Realising the Circular Phosphorus Economy delivers for Sustainable Development Goals

Michael Walsh[1*], Gerhard Schenk[2], Susanne Schmidt[1]

[1]School of Agriculture and Food Sciences, [2]School of Chemistry and Molecular Biosciences, The University of Queensland, Brisbane, 4067, Queensland, Australia

*author for correspondence mike.walsh@uq.edu.au

ORCID and CRediT:

- Mr. Michael Walsh:
    - 0000-0002-0227-5759
    - Conceptualization, Data curation, Formal analysis, Investigation, Visualization, Writing – original draft
- Prof. Gerhard Schenk:
    - 0000-0001-8619-0631
    - Supervision, Writing – review & editing
- Prof. Susanne Schmidt:
    - 0000-0001-8369-1238
    - Supervision, Writing – review & editing

Key Points

1) The Linear Phosphorus Economy (LPE) threatens food sovereignty, environmental integrity, and public health
2) A transition away from an LPE into phosphorus circularity requires innovation and institutional support
3) Adopting a Circular Phosphorus Economy (CPE) contributes to numerous Sustainable Development Goals

Abstract

While it remains debated if the mineral deposits mined for phosphorus fertilizer are running out, phosphorus insecurity is an emerging global issue. We explore how it is linked to the current linear phosphorus economy (LPE) and the historic and current implications. The problems are multifold: there are geopolitical concerns over phosphorus deposits held only by a few nations, sharply rising costs of phosphorus fertilizers, heavy metal contaminants affecting soil and food, problematic phosphorus mining wastes, and the widespread environmental degradation caused by fertilizer inefficiencies. A new phosphorus economy can resolve these problems. Transitioning to a sustainable use of phosphorus demands a circular phosphorus economy (CPE). A CPE supports several Sustainable Development Goals and enables countries without phosphorus deposits to achieve greater phosphorus autonomy. We illustrate current problems with case studies and outline opportunities for change. The CPE will feature phosphorus recovery facilities, waste valorisation technologies, and improved fertilizer formulations that are customised to crop systems. We highlight examples of the rapidly advancing CPE that forms an integral part of the bioeconomy and the circular economy.

Index terms

1) 0215 Economic Geology
2) 0402 Agricultural Systems
3) 0439 Ecosystems, structure and dynamics (4815)
4) 0470 Nutrients and nutrient cycling (4845, 4850)
5) 0478 Pollution: urban, regional and global (0345, 4251, 5325)

Keywords

1) Phosphorus, Food security, Bioeconomy, Sustainable agriculture, Circular Nutrient Economy, Circular Phosphorus Economy

1. Introduction

Phosphorus (P), a focal point of economic, agricultural, and environmental challenges, is an essential, non-substitutable element required for all life on Earth. It is a central component of biochemicals such as DNA, cell membranes and proteins, a functional element for cellular energy cycles and the structural integrity of bones, stems and root systems (Plaxton & Lambers, 2015). In nature, P originates from the biogeochemical breakdown of parent material (rock) to form soils and sediments. Slow P regeneration via rock weathering and nutrient cycling, together with P losses through erosion and leaching, result in infertile soils over long geological times (Lizcano-Toledo et al., 2021). Much of the soils' P occurs as mineral or organic complexes with varying degrees of bioavailability. Because P bioavailability often limits crop growth, soils must be supplemented with P. Conventional high-production farming mostly uses mineral P-fertilizers (we use the term 'chemical' to distinguish other P form). The most common chemical P-fertilizers consist of immediately bioavailable formulations derived from P-rich mineral deposits which undergo physical and chemical processing. The efficiency of these chemical fertilizers is however low. It is estimated that approximately 70% of the 45 million tonnes of P fertilizer applied to soils annually are not used by crops (Brownlie et al., 2021; FAO, 2021b). Fertilizer is converted into largely inaccessible 'legacy P' in agricultural soils or lost from soil, polluting the hydrosphere. Thus, from mining and agriculture to human consumption, it is estimated that in total 95% of P is lost to inefficient utilization, epitomizing the current Linear Phosphorus Economy (LPE) (Geissler et al., 2018).

The inefficiencies associated with chemical P-fertilizers and P-containing wastes come at a cost. They have caused (i) global biogeochemical flows to push beyond the safe planetary boundaries (Steffen et al., 2015) and (ii) the circulation and accumulation of heavy metals (cadmium, uranium, lead, mercury) in agricultural soils and food (Kubier et al., 2019). Furthermore, they have caused imbalances that contribute to soil degradation and acidification (Lal, 2015). Despite these profound consequences, a level of apathy prevails regarding mineral deposits and P-fertilizer industries, which are characterized by monopolized markets, commodity exploitation and lower food production capacity in vulnerable nations (Cordell et al., 2021; Mayer et al., 2016; Schnug & De Kok, 2016). Furthermore, achieving the Sustainable Development Goals (SDG) in developing nations through adopting an LPE framework places greater pressures on an already fragile system (Prăvălie et al., 2021) and a heavy price on planetary boundaries (Randers et al., 2019).

Many of the 17 SDGs interconnect with agriculture, food security and environmental integrity (Brooks, 2016; El Wali et al., 2021). However, it has highlighted how difficult it will be to achieve the SDGs by 2030 with current strategies (Kruk et al., 2018; Leal Filho et al., 2018; Sachs et al., 2019; Salvia et al., 2019) while maintaining favorable economic, environmental, and social symbiosis (Ibeh & Walmsley, 2021). To achieve SDG targets, "urgent" and "bold" interventions are required (United Nations, 2019). In recent years, an increase in political conflicts, climate change and the Covid-19 pandemic have led to stagnation and, in some cases, to regression of SDG advancements (Sachs et al., 2021). Extreme poverty has increased for the first time in two decades (World Bank, 2020), with almost 1 billion people going hungry and the cost of food rapidly rising (FAO, 2021a; Laganda, 2021). Only one quarter of countries are on track to meet their 2030 child malnutrition targets (WHO, 2021), while 17% of global food is wasted (UNEP, 2021). Furthermore, the expansion of croplands, which cover 12-14% of the world's ice-free surface, is forecast to further exacerbate biodiversity loss (Shukla et al., 2019; Zabel et al., 2019). Compounding the hurdles to achieving the SDG targets, the Covid-19 pandemic is expected to cause foreign investments to fall sharply and strongly impact developing countries (Giroud & Ivarsson, 2020). Together, these problems points to the urgent need for the current LPE to pivot into a framework of circularity and sustainability.

Drawing on historic and current circumstances, we explore the implications of the current LPE and possible strategies to transition into a Circular Phosphorus Economy (CPE). With principal themes of foreign market dependency, environmental degradation, and human health, we aim to illustrate these themes with case studies at country or region level. We address the SDGs with the four pillars of sustainable systems - governance, social, environment and economy - as a foundation for the CPE. Further, we outline the challenges and opportunities associated with a CPE to overcome initial investment limitations, support domestic nutrient autarky, optimise agricultural autonomy, and promote environmental integrity relative to SDG targets. Lastly, we summarise the challenges and opportunities associated with the successful adoption of a CPE.

2. Foreign market dependency – scarcity or insecurity?

Largely defined by improvements to crop genetics, crop management and the widespread adoption of chemical fertilizers, the Green Revolution commencing in the 1950s represented an inflection point for the rapid increase of agricultural productivity. Unlike synthetic nitrogen fertilizers that are generated through the conversion of atmospheric di-nitrogen gas, chemical P-fertilizers are manufactured by extracting and processing a finite supply of rock phosphate. Although rock phosphate deposits occur globally, 90% are inaccessible due to technological or economic limitations (Köhn et al., 2018), and the economically exploitable P deposits (reserves) are becoming increasingly monopolized and depleted (Brownlie et al., 2021; Cordell, 2013; Nassar et al., 2020).

Since the Green Revolution, food insecurity has largely affected developing nations, but the rapidly increasing human population, climate change and depleting resources, including declining availability of fertile land, has provoked a global food insecurity (Bobba et al., 2020; Hayes & McCullough, 2018; Wackernagel et al., 2021). Sustaining food production demands P fertilizers to replenish the P removed during harvest, and some scholars consider the monopolisation of the world's sporadically distributed P reserves as one of the greatest challenges facing humanity today (Cordell, 2013; Cordell & White, 2014; Nassar et al., 2020; Reijnders, 2014). A priority concern is the geopolitical positioning and trade agreements which have centralized control over domestic and international P trade and will likely intensify in the future (Nassar et al., 2020). Recent events reveal how the LPE influences price hikes and capitalises on global supply shortages. This caused a decline in P fertilizer use (FAOSTAT, 2021a) , a rise in global food prices (FAO, 2021a), and sadly, tragic increases in farmer suicides in highly impacted regions (Cordell et al., 2009).

For "*those who cannot remember the past are condemned to repeat it"* (Santayana, 1910), the story of Nauru may serve as a warning. Nauru, a once pristine Pacific island that gained colonial attention in 1905 due to its vast deposits of P-rich seabird guano. Subsequent extensive guano mining stripped off over 83% of Nauru's land surface with catastrophic environmental consequences that have left much of is island degraded and devoid of vegetation (Gale, 2016; Kawatra & Carlson, 2013). Guano and its volatile market trading prices and bottlenecks, controlled and manipulated by a monopolized industry (Australian Parliment, 2009), eventually caused an abrupt market shortage and a decline in market share (Ulrich & Frossard, 2014). Once deemed the nation with the highest GDP *per capita* in the world, the economy of Nauru collapsed following the exhaustion of guano deposits in 2004 (Fenner, 2019).

While Nauru mirrors the fate of other Pacific islands and the Meso-American West Coast, where seabird-deposited guano has long been mined for fertilizer, most P-fertilizer originates from rock phosphate (Cordell et al., 2009). Leading up to the 2008 global financial crisis, the cost of rock phosphate and fertilizer commodities abruptly rose by approximately 800% (Figure 1). This coincided with a 25% Real Food Price Index increase during the same period (FAO, 2021a). Although this phenomenon has yet to be "completely understood" (Khabarov & Obersteiner, 2017), it is likely a compounding combination of global factors that include a steady growth in East Asian middle-class and associated demand for resource-intensive foods (Tie-jun, 2008), India's import policy in 2007 encouraging the import and use of fertilizer (Khabarov & Obersteiner, 2017), the USA's renewable energy production and consumption policy stimulating plant-based biofuel production (Sissine, 2007), record oil prices in 2007 increasing P fertilizer production and transportation costs (Hamilton, 2009), China's response to global market disarray by imposing a 135% tariff on fertilizer exports (Cordell et al., 2015), and the aforementioned factors heightening market speculation and manipulation (*i.e.*, commodity hoarding). This 2007-08 episode has stressed the inability of rigid markets to adapt and meet higher demands while simultaneously profiting on the very shortfalls it created.

