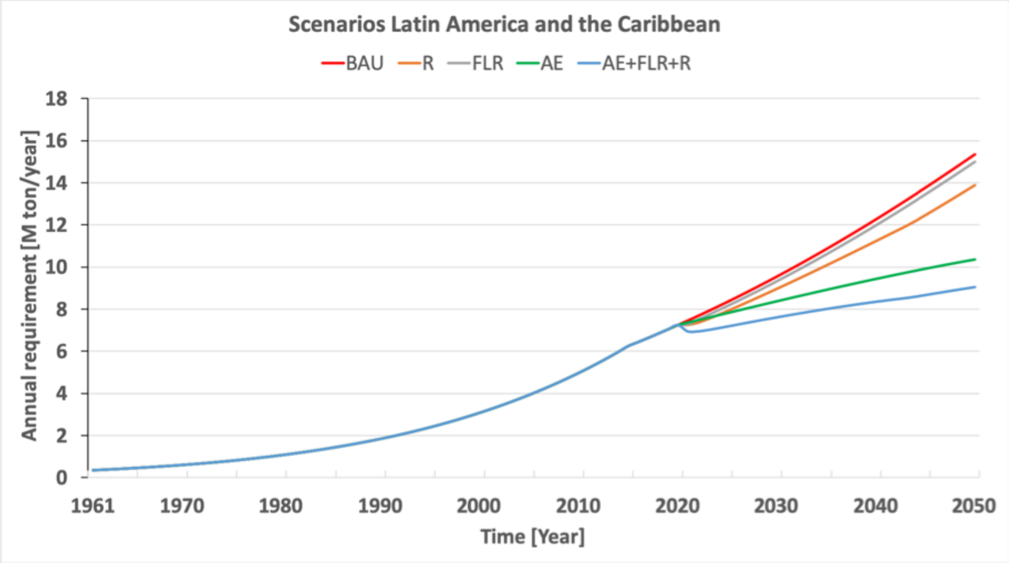

Figure 23. Simulation results for Latin America and the Caribbean (LAC). BAU stands for business-as-usual, R for recycling, FLR for Food Loss Reduction, AE for agroecology and AE+FLR+R for a combination of the three scenarios

An analogous situation can be observed for NAWA (Fig. 3), where food loss reduction and recycling do not significantly impact the high rate of increase in phosphate requirement. Agroecology reduces this increase, which is nevertheless kept at 1961-2020 levels, while a combination of recycling, food loss reduction and agroecology further slows the increase rate of inorganic P requirement, albeit without a significant change from the agroecology scenario. Food loss reduction and agroecology remain the interventions with the lowest and, respectively, highest impacts on phosphate requirement reduction.

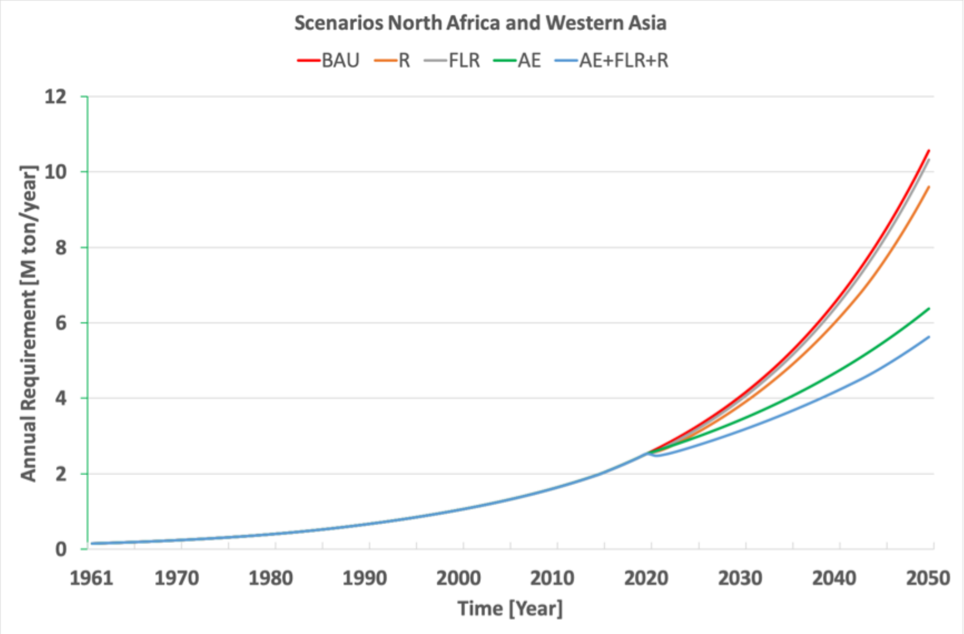

Figure 24. Simulation results for North Africa and Western Asia (NAWA). BAU stands for business-as-usual, R for recycling, FLR for Food Loss Reduction, AE for agroecology, and AE+FLR+R for a combination of the three scenarios

Mirroring the results in LAC, Southern Asia (SA) registers an increase in its phosphate requirement to 2050 in all scenarios. Food loss reduction is still the scenario with the lowest impact on decreases for phosphate requirement, however it has a higher impact compared to the food loss reduction scenarios in all other regions. Agroecology remains the standalone measure with the highest phosphate requirement reduction, with the potential to reduce phosphate requirement to 2050 by 32%. A combination of food loss reduction, recycling and agroecology can reduce the phosphate requirement to 2050 by 43%.

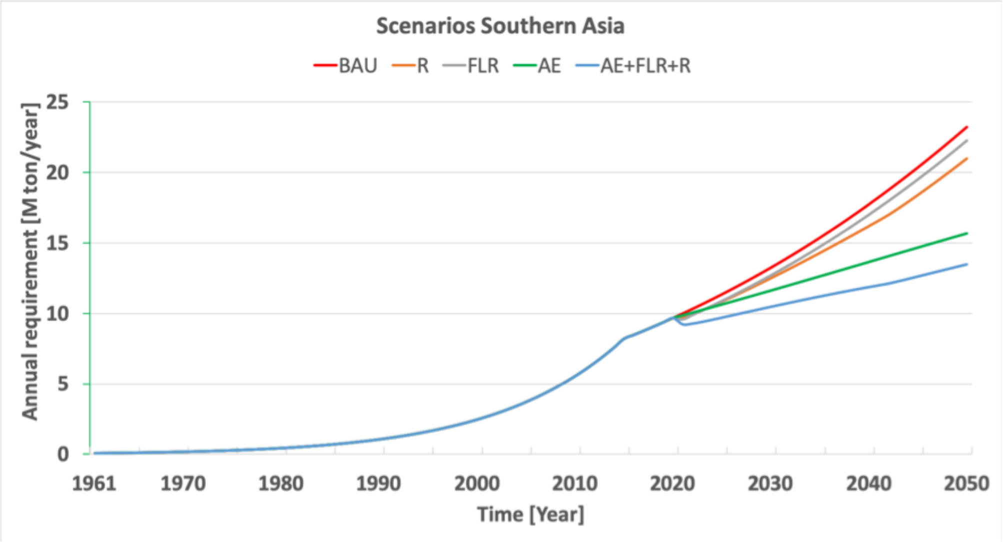

Figure 25. Simulation results for Southern Asi (SA)a. BAU stands for business-as-usual, R for recycling, FLR for Food Loss Reduction, AE for agroecology and AE+FLR+R for a combination of the three scenarios

In SSA, the difference between the set scenarios is the most sizeable. Food loss reduction and recycling follow the high rates of phosphate requirement increase exhibited by the business-as-usual base run. However, agroecology and the combination of agroecology, food loss and recycling nearly flatten the requirement trend to 2050. This is due to the very high yield increase numbers from Table 1, which translate in the highest fertilizer use efficiency ratio of all regions (see Table 2).