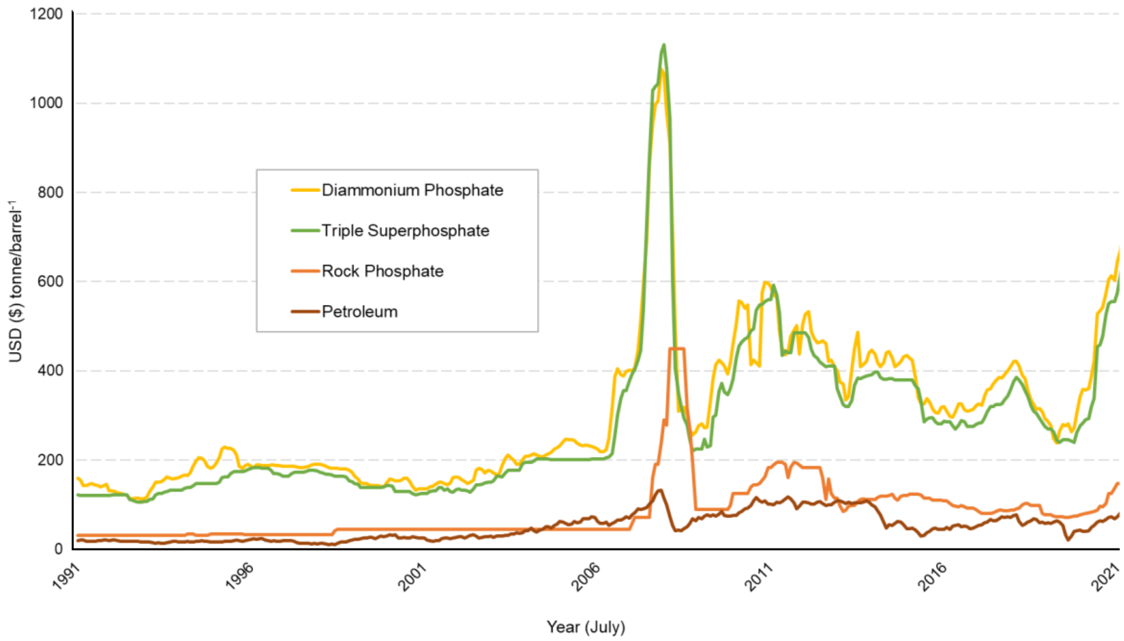


Figure 1 A 30-year period of global price respective to phosphorus commodites (USD tonne^{-1}) rock phosphate (orange), triple superphosphate (green), diammonium phosphate (yellow), and petrolum (USD barrel^{-1}) (maroon) (IndexMundi, 2021). The sharp price hike in 2007-08 was only mitigated shortly after the Global Financial Crisis. Prices of phosphorus commodies are yet to fall back and stabilise to pre 2007-08 price hike prixes. Commodites since the Global Financial Crisis are in a constant state of flux causing much unpredictability. Prices have sharply risen begenning July 2020 to November 2021 and continue on an upward trend.

The United States Geological Survey (2021) details the monopoly of global national rock phosphate reserve ownership and rock phosphate mine production (

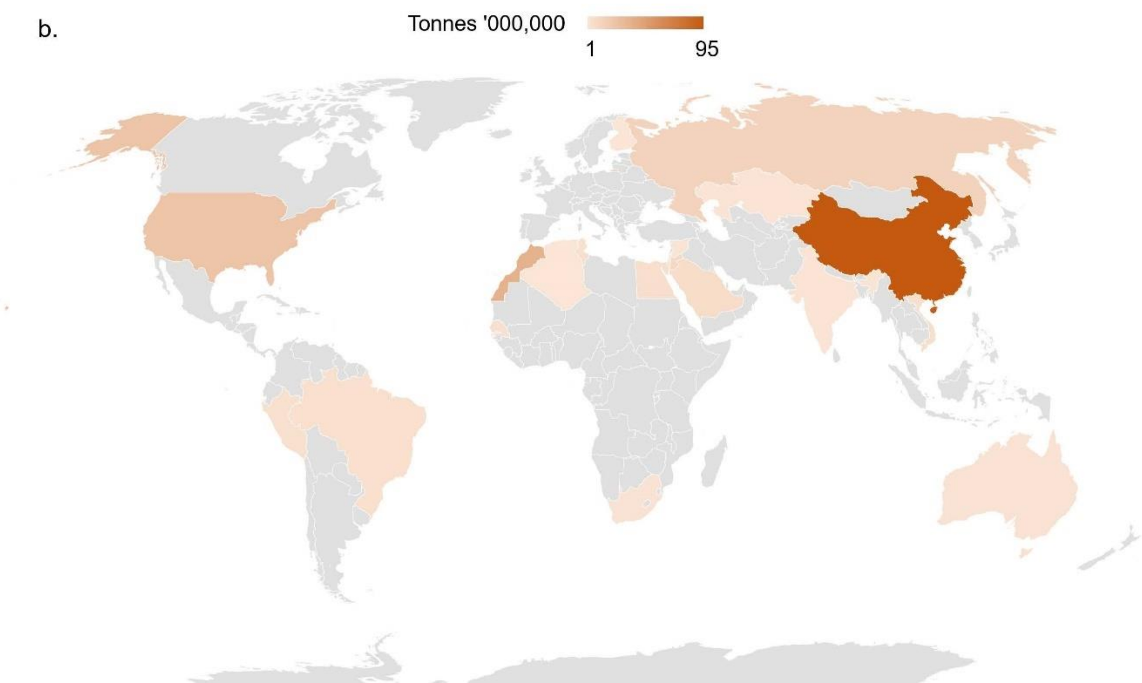
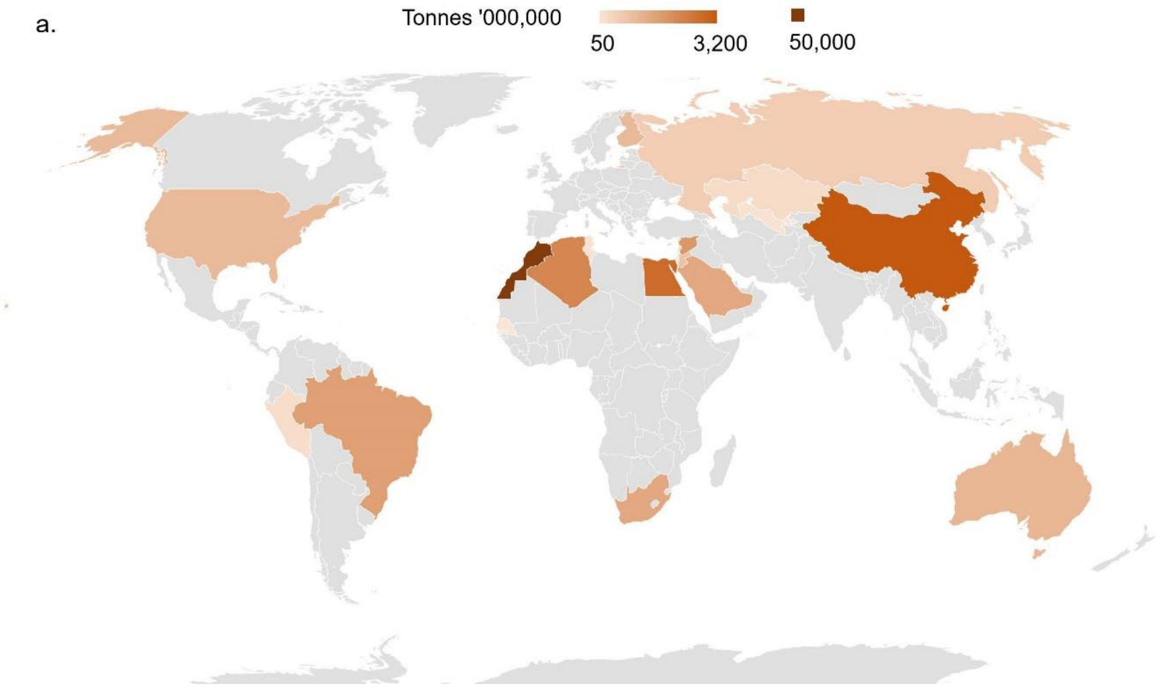


Figure *2*). The reserve quantity of the top holding entities, Morocco and Western Sahara, China and Egypt, account for over 78% of the global reserves, and together with the USA, they generate 70% of total global production. Within Europe, only Finland has notable reserves and mine production (representing 1.4% and 0.43% of the global total, respectively). The rest of the EU and Britain are reliant on importing P-fertilizers or rock phosphate for their domestic fertilizer production industry (Geissler et al., 2019). In the USA, rock phosphate deposits represent 1.4% of global reserves and account for 10% of global output (USGS, 2021), although their reserves are expected to become depleted within the upcoming decades (Jasinski, 2014). Florida's ore grade, the USA's major rock phosphate-producing state, has been declining since the exhaustion of higher grade northern deposits and supplanted by the lower grade southern deposits (Steiner et al., 2015; Zhang, 2019). The USA's declining presence and contribution to the global markets (rock phosphate and P-fertilizers) has increased their import demand (Figure 3 a-b) (USGS, 2021) to supplement national P-fertilizer use (Figure 3 c) (FAOSTAT, 2021a). Declining P fertilizer exports from the USA and concomitant increase in imports may further monopolise producers such as China and Morocco, thus exacerbating geopolitical leveraging and commodity supply chain instabilities.

A recognized problem is that the rock phosphate industry has a long history of providing incomplete datasets (Ulrich & Frossard, 2014) and often overestimating reserve data (Cordell

& Neset, 2014; Geissler et al., 2015). The lack of transparency concerning reserves, resources and ore grades prevents a holistic understanding of the LPE and subsequently reduces our ability to accurately plan for the future (Cordell et al., 2009; De Ridder et al., 2012; Ulrich & Frossard, 2014; Van Kauwenbergh et al., 2013). Shortly after '*The story of phosphorus: global food security and food for thought'* (Cordell et al., 2009) was published, Morocco and Western Sahara revaluated and increased their reserve estimations by 877% from 5,700 to 50,000 million tonnes (USGS, 2011). These estimations did not comply with standardized geological reporting used by the geoscience governing bodies of the United Nations (Kommission et al., 2015), USA (USGS, 2021), Australia (JORC, 2012) and Britain (BGS, 2015), drawing criticism over its legitimacy (Edixhoven et al., 2014). Rather than fostering transparency, reserve data and information disclosed by the Moroccan rock phosphate industry remains, however, ambiguous.



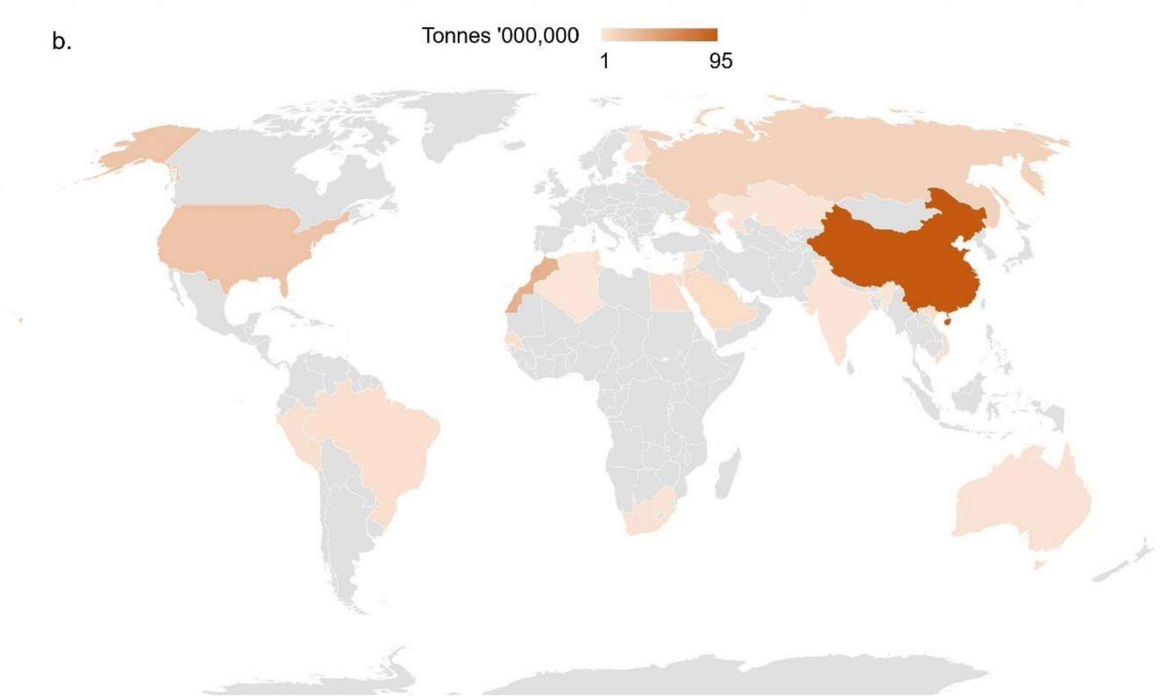
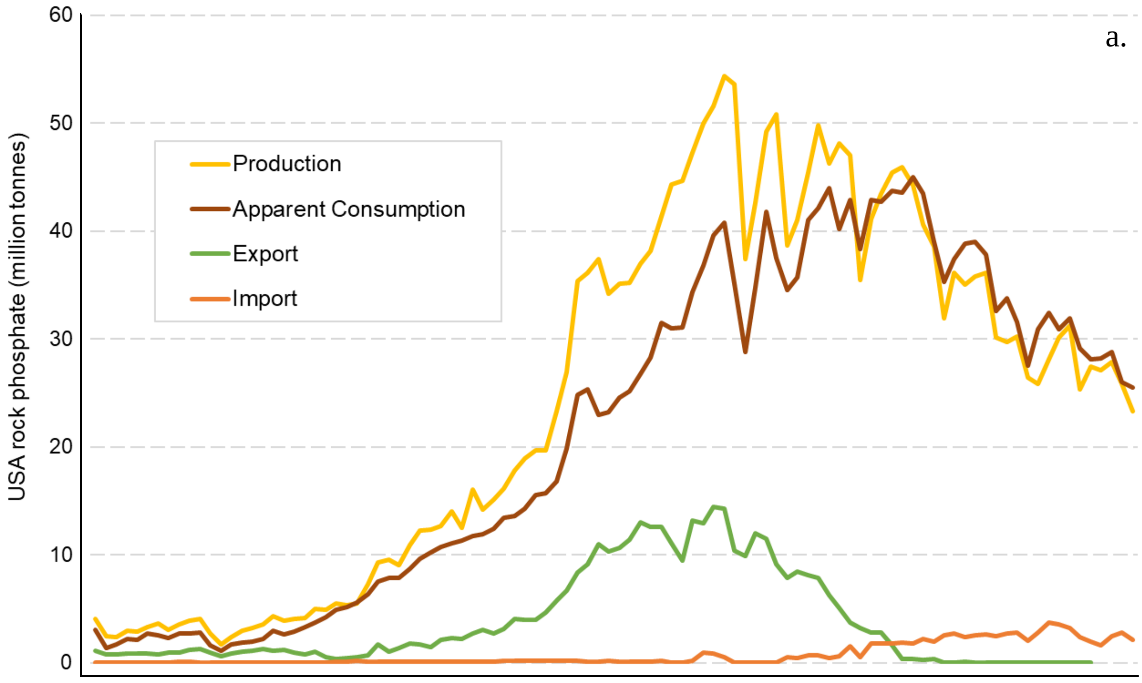


Figure 2 a) Global rock phosphate reserves in the leading 20 countries in 2019 (million metric tonnes) (USGS, 2021) b) Global rock phosphate mined from reserves in the leading 20 countries in 2019 (million metric tonnes) (USGS, 2021)



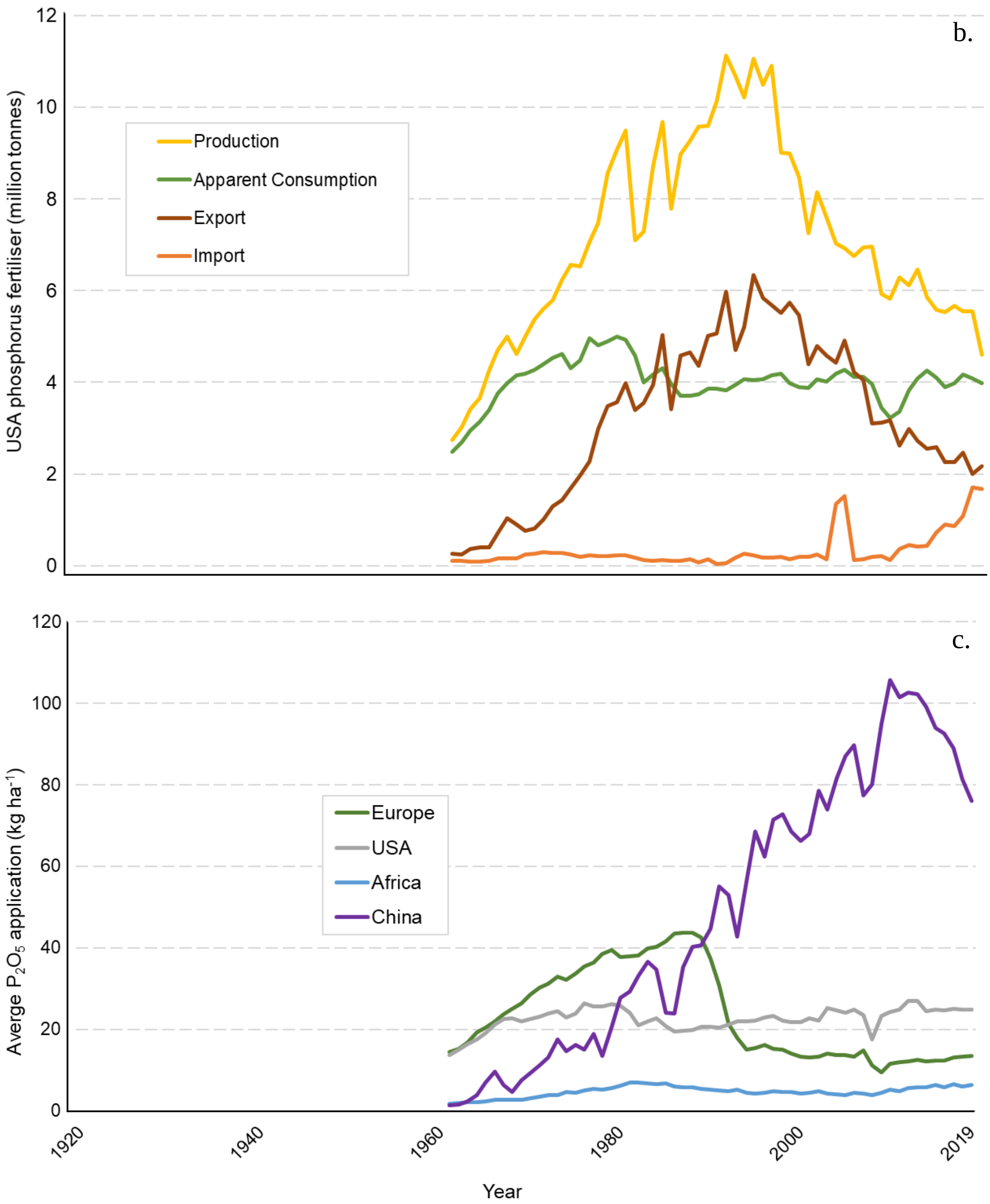


Figure 3 Global trends in rock phosphate and P-fertiliser from 1920-2019 a) USA's rock phosphate industry; b) USA's P-fertiliser industry; c) Average P-fertiliser use of Europe, USA, Africa and China from 1960-2019 (Buckingham & Jasinski, 2020; FAOSTAT, 2021a; USGS, 2021).

Moroccan deposits and mine production are solely owned and operated by the Office Chérifien des Phosphates, which itself is owned by the Moroccan government (95%) and the Banque Populaire du Maroc (5%) (OCP, 2021). Unlike publicly listed companies that disclose deposit grades and quantities to attract investment, shareholders, and trade alliances, or adhere to international standards and public disclosure policies, the Office Chérifien des Phosphates is not obliged to provide such information. Morocco has made two amendments to their reserve estimations since 1994 (Figure 4) (USGS, 2021), which is substantially less compared to that of other major reserve holders such as Australia, China, USA and Jordan (9, 8, 7 and 7 amendments, respectively). A portion of Morocco's reserves reside in the geographically contested region at the Western Sahara border (Allan & Ojeda-García, 2021). The region was annexed by Morocco in 1975 and de-escalated 16-years later through a UN-brokered truce promising regional independence (United Nations, 2020). International discussions, however, continue debating the ethics of extracting rock phosphate in mines located in the contested region of Boucraa (Irwin, 2021; Kutz, 2021). In 2017, two Moroccan cargo ships containing rock phosphate mined at this location were stopped and detained on route by South Africa and Panama on the grounds of cargo illegalities (Ruys, 2019). In December 2020, the Trump Administration's decision to recognise Morocco's claim over the region was widely criticised

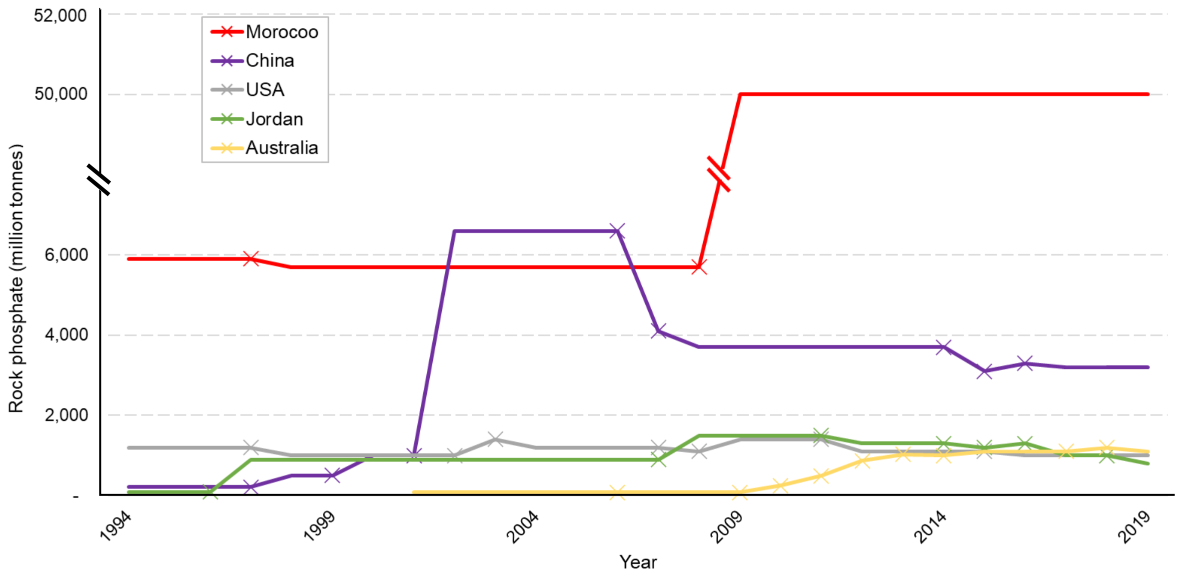


Figure 4 History of amendments to rock phosphate reserve estimations per country (USGS, 2021). Crosses along the coloured lines indicate time points of the amendments respective to the individual country. Since 1994, Morocco and Western Sahara, China, USA, Jordan, and Australia have amended their reserve data 2, 8, 7, 7, and 9 times, respectively.

and was met with considerable resistance from the African Union, neighboring Algeria and Sahrawians (Bradley, 2021). The above examples illustrate the problems relating to the reporting, exploitation and trading of P reserves and fertilizers. They also highlight the lack of industry transparency, the hazards of deposits residing in disputed territories, the exacerbation of monopolized markets and their evident fragility illustrates the P insecurity for many nations reliant on imports worldwide.

3. Environmental soil degradation soil and phosphorus management

There is global consensus on recognizing the fundamental role of soil in safeguarding sustainable food production and environmental integrity (FAO et al., 2020). Considered a non-renewable resource due to slow regenerative processes (Pennock et al., 2015), soil preservation and integrity must become an essential component of circular agriculture frameworks. Currently, poor land use management and unsustainable agricultural practises are causing soil degradation and decrease our ability to produce food (Dubois, 2011; Prăvălie et al., 2021). Following aridity, soil erosion is the single greatest factor responsible for soil degradation in agricultural land (Prăvălie et al., 2021) and a primary cause of P flows into waterways. Intensive agriculture can cause soils to erode at a rate up to 1000-times that of natural rates (Pennock et al., 2015) and, as a consequence, a global average of 5.9 kg P per hectare is lost to the hydrosphere every year (Alewell et al., 2020). Tillage, nutrient stoichiometric imbalances and harvesting are major anthropogenic causes inducing soil erosion (Lehman et al., 2015). In Europe alone, harvesting crops causes 14.7 million tonnes of soil loss every year (Panagos et al., 2019).