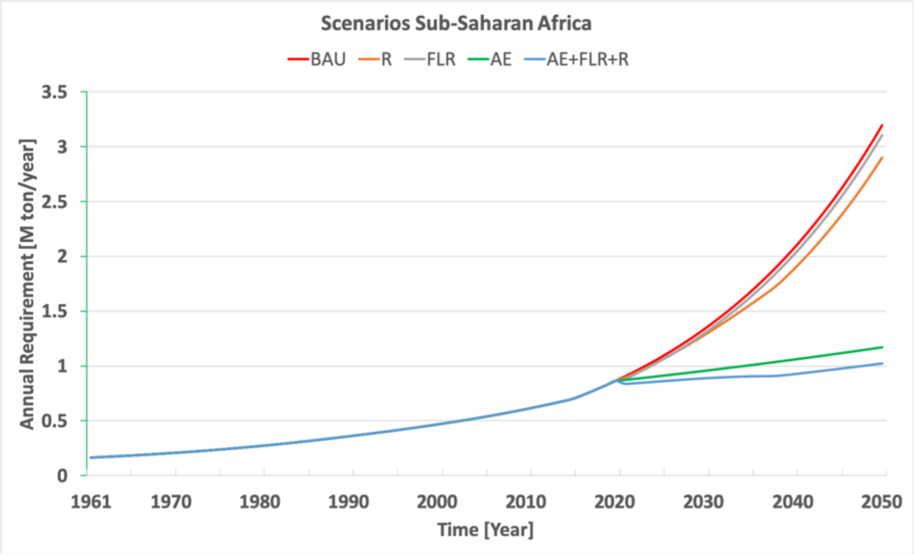

Figure 26. Simulation results for Sub-Saharan Africa (SSA). BAU stands for business-as-usual, R for recycling, FLR for Food Loss Reduction, AE for agroecology and AE+FLR+R for a combination of the three scenarios

For all regions, food loss reduction proved to be the least effective measure at decreasing phosphate requirement. On the other hand, agroecology led to either significant reduction of phosphate requirement (LAC, SA, NAWA), to a flattening of the requirement rate (SSA) or, in the case of ESEA, to a considerable decrease (see Table 3). With the exception of ESEA, a combination of food loss reduction, recycling and agroecology did not yield sizeable reductions in phosphate requirement when compared to the agroecology scenario.

Table 3. Results of the phosphate system dynamic model simulations for all regions. Numbers are in million tons of phosphate fertilizer per year. BAU = Business As Usual; FLR = Food Loss Ratio; R = Recycling; AE = Agroecology

Region	*BAU 2020*	*BAU 2050*	*FLR 2050*	*R 2050*	*AE 2050*	*AE+FLR+R 2050*
ESEA	19.2	21.7	21.3	19.5	15.8	12.4
LAC	7.2	15.3	15	13.9	10.4	9
NAWA	2.5	10.6	10.3	9.6	6.4	5.6
SA	9.7	23.2	22.2	21	15.6	13.5
SSA	0.9	3.2	3.1	2.9	1.2	1
All	**39.5**	**74**	**71.9**	**66.9**	**49.4**	**41.5**

When all industrializing regions are considered, food loss reduction was only gave a 3% decrease in phosphate requirement to 2050 (see Table 3). Recycling scenarios gave a flat 10% decrease in phosphate requirement in all regions, which is reflected in the sum total. Agroecology scenarios gave an aggregate reduction of 33%, while a combination of agroecology, food loss reduction and recycling would keep the total phosphate requirement increase in industrializing regions to only 5% in 2050 compared to 2020 levels (see Table 3).

4. Discussion

At first glance, the very low impact of a food loss reduction scenario on phosphate requirement may appear surprising. The low impact is owing to the fact that food loss at the retailer, catering and consumer levels are not included in the model but that, additionally, the absolute numbers on food loss reduction is fixed at 20% of the losses from post-harvest to processors – this may be an underestimation in some contexts. Further research into regional cost and benefit analyses of reducing food loss could provide a more accurate picture of what is possible to achieve in industrializing regions though the degree of impact is currently hard to gauge. At the same time, including food loss reduction at retailing, catering and consumer levels may increase the impact food loss reduction has on reducing phosphate requirement.

Recycling of P from municipal wastewater is dependent on wastewater treatment levels. In the model, 100% of the municipal water is treated by 2050 in all industrialized regions – this clearly is a best case assumption. A lower treatment ratio would reduce the amount of P that can be recycled. At the same time, wastewater treatment alone is not a guarantee for efficient P recycling, which is subject to additional technology and infrastructure development needs. The choice and cost of recycling techniques can have significant impact on the extent to which P will be recycled in industrializing countries. While these two aspects can represent a setback in achieving the 10% reduction in BAU requirement, it is worth noting that industrial wastewater is not included in the model. Recycling phosphate from industrial wastewater – particularly the food industry – could compensate for some of the ambitious aforementioned assumptions. Another important aspect of recycling, which could increase the relevance of this end-of-pipeline measure in decreasing phosphate requirement, is exploring other potential recycling sources. One example is phosphogypsum, a highly toxic and radioactive byproduct resulting from processing phosphate rock. Nonetheless, this would apply only to regions with PR mines, namely NAWA and ESEA and would be subject to the development and implementation of a safe recycling technology. Another potential source would be recycling phosphate from iron ore waste (Pereira and Papini 2015), a process which would also be subject to the geographical distribution of iron resources and recycling infrastructure development.

Agroecology had the highest impact out of the three scenarios on reducing, flattening or decreasing phosphate requirement to 2050 compared to 2020. While understanding of agroecological measures in this study precede the 2019 FAO elements of agroecology, it is very likely that the role of agroecology in reducing fertilizer use is underestimated in our model. Besides its role in decreasing the need for inorganic fertilizers, agroecology has the benefit of increasing farmers' income, as shown in the causal loop diagram from Fig. 6. This is done through reinforcing loops R1 – decreasing costs for fertilizer purchase – and R2 – increased income derived from increased production. The two reinforcing loops are balanced by loop B1, in which adoption of agroecological practices is subject to the need to produce more food.

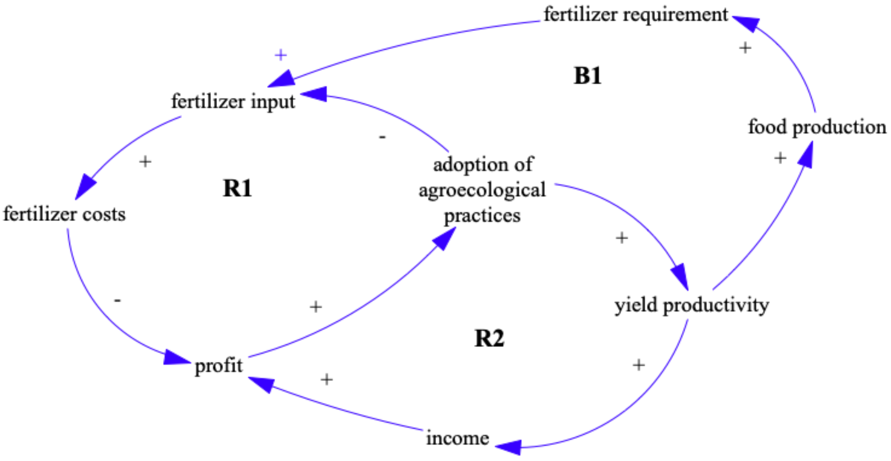

Figure 27. Causal loop diagram of the dynamics of agroecology development

A combination of recycling, food loss reduction and agroecology could flatten the overall trend for increased phosphate in industrializing regions. However, such a scenario would not only assume the widespread adoption of agroecological measures, but also comprehensive and integrated measures along the supply chain to reduce food loss and recycle P. A switch to agroecology would need to be accompanied by investments in infrastructure and technology related to food storage, food transportation or recycling. Moreover, a holistic package of regulations would be needed to ensure that the legal framework does not work counter to food loss reduction strategies. A regulating process would be required for recycling, in order to guarantee the safety of reusing recycled P in agriculture.