Soil and nutrient loss from agricultural land and inadequate sewage treatment are primary factors for the disruption of marine nutrient cycles (Malone & Newton, 2020; Withers et al., 2019). The impact of P pollution in marine systems manifests in many regions. Examples are the infestations of coral-predating Crown of Thorns starfish in Australia’s Great Barrier Reef and toxic algal red tides along Florida’s coastline, killing marine life and causing other detrimental effects (Brodie et al., 2017). In the Baltic Sea, partial or complete cessation of P and other nutrient inputs are predicted to take centuries before pre-anthropogenic conditions are reached (McCrackin et al., 2017). Anthropogenically-induced eutrophication is responsible for coastal ecological degradation and is considered as one of the greatest threats to marine ecosystems worldwide (Malone & Newton, 2020), thus demanding the strict management of nutrient inputs and the development of water quality strategies to mitigate the rapid deterioration of coral reefs (Chazottes et al., 2017; Withers et al., 2019; Wooldridge, 2020). The projected increase in global demands for food, energy, clean water and waste will, however, exacerbate anthropogenic pollution and place even greater stress on fragile aquatic ecosystems (Glibert, 2020; Randers et al., 2019).

Algal blooms (*i.e.*, green tides, red tides, phototropic blooms) are the result of nutrient enrichment caused by agricultural run-off, municipal and industrial waste, aquaculture and biogenic recycling (Figure 5) (Gladyshev & Gubelit, 2019). Correlating with the initiation of intense farming and the use of chemical fertilizers, the first recorded instances of anthropogenic eutrophication in the Baltic Sea commenced in the 1950s (Andersen et al., 2017). Today approximately 22,000 tonnes of P flow into the Baltic Sea annually (Svendsen & Gustafsson, 2020). Although localized eutrophication management commenced in the 1980s, the low burial and high remobilization potential of deep biogeochemical P sediments are largely responsible for reoccurring green tide cycles (Kuliński et al., 2021; Savchuk, 2018). The biochemical breakdown of algae during nightfall causes a reduction in dissolved oxygen creating hypoxic conditions (*i.e.*, dead zones). Dead zones in the Baltic Sea are estimated to impact an area of similar size to that of Ireland (Meier et al., 2019). If nutrient reduction is met according to the

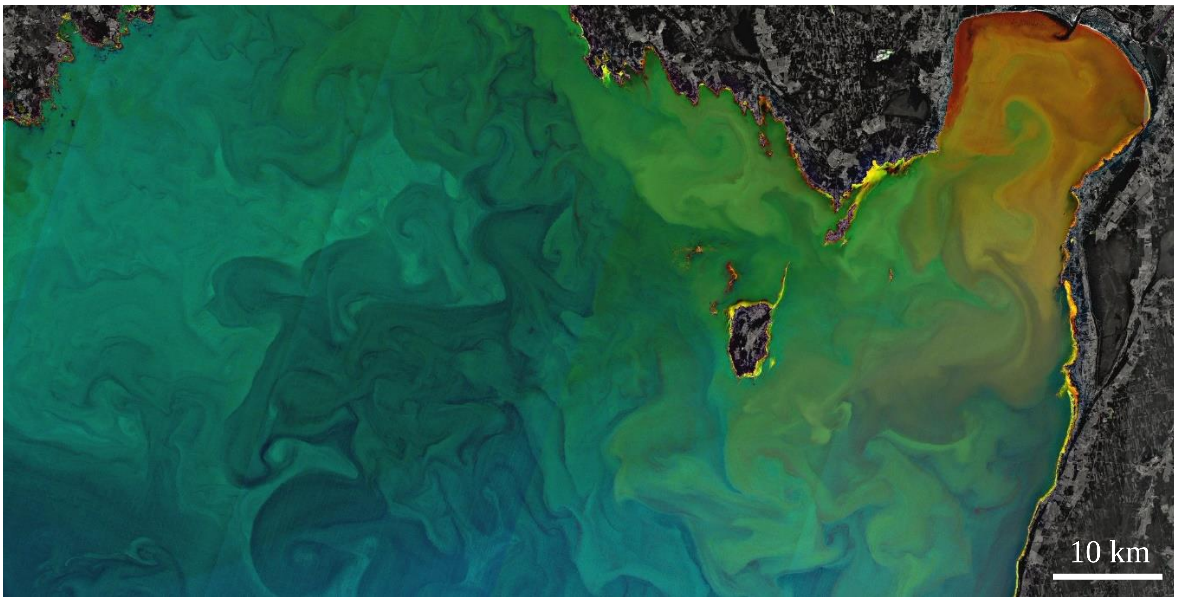


Figure 5 Satellite image showing eutrophication caused by nutrient rich run-off from neighbouring countries Estonia and Latvia in the Gulf of Riga, Baltic Sea (image credit: European Union - contains modified Copernicus Sentinel data [2020]. The image is reproduced with permission from Valters Žeižis).

Baltic Sea Action Plan (2007), most of its oceanic basins are forecast to become clean from eutrophication in 180 years (Murray et al., 2019).

The accumulation of reactive P in the biosphere is a global problem and is likely to magnify considering world fertilizer trends (P, nitrogen, potassium) experienced a 33% increase from 141.7 to 188.5 Mt between 2002 and 2019 (FAOSTAT, 2021a) in parallel to rising food demands. The European Commission's strategy to combat nutrient loading will require the reduction of fertilizer use by 20% by 2030 (European Commission, 2020). Achieving this through preventing P fertilizer inefficiencies and avoiding losses from agricultural soils requires innovative strategies, some of which we outline in later sections.

4. Heavy metal contaminants in phosphorus deposits and fertilizers

Sedimentary rock phosphate, geologically distinctive from its counterpart igneous rock phosphate, constitutes the major deposits in China, Morocco and the USA (USGS, 2021). Sedimentary rock phosphate contains varying levels of toxic heavy metals including cadmium, uranium, mercury and lead (De Boer et al., 2019). The production of phosphoric acid, the chemical precursor for commercial triple superphosphate fertilizer and other P fertilizer blends, is produced through the physical and chemical treatment of rock phosphate to remove constituent undesirable minerals (Revuelta, 2018; Wingate & Kohmuench, 2016). The process of removing predominant constituent minerals, notably different from extracting P as a pure element, causes associated heavy metal contaminants to remain within the fertilizers. The concentrations of these contaminants vary depending on the parent ore and fertilizer manufacturing processes (Gray et al., 1999; Kratz et al., 2016). There are currently no economically viable methods or technologies to remove these heavy metals from the ore and consequently up to 80% supersedes into the phosphoric acid (Kouzbour et al., 2019). Contaminants such as cadmium and uranium are considered to have the most detrimental effects for toxicity, accumulation in soils, plant bioavailability and leaching potential (Taylor et al., 2016). Here we focus on cadmium due to its recognized consequences for public health.

Cadmium is considered a non-threshold toxin which can induce negative health effects at low concentrations (CDC, 2017; Rahman & Singh, 2019). Exposure can have grave effects including kidney disease, cancer and, in some cases, death (Adams & Newcomb, 2014; WHO, 2019a). The extent of cadmium exposure is largely determined by an individual's smoking status, dietary habits and consumption of foods produced in proximity to cadmium pollution (Pizzol et al., 2014; WHO, 2000). In Europe, approximately 45-60% of soil cadmium derives from P-fertilizers and 55% of human cadmium exposure originates from consuming contaminated foods (Smolders, 2017; Ulrich, 2019).

Although native geogenic concentrations of cadmium in soils vary, its presence in soils and water is largely associated with soil applications including chemical P-fertilizer, manures, wastewater and biosolids, and also atmospheric deposition from industrial processing (Hou et al., 2020; Kubier et al., 2019). With a high solubility and desorption potential, cadmium is one of the most mobile heavy metals in soils, a primary reason for its high bioavailability to plants and fast migration into groundwater (Kubier et al., 2019; Nino-Savala et al., 2019). Promisingly, cadmium concentrations in the upper layers of European soils are decreasing as less P-fertilizer is applied (Figure 3C) and regulations on industry emissions have tightened, although clear trends are still difficult to establish due to variable data (Smolders, 2017). Furthermore, since cadmium bioavailability increases with soil acidity (FAOSTAT, 2021a; Shahid et al., 2016), and agricultural soils acidify with unsustainable practices (Tkaczyk et al., 2020), formerly inaccessible cadmium in soils may become bioavailable, stressing the importance of comprehensive risk mitigation strategies. A comparison between Europe and the USA illustrates the complexity of the problem. While the average application of P-fertilizer by farmers in the USA has remained relatively constant since the 1970s (Figure 2C) (Adams & Newcomb, 2014; Kowal et al., 1979), it has substantially declined in Europe since the early 1990s (FAOSTAT, 2021a). Furthermore, cadmium levels *via* aerosols in Europe have reduced four-fold since the 1960s (Smolders & Six, 2013). Thus, the combined impact of decreased input from aerosols and P-fertilizers over several decades would be anticipated to lead to a decrease in cadmium concentrations in European topsoils. However, no clear decrease in the bioavailability of cadmium is apparent (
Figure *6*).

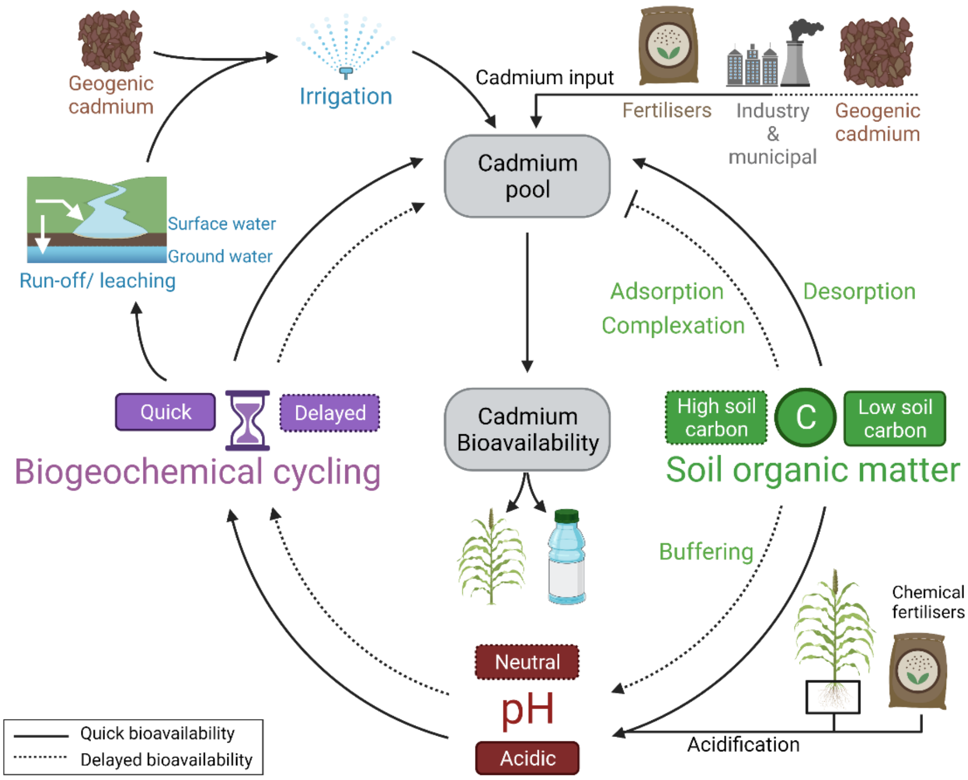


Figure 6 Conditions influencing the plant bioavailability and mobility of cadmium in soils. The dotted lines represent a delay in the biogeochemical cycle. The solid line represents the potential hastening of cadmium's biogeochemical cycling agriculture. The arrow direction represents the feedback direction. Inputs into the cadmium pool include phosphorus fertilisers, industry and municipal aerosols and waste, natural geogenic deposits, and irrigation using contaminated water. The primary contributing factors of cadmium bioavailability influenced by anthropogenic farming is soil carbon, pH, and input.

The risks associated with dietary cadmium exposure is amplified for individuals in developing nations, especially in women and children (CDC, 2017; Kowal et al., 1979). Largely determined by lower iron reserves, gastrointestinal absorption of cadmium is twice as high for women than men (10% and 5% absorption rates, respectively), and up to 15% for anaemic individuals (CDC, 2017; Nordberg, 2004; WHO, 2000). In areas such as Africa, over 30% of women suffer from anaemia due to dietary limitations (FAO et al., 2021). Therefore, using P-fertilizers contaminated with cadmium will likely increase the rate of exposure and further exacerbate health complications in compromised populations. However, it needs to be re-iterated that cadmium exposure is not limited to the developing world. Although data of increasing levels of cadmium exposure over time in Europe are still largely inconclusive

(Lundh et al., 2016), a recent analysis found cadmium levels in French citizens are still above national health recommendations in almost half the population (Oleko Amivi et al., 2021).

Since 2015, China has pursued a ‘Zero Increase of Fertilizer Use’ strategy to flatline the extremely high use of chemical fertilizers and reduce the environmental and health consequences of over-fertilization (Ji et al., 2020). Cadmium is considered China’s most abundant inorganic soil pollutant (MEP, 2014) with 10-50% higher average concentrations than native geogenic levels since analyses began in 1986 (L. Wang et al., 2015). Cadmium analysis in North China soils identified P-fertilization as the primary factor to the 41-62% increase in cadmium concentrations from 1989 to 2009 (Qi et al., 2018). On a national level, P-fertilizers are recognized as a primary cause of cadmium contamination of China’s soil (Nino-Savala et al., 2019), which correlates with the steady and comparatively steep rise in the average use from 41 to 95 kg ha^{-1} over the same period of time (Figure 3C) (FAOSTAT, 2021a).

Due to the known consequences of contaminated P-fertilizers, the European Commission has proposed a universal limit on cadmium concentrations to 60 mg Cd/kg P_2O_5, with a tiered reduction to a maximum of 20 mg Cd/kg P_2O_5 by 2032 (Ulrich, 2019). The proposal has been met with some resistance by the fertilizer industry stating the reduction plan is “impossible” (Fertilizers Europe, 2017). A review conducted by Bloem et al. (2017) found average cadmium concentrations in mineral P-fertilizers sold in Europe ranging from 32-348 mg Cd/kg P_2O_5. Furthermore, other OECD countries have been slow to adopt similar regulations. California (the USA’s most regulated state for P-fertilizer contamination) has set its limit to 400 mg Cd/kg P_2O_5 (CDFA, 2020), and Australian states and territories have adopted a voluntary limit of 644 mg Cd/kg P_2O_5 (Warne et al., 2007). Considering these vastly different standards and practices, and keeping in mind the significant health hazard posed by cadmium, it is now imperative that a global approach is developed to minimize heavy metal contaminants in P-fertilizers.

5. Wastes from phosphorus fertilizer production

Current technologies to process rock phosphate for the manufacture of chemical P-fertilizers are plagued by inefficiencies and waste production. Depending on the ore grade and processing technology, P recovery from rock phosphate ranges from 65-90% (Ruan et al., 2019). This is a substantial improvement from pre-1990s recovery rates of 40.5-79% (Van Kauwenbergh et al., 2013). However, while some technologies can increase P recovery to more than 95% (Günther et al., 2018; Hobert et al., 2020; Wingate & Kohmuench, 2016), implementing them on an industrial scale presents theoretical and practical challenges (Wingate & Kohmuench, 2016). Industry standards generally require the beneficiation of low to medium grade ores to improve P concentrations, which inevitably increases production costs, energy demand and associated waste (Steen, 1998).

The process of manufacturing chemical P-fertilizers involves the mixing of crushed rock phosphate with sulfuric acid to produce phosphoric acid, the base ingredient required for P-fertilizers such as superphosphates, mono- and di-ammonium-phosphate. During the process of phosphoric acid production, the hazardous waste by-product phosphogypsum, hydrated calcium sulfate, is produced at a quantity 5-times that of phosphoric acid (Taylor et al., 2016). In Europe and the USA, disposal of phosphogypsum into waterways has been outlawed due to the associated environmental impacts (Environmental Protection Agency, 2021). In 2010, the European Commission sent Spain a final warning concerning Rio Tinto's illegal dumping of 120 million tonnes of phosphogypsum into a local waterbody (European Commission, 2010). It is reported that a portion of Morocco's operations still disposes their phosphogypsum into the Atlantic Ocean (Taylor et al., 2016). Globally, approximately 10% of phosphogypsum is dumped into marine environments (Jupp et al., 2021) which equates to 16 million tonnes per year (Rashad, 2017).

Phosphogypsum has minimal recycling utility due to its contaminants including cadmium, uranium, and other radionuclides. The USA's phosphogypsum waste is held in over 70 mountainous 'stacks' up to 3.2 km long and 60 m high (EPA, 2021). In 2005, Florida, the USA's primary rock phosphate mining and fertilizer-producing state, has 1.1 billion tonnes of phosphogypsum spread over 1820 km^2 (Taylor et al., 2016). The high solubility of phosphogypsum, its leaching potential, acidity, combined with its poor management by the industry has caused numerous environmental disasters. Since 1994, leaching, sink holes, stack breakages and overflows have caused water contamination and polluted drinking reservoirs, aquifers and waterways (Taylor et al., 2016). In 2015, the EPA and Florida's environmental agencies successfully sued the largest operating company, Mosaic, for US$1.8 billion for law violations, clean-up costs and future mitigation strategies (EPA, 2015). In 2021, the Governor of Florida declared a State of Emergency and evacuated local residents when a fragile phosphogypsum stack holding 2.3 billion liters of fluid was on the verge of collapse (Center for Biological Diversity, 2021; FDEP, 2021).

The ongoing legacy of mining waste that is disposed into waterbodies or stored over large areas of land is clearly of concern. Where regulators can instigate and enforce change, marine pollution through the dumping of phosphogypsum can be prevented, although storage on land, as the Florida example shows, is not an adequate alternative. The cost of such waste disposal practices should be considered as part of the negative externalities of the LPE.

6. Reimagining phosphorus in a circular phosphorus economy

Orchestrating a P framework which sustains humanity throughout the 21st century and beyond will require the transition into a CPE. This must be achieved through greater agricultural efficiencies, soil management strategies and adoption of circular P technologies (Garske & Ekardt, 2021; Köhn et al., 2018; Koppelaar & Weikard, 2013; Lal, 2015; Mogollón et al., 2021; Smol et al., 2020; Van Vuuren et al., 2010; Withers, 2019). It will take careful deliberation how best to achieve an intersect between high agricultural demand and output through a circular framework while maintaining environmental integrity and economic feasibility (Gerten et al., 2020; Hebinck et al., 2021; McDowell et al., 2020; Mogollón et al., 2021; Walsh, 2021). This must, however, be a priority for global objectives to reduce the ongoing cropland expansion into natural ecosystems, which target fertile lands in critical areas hosting concentrated levels of clean water, biodiversity and carbon stocks (Jung et al., 2021).

The continued use of chemical P-fertilizers combined with the likelihood of increasing extreme weather events caused by climate change has strong potential to lead to even higher rates of P losses from soil due to intensified erosion (Ockenden et al., 2017), and exacerbate the degradation of marine ecosystems and the loss of biodiversity (Meier et al., 2012; Takolander et al., 2017). Therefore, improving P efficiency in agriculture must be a central consideration for all societies and nations.

Advancing the CPE requires innovative measures to successfully implement a framework required for achieving circularity. A proposed strategy to alleviate foreign market dependency, environmental degradation and public health deterioration can be achieved through adopting such a framework (
Figure *7*). This interconnected system aims to achieve three primary goals, (i) Food Sovereignty, (ii) P Autonomy and (iii) Ecosystem Preservation, which are facilitated by three principal levers: (a) Nutrient Recovery Facilities, (b) Valorisation Technologies and (c) Sustainable Agriculture and Soil Management strategies. A CPE will support several SDGs, *i.e.*, Zero Hunger (2), Clean Water and Sanitation (6), Decent Work and Economic Growth (8), Life Below Water (14) and Partnerships for the Goals (17). Furthermore, the CPE contributes to achieving No Poverty (1), Good Health and Well-Being (3), Industry, Innovation, and Infrastructure (9), Sustainable Cities and Communities (11), Responsible Consumption and Production (12) and Life on Land (15) (see Supporting Information, Table 1). The successful transition into a CPE will, however, require the addressing of existing endemic economic, technological, and agronomic constraints. Below we elaborate on the three principal levers.

6.1. Nutrient Recovery and Valorisation Technologies

Resource accessibility and security is fundamental for eradicating poverty and transitioning nations into a circular economy (Wackernagel et al., 2021). Government legislation plays a central role in catalyzing innovation and initiation. However, many governments have historically been hesitant to introduce legislation that demands greater resource security (Wackernagel et al., 2021). This is notable considering that adoption of waste treatment technologies by the industry is largely compelled by legislative compliance, not economic incentives (Campos et al., 2019; Chrispim et al., 2020). Therefore, the adoption of nutrient recovery and valorisation technology requires policy-driven support and economic incentives to alleviate high upfront capital and ongoing costs (De Boer et al., 2018). Examples of this can be seen in Europe, where ongoing projects facilitate (i) collaborative partnerships between

Figure 7 Circular Phosphorus Economy: *Goals* Food Sovereignty (i), Ecosystem Preservation (ii), Phosphorus Autonomy (iii) can be achieved through *Levers* Nutrient Recovery Facilities (a), Valorisation Technology (b), and Sustainable Agricultural and Soil Management strategies (c), respectively. SDGs No Poverty (1), Zero Hunger (2), Good Health and Well-Being (3), Clean Water and Sanitation (6), Decent Work and Economic Growth (8), Industry, Innovation, and Infrastructure (9), Sustainable Cities and Communities (11), Responsible Consumption and Production (12), Life Below Water (14), Life on Land (15), and Partnerships for the Goals (17) are position respective to the Levers in which they are accomplished. Underlined SDG numbers represent immediate SDG targets met through a Circular Phosphorus Economy (see Supporting Information Table 1); non-underlined SDG numbers represent Circular Phosphorus Economy Levers which contribute to achieving SDGs targets.

governments, academic institutions and industry (European Commission, 2021), but also (ii) assess and potentially declare recycled materials (such as struvite and ashes) as fertilizers and soil conditioning agents (EU, 2019).

Governments must factor in the environmental and public health consequences associated with an LPE into their broader socio-economic analyses. When considering public health (Pizzol et al., 2014; WWAP, 2017), the potential for resource recovery (Nižetić et al., 2019), the UN Impact Categories of 'terrestrial acidification potential' and the 'freshwater eutrophication potential' (Campos et al., 2019; Sud, 2020), moving beyond current chemical P-fertilizers and P recovery from waste streams can become economically beneficial. Conventional waste management and valorisation technologies for P-wastes include (i) enhanced biological P removal, (ii) chemical precipitation, (iii) thermal- or wet-chemical treatment, (iv) mono- and (v) thermo-chemical incineration (Adam et al., 2009; Jupp et al., 2021). Techno-economic advantages and disadvantages are dependent on relevant processes, which include P recovery efficacy, upfront and upkeep costs, and additives (such as chemicals) required for valorisation (Nättorp et al., 2017). Many of these technologies have yet to reach techno-socio-ecological maturity (Robles et al., 2020; van der Kooij et al., 2020) with continuous improvements including (i) greater extraction and resource recovery efficiencies, (ii) smaller scale operations which can be established at a closer proximity to P-waste feedstocks, (iii) lower upfront capital investments, and (iv) desired properties of the final product (Cieślik & Konieczka, 2017; Zhao et al., 2020).