5. Conclusion

Most of the population growth is taking place in industrializing regions, where food security is already an issue. At the same time, these regions are generally scarce in phosphate resources and thus dependent on imports from a handful of producing countries. Crises such as the price spike in phosphate fertilizers in 2008-2009 and the COVID-19 pandemic unraveled the fragility of the food system and the increasing supply-related vulnerabilities that farmers are subject to. From the simulation of scenarios considered in this study, agroecology alone can, either greatly reduce, flatten or even decrease the phosphate requirement in the coming decades. Food loss reduction had the least impact on requirement decrease, due to the reduced amount of loss reduction, which can be achieved in a feasible way: the higher the share of food loss reduction, the higher the costs. However, the numbers on food loss reduction used for scenario-building are based on the one available study, which is also not representative of developing countries. Recycling can somewhat reduce phosphate requirement, but it will be highly dependent on wastewater treatment rates and deployment of recycling technology, both of which are currently underdeveloped in industrializing regions. A combination of the three measures would yield best results. Nonetheless, this would require significant investments in infrastructure and coordinated legal frameworks to enable implementation. Improvements in the parametrization for the different scenarios is needed. In particular, future research should focus on a case-by-case regional approach, with scenarios taking into account specific regional numbers on reduction potential and the speed of the implementation of reduction measures.

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Appendix A

Methodology for the System Dynamics model in Paper III (extended)

The model divides the world into eight regions, as shown in Table A1. The selection of regional boundaries was made by combining the regional categorization in the Fertilizer Outlook reports of the Food and Agriculture Organization (FAO) of the United Nations and the regional categorization employed by the Population Division of the United Nations. Each region was also assigned an income-based category, reflecting its development status. These categories are used in the model in order to assign the current state of wastewater treatment rates as presented in the UN Wastewater Assessment (UN 2017). In the discussion section, the income-based categories are used to discuss the implications of regional P import dependency on food security and the economic potential of certain regions to improve their wastewater and P recycling infrastructure.

Table A1. Regional classification made by combining FAO Fertilizer Outlook classification with UN's Population Division classification. However, when this was not the case, the preferred classification is indicated in brackets (source: Supplementary Data in Nedelciu et al. 2020b)

Region and income level	***Countries***
North Africa and West Asia (NAWA): *upper middle-income region*	Northern Africa: Algeria, Egypt, Libya, Morocco, Sudan, Tunisia, Western Sahara. West Asia: Afghanistan, Armenia, Azerbaijan, Bahrain, Cyprus, Georgia, Iraq, Iran (Islamic Republic of), Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, State of Palestine, Syrian Arab Republic, Turkey, United Arab Emirates, Yemen ***(FAO Fertilizer Outlook).***
Sub-Saharan Africa (SSA): *low-income region*	Angola, Benin, Botswana, Burkina Faso, Burundi, Cabo Verde, Cameroon, Central African Republic, Chad, Comoros, Congo, Cote d'Ivoire, Democratic Republic of the Congo, Djibouti, Eritrea, Equatorial Guinea, Eswatini, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mayotte, Mozambique, Namibia, Niger, Nigeria, Reunion, Rwanda, Saint Helena, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Uganda, United Republic of Tanzania, Togo, Zambia, Zimbabwe.
North America (NA): *high-income region*	Canada, Unites States of America ***(FAO Fertilizer Outlook).***
Latin American and the Caribbean (LAC): *upper middle-income region*	Antigua and Barbuda, Argentina, Bahamas, Barbados, Belize, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, Grenada, Guatemala, Guyana, Haiti, Honduras, Jamaica, Mexico, Nicaragua, Panama.
East and South East Asia (ESEA): *upper*	East Asia: China, Hong Kong SAR (China), Macao SAR (China), Taiwan Province of China (China), Democratic People's Republic of Korea, Japan,

middle-income region	Mongolia, Republic of Korea. South-Eastern Asia: Brunei Darussalam, Cambodia, Indonesia, Lao People‘s Democratic Republic, Malaysia, Myanmar, Philippines, Singapore, Thailand, Timor-Leste, Viet Nam.
Southern Asia (SA): *lower middle-income region*	Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, Sri Lanka ***(FAO Fertilizer Outlook).***
Europe and Central Asia (ECA): *high-income region*	Europe: Albania, Andorra, Austria, Belarus, Belgium, Bosnia and Herzegovina, Bulgaria, Channel Islands, Croatia, Czechia, Denmark, Estonia, Faroe Islands, Finland, France, Germany, Gibraltar, Holy See, Hungary, Iceland, Ireland, Isle of Man, Italy, Latvia, Liechtenstein, Lithuania, Malta, Monaco, Montenegro, North Macedonia, Netherlands, Norway, Poland, Portugal, Republic of Moldova, Romania, Russian Federation, San Marino, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Ukraine, United Kingdom. Central Asia: Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan ***(Population Division of the UN).***
Oceania: *high-income region*	American Samoa, Australia, Cook Islands, Fiji, French Polynesia, Guam, Kiribati, Marshall Islands, Micronesia (Fed. States of), Nauru, New Caledonia, New Zealand, Niue, Northern Mariana Islands, Palau, Papua New Guinea, Samoa, Solomon Islands, Tokelau, Tonga, Tuvalu, Vanuatu, Wallis and Futuna Islands ***(Population Division of the UN).***