Valorisation technologies can remove harmful pollutants from feedstocks while concentrating P in the final product (Hall et al., 2020; Herzel et al., 2016). Technologies such as advanced thermo-chemical incineration, for example of sewage-derived materials, removes undesired heavy metals from biowastes to produce a pollutant free P-fertilizer (Hermann & Schaaf, 2019). This supports the aim of achieving a negative soil-cadmium mass balance which requires cadmium concentrations in fertilizers to be limited to below 20 mg cadmium kg^{-1} P (Smolders, 2017). Heavy metal removal technologies to produce low contaminant P-fertilizers from wastes form an essential component of the CPE by reducing the current and ongoing input of heavy metals into agricultural soils.

6.2. Improving phosphorus use efficiency in agriculture

The Green Revolution launched the widespread use of chemical nitrogen-phosphorus-potassium (NPK) fertilizers and related technological innovations. Input of such concentrated and immediately crop-available nutrients left soil health and biology largely ignored (Lehman et al., 2015). Soils are complex systems governed by a multitude of interconnected biogeochemical characteristics influenced by soil type, climate, vegetation and, in the case of agricultural systems, management. Chemical fertilizers lack carbon (unlike manures and other organic materials), which can cause biogeochemical stoichiometric imbalances and a series of undesirable soil and agronomic consequences (Bui & Henderson, 2013; Kopittke et al., 2017). Organic carbon has a key function for soil structural integrity (Kay, 2018), soil fertility (Herrick

& Wander, 2018), water retention and availability (Eden et al., 2017), soil biological health (Brackin et al., 2017; Lehman et al., 2015), reducing uptake of contaminants (*e.g.*, cadmium) by crops (Prokop et al., 2003; Q. Wang et al., 2014) and pH-neutralising effects in acidic soils (Qi et al., 2018). Thus, carbon and the other crop essential nutrients must be part of the solutions aimed at achieving greater P efficiency in agriculture (Arif et al., 2017; Schneider et al., 2019).

Many of the P recovery technologies are primarily focused on the extraction of nutrients in the most efficient and economically viable manner with secondary consideration for desirable agronomic characteristics (Mayer et al., 2016). The agronomic efficacy of valorised P-materials are largely influenced by their respective chemical and physical characteristics (González et al., 2021) and respective relationships to soil properties (Hertzberger et al., 2020). For example, the agronomic performance of the precipitant struvite (magnesium-ammonium-phosphate), a by-product of P-rich effluent treatment which removes P and nitrogen, is largely influenced by its particle size (González et al., 2021) and soil pH (Ahmed et al., 2018; Hilt et al., 2016). Raniro *et al.* (2022) found that the solubility of the valorised P materials struvite, AshDec© (thermo-chemical product) and hazenite (chemical precipitant) was largely influenced by soil pH and exposure to different solvents. Therefore, enhancing the agronomic efficacy of valorised P-materials requires tailoring their physiochemical properties to complement soil conditions and the crop's P-mobilisation efficiency (Talboys et al., 2016; Y. Wang & Lambers, 2020). Improving P-fertilizer formulations thus requires empirical research and modelling to design crop-system targeted P-fertilizers (Bindraban et al., 2020; Das et al., 2019).

The improvement of P bioavailability of recycled materials can also be achieved *in situ* without prior processing. For example, improving P bioavailability from organic wastes such as manures can be achieved through the use of phosphate-liberating enzymes (*e.g.*, purple acid phosphatases or organophosphate-degrading enzymes) (Feder et al., 2020; Pedroso et al., 2014) deployed, for instance, on nanoclays (Calabi-Floody et al., 2012; Menezes-Blackburn et al., 2014). The availability of inorganic P, such as chemical precipitates and ash, can also be potentially improved with P-solubilizing microbes that excrete particular organic acids (Saeid, 2018).

6.3. Realising a Circular Phosphorus Economy in the developing world - Africa

The Covid-19 pandemic highlighted that communities with food insecurity live at the mercy of foreign markets (Andam et al., 2020). This was especially prevalent in Africa, where many countries rely on imports for their staple food supply (Sachs et al., 2020). In 2020, Africa saw 800 million people suffer from moderate to severe food insecurity, with one in five persons undernourished, and one third of children had stunted growth due to malnutrition (FAOSTAT, 2021b). To further compound this issue, the true socio-economic consequences of heightening resource insecurity and the subsequent repercussions on food production may have been underestimated by previous reports (Wackernagel et al., 2021). Furthermore, the increasing adoption of an LPE framework is likely to generate a spectrum of contemporary complications observed across the developed world.

The challenges and respective antidotes facing the developed world are fundamentally different when compared to developing nations such as those experienced in Africa. While there is a universal desire for food security, high yields and economic affluency enables the developed world to focus its efforts on mitigating the environmental degradation caused by an LPE, while developing nations delay environmental concerns in favor of achieving socio-economic objectives detailed in the SDGs. Dissimilar to developed nations, achieving a CPE within Africa is not a process of retrofitting pre-existing infrastructure or implementing novel technologies, but a process of introducing the systems, technologies and frameworks required for fertilizer production, application, and management. This process is necessary to address the primary limitations associated with food production and insecurity caused by the lack of access to fertilizers necessary to produce and sustain high yields.

6.3.1. Nutrient Recovery and Valorisation Technologies

For Africa, it is estimated that adequate wastewater management systems could save 325,000 lives annually through reducing the spread of diseases, while a reduction of nutrient loading into waterways could mitigate a further 613,000 annual deaths caused by poor quality drinking water and insufficient sanitation (WHO, 2019b). However, the development of efficient wastewater management systems and the provision of basic sanitation facilities poses a great logistical and economic challenge (African Development Bank et al., 2020), especially when considering the requirements necessary for establishing infrastructure in areas with pre-existing municipal buildings in high density areas. Currently, much of the sewage produced in African cities ends up in local waterways due to the lack of wastewater management facilities (Nyenje et al., 2010) leaving this potential nutrient resource largely unexploited. The direct reuse of humanure does, however, offer a low economic and technological solution with a potentially high return on investment (Sharma et al., 2019). In contrast, technological and infrastructure requirements for rural African communities present unique challenges due to low density and sporadic populations (Oloo & Asbon, 2020). Feedstocks excluding wastewater management can be sourced from a variety of other P-rich biowastes other than humanure, including livestock manure, composts, food waste and digestates (Kratz et al., 2019). However, consideration must be given to such resources as they may already serve a secondary purpose such as use for shelter or livestock feed.

6.1.3. Sustainable agriculture and soil management

Agricultural run-off is considered a primary contributing factor of Africa's declining water quality (WWAP, 2017) and thus demands improved agricultural and soil management strategies. Reaching high agricultural output without mirroring the chemical P-fertilizer inputs seen in the developed world (Figure 3C) will require great agricultural methodological and industrial innovations. The development of localized management strategies should include the recruitment of local farmers to ensure integration of indigenous knowledge which can help mitigate biodiversity loss (Vogliano et al., 2021) and identify localized best management practises (Prober et al., 2011). Through education, access to technological resources that promote soil management schemes, and nutrient biofortification targeting P-deficient soils, the loss of biodiversity to agricultural expansion can be eliminated in sub-Saharan Africa (Mogollón et al., 2021). However, due to the complexity of P in soils, previous analyses may have underestimated the quantity of P required to meet the agricultural demands in this region (Haygarth & Rufino, 2021). The high variability in soil characteristics and environmental conditions across Africa requires an advanced approach to articulate a farmer's unique fertilizer requirements, especially when considering that conventional methods that rely on single point soil analyses are highly variable and largely inaccurate (Schut & Giller, 2020). Providing advanced resources such as spatial data (*e.g.*, Africa Soil Information Service) can be used to help calculate the required quantities of P-fertilizer (Hengl et al., 2021). Other immediate and low-barriers to adoption solutions which can conserve soil P and moderate nutrient loading into waterways are linked to regenerative agricultural techniques that include (i) cover cropping, (ii) conservation tillage and (iii) precision fertilizer management strategies (Ahmad et al., 2020; Bradford et al., 2019; Karlen & Cambardella, 2020; Shi & Schulin, 2018).

7. Conclusions

The LPE continues to undermine food security, public health, and environmental integrity across the globe. Adopting an LPE framework to accomplish SDGs will encounter contemporary global challenges while exacerbating the shortfalls of an already fragile system. Continued monopolisation and resource nationalism, increasing demands from emerging economies, and the USA withdrawing from the global market will likely further undermine supply security and exacerbate P access inequality. Furthermore, without advancing P management in agro-ecosystems, reducing heavy metal contamination and limiting the continued loss of biodiversity through agricultural land expansion and eutrophication, these issues will likely intensify in the future. By harnessing P in waste streams that currently contribute to environmental degradation, the successful pivot into a CPE based on nutrient recovery and valorisation technologies can promote P autarky and, therefore, agricultural autonomy. Policy and financial support from governments and cooperative partnerships must be the backbone behind CPE innovation and implementation.

Acknowledgments

This research was supported by an HDR Industry Scholarship to MW provided by Fight Food Waste Cooperative Research Centre whose activities are funded by the Australian Government's Cooperative Research Centre (CRC) Program.

Data Availability Statement

No new data has been generated or used for writing this article

References

Adam, C., Vogel, C., Wellendorf, S., Schick, J., Kratz, S., & Schnug, E. (2009). *Phosphorus recovery by thermo-chemical treatment of sewage sludge ash–results of the European FP6-project SUSAN*. Paper presented at the International conference on nutrient recovery from wastewater streams. IWA Publishing, London.

Adams, S. V., & Newcomb, P. A. (2014). Cadmium blood and urine concentrations as measures of exposure: NHANES 1999–2010. *Journal of exposure science & environmental epidemiology, 24*(2), 163-170.

African Development Bank, United Nations Environmental Programme, & GRID-Arendal. (2020). Sanitation and Wastewater Atlas of Africa.

Ahmad, N. S. B. N., Mustafa, F. B., & Didams, G. (2020). A systematic review of soil erosion control practices on the agricultural land in Asia. *International Soil and Water Conservation Research, 8*(2), 103-115.

Ahmed, N., Shim, S., Won, S., & Ra, C. (2018). Struvite recovered from various types of wastewaters: Characteristics, soil leaching behaviour, and plant growth. *Land Degradation & Development, 29*(9), 2864-2879.

Alewell, C., Ringeval, B., Ballabio, C., Robinson, D. A., Panagos, P., & Borrelli, P. (2020). Global phosphorus shortage will be aggravated by soil erosion. *Nature communications, 11*(1), 1-12.

Allan, J., & Ojeda-García, R. (2021). Natural resource exploitation in Western Sahara: new research directions. In: Taylor & Francis.

Andam, K., Edeh, H., Oboh, V., Pauw, K., & Thurlow, J. (2020). Impacts of COVID-19 on food systems and poverty in Nigeria. *Advances in Food Security and Sustainability, 5*, 145.

Andersen, J. H., Carstensen, J., Conley, D. J., Dromph, K., Fleming‐Lehtinen, V., Gustafsson, B. G., . . . Murray, C. (2017). Long‐term temporal and spatial trends in eutrophication status of the Baltic Sea. *Biological Reviews, 92*(1), 135-149.

Arif, M., Ilyas, M., Riaz, M., Ali, K., Shah, K., Haq, I. U., & Fahad, S. (2017). Biochar improves phosphorus use efficiency of organic-inorganic fertilizers, maize-wheat productivity and soil quality in a low fertility alkaline soil. *Field crops research, 214*, 25-37.