Data on global PR reserves, as well as data on PR production rates are taken from USGS, for the interval 1961, when the model starts, to 2014 (USGS 2016), which is the latest reporting year in “Our World in Data”, used for fertilizer production data. This is used to calculate the compound annual growth rate (CAGR) for this period and assign it further to 2050. Data on fertilizer production is taken from the open source database on fertilizers available from “Our World in Data” for 1961 to 2014. This data was also used to calculate the ratio between PR mining for fertilizer production and the resulting fertilizer production – in other words the units of PR required to produce one unit of phosphate fertilizer. In the model, PR production for fertilizer production is set at a flat 85% of all mined PR, consistent with literature findings (Cordell et al. 2009). The ratio was used to calculate its respective CAGR for 1961-2014, which is assigned further to 2050.

The population submodels for each region are highly simplified and designed only to show the total number of people in any given region, without going into details on age groups. They are used to show the overall dynamics of the population to 2050 and whether it will increase, decrease or remain stable. Data for population submodels was taken from the 2019 Population Division of the UN estimates. The model uses UN data – birth rates and death rates for 1961-2019, and initial population sizes in 1961 – and it runs this trend to 2050. The model does not account for limiting factors like water or food availability.

A CAGR for P requirement based on population is calculated for 1961-2014 with data from the database in Our World in Data. It is undertaken by first dividing the total population in a regional submodel for 1961 and 2014 by the total amount of phosphate fertilizer consumed in 1961 and 2014, respectively. Then, the results are used to calculate CAGR for 1961-2014. For post-2014, the model uses data calculated from the FAO Outlook and relies on FAO‘s CAGR for fertilizer consumption at a regional level. It then carries out the same calculation connected to population, by applying FAO‘s CAGR to predict consumption from 2015 to 2020 and dividing this consumption by the total population as resulting from regional submodels. This new CAGR is used for 2015-2050 to calculate P requirement rates.

In terms of treated wastewater, the model starts “treating” wastewater from 2012, year for which there is data in the literature with regard to wastewater treatment rates. These rates are for high-income countries (70% treatment rates), upper middle-income countries (38%), lower middle-income countries (28%) and low-income countries (8%) (UN 2017). Table A1 indicates what income category is assigned for each world subregion in the model. For 2012-2030, the model calculates a CAGR for wastewater treatment in world regions. It starts from the 2012 levels found in the literature and it assumes that the Sustainable Development Goal (SDG 6 target 6.3) is achieved globally, namely the quantity of untreated water is reduced by halve by 2030 (UN 2017). This CAGR is used from 2030 onwards too – once a region reaches 100% treatment, the model simulation assumes all wastewater is treated to 2050. In order to calculate the amount of recycled P from wastewater, the model sends a signal to world subregions when world requirement for fertilizers exceeds global supply. The recycling sector then starts to develop exponentially in each region, after which it is assumed all P in wastewater is recycled to 2050. The recycled P then flows into the global supply. The model also sends a signal to mine more PR from mines once P requirement surpasses P supply.

The delay in the case of P recycling from wastewater is 10 years, which under current circumstances is an optimistic supposition, in line with the developments in Switzerland (Swiss Federal Council 2015). The increase in mining production, however, is subject to a delay of 5 years, which has been calculated by analysing the operationalisation and plans for future mining facilities for Office Cherifien des Phosphates (OCP), Morocco’s phosphate corporation (OCP 2017).

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