Australian Parliment. (2009). *Pricing and supply arrangement in the Australian and global fertiliser market*. Parliment of Australia

BGS. (2015). British Geological Survey: Risk list 2015.

Bindraban, P. S., Dimkpa, C. O., White, J. C., Franklin, F. A., Melse‐Boonstra, A., Koele, N., . . . Demokritou, P. (2020). Safeguarding human and planetary health demands a fertilizer sector transformation. *Plants, People, Planet, 2*(4), 302-309.

Bloem, E., Albihn, A., Elving, J., Hermann, L., Lehmann, L., Sarvi, M., . . . Ylivainio, K. (2017). Contamination of organic nutrient sources with potentially toxic elements, antibiotics and pathogen microorganisms in relation to P fertilizer potential and treatment options for the production of sustainable fertilizers: a review. *Science of the Total Environment, 607*, 225-242.

Bobba, S., Carrara, S., Huisman, J., Mathieux, F., & Pavel, C. (2020). Critical Raw Materials for Strategic Technologies and Sectors in the EU—A Foresight Study. *European Commission: Brussels, Belgium*.

Brackin, R., Schmidt, S., Walter, D., Bhuiyan, S., Buckley, S., & Anderson, J. (2017). *Soil biological health-what is it and how can we improve it?* Paper presented at the Proceedings of the Australian Society of Sugar Cane Technologists.

Bradford, M. A., Carey, C. J., Atwood, L., Bossio, D., Fenichel, E. P., Gennet, S., . . . Kane, D. A. (2019). Soil carbon science for policy and practice. *Nature Sustainability, 2*(12), 1070-1072.

Bradley, C. A. (2021). United States Recognizes Morocco's Sovereignty Over Western Sahara. *American Journal of International Law, Cambridge University Press, 115*(2), 318-323.

Brodie, J., Devlin, M., & Lewis, S. (2017). Potential enhanced survivorship of crown of thorns starfish larvae due to near-annual nutrient enrichment during secondary outbreaks on the central mid-shelf of the Great Barrier Reef, Australia. *Diversity, 9*(1), 17.

Brooks, J. (2016). *Food security and the Sustainable Development Goals* (P. Love Ed. Debate the Issues: New Approaches to Economic Challenges ed.). Paris: OECD Publishing.

Brownlie, W. J., Sutton, M. A., Reay, D. S., Heal, K. V., Hermann, L., Kabbe, C., & Spears, B. M. (2021). Global actions for a sustainable phosphorus future. *Nature Food, 2*(2), 71-74.

Buckingham, D., & Jasinski, S. (2020). *Historical Statistics for Mineral and Material Commodities in the United States*.

Bui, E. N., & Henderson, B. L. (2013). C: N: P stoichiometry in Australian soils with respect to vegetation and environmental factors. *Plant and soil, 373*(1), 553-568.

Calabi-Floody, M., Velásquez, G., Gianfreda, L., Saggar, S., Bolan, N., Rumpel, C., & Mora, M. L. (2012). Improving bioavailability of phosphorous from cattle dung by using phosphatase immobilized on natural clay and nanoclay. *Chemosphere, 89*(6), 648-655.

Campos, J. L., Crutchik, D., Franchi, Ó., Pavissich, J. P., Belmonte, M., Pedrouso, A., . . . Val del Río, Á. (2019). Nitrogen and phosphorus recovery from anaerobically pretreated agro-food wastes: a review. *Frontiers in Sustainable Food Systems, 2*, 91.

CDC. (2017). Biomonitoring Summary. Retrieved from https://www.cdc.gov/biomonitoring/Cadmium_BiomonitoringSummary.html

CDFA. (2020). *Food and agricultural code, Division 7, Agricultural chemicals, livestock remedies, and commerical feeds, Chapter 5. Fertilizing materials [14501-14682]*. Retrieved from https://www.cdfa.ca.gov/is/docs/Fertilizer_Law_and_Regs.pdf

Center for Biological Diversity. (2021). Imminent Failure of Phosphogypsum Stack in Tampa Bay Exposes Phosphate Industry Risks Catastrophic Wastewater Release Highlights Need for Federal Action [Press release]. Retrieved from https://biologicaldiversity.org/w/news/press-releases/imminent-failure-of-phosphogypsum-stack-in-tampa-bay-exposes-phosphate-industry-risks-2021-04-03/

Chazottes, V., Hutchings, P., & Osorno, A. (2017). Impact of an experimental eutrophication on the processes of bioerosion on the reef: One Tree Island, Great Barrier Reef, Australia. *Marine pollution bulletin, 118*(1-2), 125-130.

Chrispim, M. C., Scholz, M., & Nolasco, M. A. (2020). A framework for resource recovery from wastewater treatment plants in megacities of developing countries. *Environmental research, 188*, 109745.

Cieślik, B., & Konieczka, P. (2017). A review of phosphorus recovery methods at various steps of wastewater treatment and sewage sludge management. The concept of "no solid waste generation" and analytical methods. *Journal of cleaner production, 142*, 1728-1740.

Cordell, D. (2013). Peak phosphorus and the role of P recovery in achieving food security. *Source Separation and Decentralization for Wastewater Management. IWA Publishing*, 29-44.

Cordell, D., Dominish, E., Esham, M., Jacobs, B., & Nanda, M. (2021). Adapting food systems to the twin challenges of phosphorus and climate vulnerability: the case of Sri Lanka. *Food Security, 13*(2), 477-492.

Cordell, D., Drangert, J.-O., & White, S. (2009). The story of phosphorus: global food security and food for thought. *Global Environmental Change, 19*(2), 292-305.
Cordell, D., & Neset, T.-S. (2014). Phosphorus vulnerability: a qualitative framework for assessing the vulnerability of national and regional food systems to the multi-dimensional stressors of phosphorus scarcity. *Global Environmental Change, 24*, 108-122.
Cordell, D., Turner, A., & Chong, J. (2015). The hidden cost of phosphate fertilizers: mapping multi-stakeholder supply chain risks and impacts from mine to fork. *Global change, peace & security, 27*(3), 323-343.
Cordell, D., & White, S. (2014). Life's bottleneck: sustaining the world's phosphorus for a food secure future. *Annual Review of Environment and Resources, 39*, 161-188.
Das, B., Huth, N., Probert, M., Condron, L., & Schmidt, S. (2019). Soil phosphorus modeling for modern agriculture requires balance of science and practicality: A perspective. *Journal of Environmental Quality, 48*(5), 1281-1294.
De Boer, M. A., Romeo-Hall, A. G., Rooimans, T. M., & Slootweg, J. C. (2018). An assessment of the drivers and barriers for the deployment of urban phosphorus recovery technologies: A case study of the Netherlands. *Sustainability, 10*(6), 1790.
De Boer, M. A., Wolzak, L., & Slootweg, J. C. (2019). Phosphorus: reserves, production, and applications. In *Phosphorus Recovery and Recycling* (pp. 75-100): Springer.
De Ridder, M., De Jong, S., Polchar, J., & Lingemann, S. (2012). Risks and opportunities in the global phosphate rock market: Robust strategies in times of uncertainty. In: Hague Centre for Strategic Studies.
Dubois, O. (2011). *The state of the world's land and water resources for food and agriculture: managing systems at risk*: Earthscan.
Eden, M., Gerke, H. H., & Houot, S. (2017). Organic waste recycling in agriculture and related effects on soil water retention and plant available water: a review. *Agronomy for sustainable development, 37*(2), 11.
Edixhoven, J., Gupta, J., & Savenije, H. (2014). Recent revisions of phosphate rock reserves and resources: a critique. *Earth System Dynamics, 5*(2), 491-507.
El Wali, M., Golroudbary, S. R., & Kraslawski, A. (2021). Circular economy for phosphorus supply chain and its impact on social sustainable development goals. *Science of the Total Environment, 777*, 146060.
Environmental Protection Agency. (2021). *Title 40: Protection of Environment. Part 61- National Emission Standards for Hazardous Air Pollutants*.
EPA. (2015). Mosaic Fertilizer, LLC Settlement. Retrieved from https://www.epa.gov/enforcement/mosaic-fertilizer-llc-settlement
EPA. (2021). TENORM: Fertilizer and Fertilizer Production Wastes. Retrieved from https://www.epa.gov/radiation/tenorm-fertilizer-and-fertilizer-production-wastes#tab-2
EU. (2019). 1009 of the European Parliament and of the Council laying down rules on making available on the market of EU fertilizing products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003.(2019). In: PDF.
European Commission. (2010). Environment: Commission sends Spain final warning over industrial waste [Press release]
European Commission. (2020). *Biodiversity Strategy for 2030 Bringing nature back into our lives COM/2020/380 final*. European Commission Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1590574123338&uri=CELEX:52020DC0380

European Commission. (2021). Capture, recycling and societal management of phosphorus in the environment. Retrieved from https://cordis.europa.eu/project/id/956454
FAO. (2021a). FAO Food Price Index. Retrieved from http://www.fao.org/worldfoodsituation/foodpricesindex/en/
FAO. (2021b). Inorganic fertilizers 1961–2019. *Analytical Brief Series, 27*.
FAO, IFAD, UNICEF, WFP, & WHO. (2021). *The State of Food Security and Nutrition in the World 2021. Transforming food systems for food security, improved nutrition and affordable healthy diets for all* (Vol. 2021). Rome: FAO.
FAO, ITPS, GSBI, SCBD, & EC. (2020). *State of knowledge of soil biodiversity - Status, challenges and potentialities*. (9251335826). Rome: FAO
FAOSTAT. (2021a). Fertilizer by Product and Nutrient. Retrieved from http://www.fao.org/faostat/en/#data/EF
FAOSTAT. (2021b). Suite of Food Security Indicators. Retrieved from https://www.fao.org/faostat/en/#data/FS
FDEP. (2021). *Piney Point - Frequenty Asked Questions*. Florida: Florida Department of Environmental Protection Retrieved from https://floridadep.gov/sites/default/files/PP-FAQs.pdf
Feder, D., McGeary, R. P., Mitić, N., Lonhienne, T., Furtado, A., Schulz, B. L., . . . Schenk, G. (2020). Structural elements that modulate the substrate specificity of plant purple acid phosphatases: avenues for improved phosphorus acquisition in crops. *Plant Science, 294*, 110445.
Fenner, D. (2019). Nauru. In *World Seas: An Environmental Evaluation* (pp. 793-805): Elsevier.
Fertilizers Europe. (2017). The European Parliament goes down a wrong path. Retrieved from https://www.fertilizerseurope.com/news/the-european-parliament-goes-down-a-wrong-path/
Gale, S. J. (2016). The mined-out phosphate lands of Nauru, equatorial western Pacific. *Australian Journal of Earth Sciences, 63*(3), 333-347.
Garske, B., & Ekardt, F. (2021). Economic policy instruments for sustainable phosphorus management: taking into account climate and biodiversity targets. *Environmental Sciences Europe, 33*(1), 1-20.
Geissler, B., Hermann, L., Mew, M. C., & Steiner, G. (2018). Striving toward a circular economy for phosphorus: The role of phosphate rock mining. *Minerals, 8*(9), 395.
Geissler, B., Mew, M. C., & Steiner, G. (2019). Phosphate supply security for importing countries: Developments and the current situation. *Science of the Total Environment, 677*, 511-523.
Geissler, B., Mew, M. C., Weber, O., & Steiner, G. (2015). Efficiency performance of the world's leading corporations in phosphate rock mining. *Resources, Conservation and Recycling, 105*, 246-258.
Gerten, D., Heck, V., Jägermeyr, J., Bodirsky, B. L., Fetzer, I., Jalava, M., . . . Schaphoff, S. (2020). Feeding ten billion people is possible within four terrestrial planetary boundaries. *Nature Sustainability, 3*(3), 200-208.
Giroud, A., & Ivarsson, I. (2020). World Investment Report 2020: International production beyond the pandemic. In: Springer.
Gladyshev, M., & Gubelit, Y. I. (2019). Green tides: new consequences of the eutrophication of natural waters (invited review). *Contemporary Problems of Ecology, 12*(2), 109-125.
Glibert, P. M. (2020). Harmful algae at the complex nexus of eutrophication and climate change. *Harmful Algae, 91*, 101583.

González, C., Fernández, B., Molina, F., Camargo-Valero, M., & Peláez, C. (2021). The determination of fertiliser quality of the formed struvite from a WWTP. *Water Science and Technology*.

Gray, C., McLaren, R., Roberts, A., & Condron, L. (1999). The effect of long-term phosphatic fertiliser applications on the amounts and forms of cadmium in soils under pasture in New Zealand. *Nutrient Cycling in Agroecosystems, 54*(3), 267-277.

Günther, S., Grunert, M., & Müller, S. (2018). Overview of recent advances in phosphorus recovery for fertilizer production. *Engineering in life sciences, 18*(7), 434-439.

Hall, R. L., Staal, L. B., Macintosh, K. A., McGrath, J. W., Bailey, J., Black, L., . . . Williams, P. N. (2020). Phosphorus speciation and fertiliser performance characteristics: A comparison of waste recovered struvites from global sources. *Geoderma, 362*, 114096.

Hamilton, J. D. (2009). *Causes and Consequences of the Oil Shock of 2007-08*. Retrieved from

Hayes, S. M., & McCullough, E. A. (2018). Critical minerals: A review of elemental trends in comprehensive criticality studies. *Resources Policy, 59*, 192-199.

Haygarth, P. M., & Rufino, M. C. (2021). Local solutions to global phosphorus imbalances. *Nature Food, 2*(7), 459-460.

Hebinck, A., Zurek, M., Achterbosch, T., Forkman, B., Kuijsten, A., Kuiper, M., . . . Leip, A. (2021). A sustainability compass for policy navigation to sustainable food systems. *Global Food Security*, 100546.

HELCOM, B. (2007). HELCOM Baltic Sea action plan. *Krakow, Poland, 15*, 2007.

Hengl, T., Miller, M. A., Križan, J., Shepherd, K. D., Sila, A., Kilibarda, M., . . . Haefele, S. M. (2021). African soil properties and nutrients mapped at 30 m spatial resolution using two-scale ensemble machine learning. *Scientific reports, 11*(1), 1-18.

Hermann, L., & Schaaf, T. (2019). Outotec (AshDec®) Process for P Fertilizers from Sludge Ash. In *Phosphorus Recovery and Recycling* (pp. 221-233): Springer.

Herrick, J. E., & Wander, M. M. (2018). Relationships between soil organic carbon and soil quality in cropped and rangeland soils: the importance of distribution, composition, and soil biological activity. In *Soil processes and the carbon cycle* (pp. 405-425): CRC Press.

Hertzberger, A. J., Cusick, R. D., & Margenot, A. J. (2020). A review and meta‐analysis of the agricultural potential of struvite as a phosphorus fertilizer. *Soil Science Society of America Journal, 84*(3), 653-671.

Herzel, H., Krüger, O., Hermann, L., & Adam, C. (2016). Sewage sludge ash—A promising secondary phosphorus source for fertilizer production. *Science of the Total Environment, 542*, 1136-1143.

Hilt, K., Harrison, J., Bowers, K., Stevens, R., Bary, A., & Harrison, K. (2016). Agronomic response of crops fertilized with struvite derived from dairy manure. *Water, Air, & Soil Pollution, 227*(10), 1-13.

Hobert, A., Dohm, E., Tallarico, F., & Dedé, C. (2020). Improved Flotation Recovery and Selectivity of an Ultra-Fine Brazilian Phosphate Ore Using Eriez' Column Flotation Technology. *SYMPHOS - 5th International Symposium on Innocation & Technology in the Phosphate Industry*.

Hou, D., O'Connor, D., Igalavithana, A. D., Alessi, D. S., Luo, J., Tsang, D. C., . . . Ok, Y. S. (2020). Metal contamination and bioremediation of agricultural soils for food safety and sustainability. *Nature Reviews Earth & Environment, 1*(7), 366-381.

Ibeh, C., & Walmsley, B. (2021). The role of impact assessment in achieving the sustainable development goals in Africa. *International Association for Impact Assessment*, 1-15.

IndexMundi. (2021). Commodity Prices. Retrieved from https://www.indexmundi.com/commodities/

Irwin, R. L. (2021). Terrains of legality and sovereignty: adjudicating the ownership of Western Sahara's phosphate in South Africa. *The Journal of North African Studies*, 1-23.

Jasinski, S. (2014). *Phosphate Rock, USGS Mineral Commodities Summary*. United States Geological Survey

Ji, Y., Liu, H., & Shi, Y. (2020). Will China's fertilizer use continue to decline? Evidence from LMDI analysis based on crops, regions and fertilizer types. *PloS one*, *15*(8), e0237234.

JORC. (2012). *Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves*. Retrieved from http://www.jorc.org/docs/JORC_code_2012.pdf

Jung, M., Arnell, A., de Lamo, X., García-Rangel, S., Lewis, M., Mark, J., . . . Pironon, S. (2021). Areas of global importance for conserving terrestrial biodiversity, carbon and water. *Nature Ecology & Evolution*, 1-11.

Jupp, A. R., Beijer, S., Narain, G. C., Schipper, W., & Slootweg, J. C. (2021). Phosphorus recovery and recycling–closing the loop. *Chemical Society Reviews*.

Karlen, D., & Cambardella, C. (2020). Conservation strategies for improving soil quality and organic matter storage. *Structure and organic matter storage in agricultural soils*, 395-420.

Kawatra, S. K., & Carlson, J. (2013). *Beneficiation of phosphate ore*: Society for Mining, Metallurgy, and Exploration.

Kay, B. (2018). Soil structure and organic carbon: a review. *Soil processes and the carbon cycle*, 169-197.

Khabarov, N., & Obersteiner, M. (2017). Global phosphorus fertilizer market and national policies: a case study revisiting the 2008 price peak. *Frontiers in nutrition, 4*, 22.

Köhn, J., Zimmer, D., & Leinweber, P. (2018). Is phosphorus really a scarce resource? *International Journal of Environmental Technology and Management, 21*(5-6), 373-395.

Kommission, E., Generaldirektion Binnenmarkt, I., Unternehmertum und KMU, Mankelow, J., Waugh, R., Walter, P., Petavratzi, E., & Bertrand, G. (2015). *Minventory, EU raw materials statistics on resources and reserves : final report*: Publications Office.

Kopittke, P. M., Dalal, R. C., Finn, D., & Menzies, N. W. (2017). Global changes in soil stocks of carbon, nitrogen, phosphorus, and sulphur as influenced by long‐term agricultural production. *Global Change Biology*, *23*(6), 2509-2519.

Koppelaar, R., & Weikard, H. (2013). Assessing phosphate rock depletion and phosphorus recycling options. *Global Environmental Change, 23*(6), 1454-1466.

Kouzbour, S., Gourich, B., Gros, F., Vial, C., Allam, F., & Stiriba, Y. (2019). Comparative analysis of industrial processes for cadmium removal from phosphoric acid: A review. *Hydrometallurgy, 188*, 222-247.

Kowal, N., Johnson, D., Kraemer, D., & Pahren, H. (1979). Normal levels of cadmium in diet, urine, blood, and tissues of inhabitants of the United States. *Journal of Toxicology and Environmental Health, Part A Current Issues, 5*(6), 995-1014.

Kratz, S., Schick, J., & Schnug, E. (2016). Trace elements in rock phosphates and P containing mineral and organo-mineral fertilizers sold in Germany. *Science of the Total Environment, 542*, 1013-1019.

Kratz, S., Vogel, C., & Adam, C. (2019). Agronomic performance of P recycling fertilizers and methods to predict it: a review. *Nutrient Cycling in Agroecosystems, 115*(1), 1-39.

Kruk, M. E., Gage, A. D., Arsenault, C., Jordan, K., Leslie, H. H., Roder-DeWan, S., . . . Doubova, S. V. (2018). High-quality health systems in the Sustainable Development Goals era: time for a revolution. *The Lancet global health, 6*(11), e1196-e1252.

Kubier, A., Wilkin, R. T., & Pichler, T. (2019). Cadmium in soils and groundwater: a review. *Applied Geochemistry, 108*, 104388.

Kuliński, K., Rehder, G., Asmala, E., Bartosova, A., Carstensen, J., Gustafsson, B., . . . Jürgens, K. (2021). Baltic Earth Assessment Report on the biogeochemistry of the Baltic Sea. *Earth System Dynamics Discussions*, 1-93.

Kutz, W. (2021). Between dependency and engagement: Centring subaltern geopolitics in multiperspectival border studies. Lessons from the Western Sahara. *Political Geography, 89*, 102431.

Laganda. (2021). 2021 is going to be a bad year for world hunger. Retrieved from https://www.un.org/en/food-systems-summit/news/2021-going-be-bad-year-world-hunger

Lal, R. (2015). Restoring soil quality to mitigate soil degradation. *Sustainability, 7*(5), 5875-5895.

Leal Filho, W., Azeiteiro, U., Alves, F., Pace, P., Mifsud, M., Brandli, L., . . . Disterheft, A. (2018). Reinvigorating the sustainable development research agenda: the role of the sustainable development goals (SDG). *International Journal of Sustainable Development & World Ecology, 25*(2), 131-142.

Lehman, R. M., Cambardella, C. A., Stott, D. E., Acosta-Martinez, V., Manter, D. K., Buyer, J. S., . . . Halvorson, J. J. (2015). Understanding and enhancing soil biological health: the solution for reversing soil degradation. *Sustainability, 7*(1), 988-1027.

Lizcano-Toledo, R., Reyes-Martín, M. P., Celi, L., & Fernández-Ondoño, E. (2021). Phosphorus Dynamics in the Soil–Plant–Environment Relationship in Cropping Systems: A Review. *Applied Sciences, 11*(23), 11133.

Lundh, T., Axmon, A., Skerfving, S., & Broberg, K. (2016). Cadmium and mercury exposure over time in Swedish children. *Environmental research, 150*, 600-605.

Malone, T. C., & Newton, A. (2020). The globalization of cultural eutrophication in the coastal ocean: causes and consequences. *Frontiers in Marine Science, 7*, 670.

Mayer, B. K., Baker, L. A., Boyer, T. H., Drechsel, P., Gifford, M., Hanjra, M. A., . . . Rittmann, B. E. (2016). Total value of phosphorus recovery. *Environmental science & technology, 50*(13), 6606-6620.

McCrackin, M. L., Jones, H. P., Jones, P. C., & Moreno‐Mateos, D. (2017). Recovery of lakes and coastal marine ecosystems from eutrophication: A global meta‐analysis. *Limnology and Oceanography, 62*(2), 507-518.

McDowell, R., Dodd, R., Pletnyakov, P., & Noble, A. (2020). The ability to reduce soil legacy phosphorus at a country scale. *Frontiers in Environmental Science, 8*, 6.

Meier, H., Eilola, K., Almroth-Rosell, E., Schimanke, S., Kniebusch, M., Höglund, A., . . . Saraiva, S. (2019). Disentangling the impact of nutrient load and climate changes on Baltic Sea hypoxia and eutrophication since 1850. *Climate Dynamics, 53*(1), 1145-1166.

Meier, H., Hordoir, R., Andersson, H., Dieterich, C., Eilola, K., Gustafsson, B. G., . . . Schimanke, S. (2012). Modeling the combined impact of changing climate and changing nutrient loads on the Baltic Sea environment in an ensemble of transient simulations for 1961–2099. *Climate Dynamics, 39*(9-10), 2421-2441.

Menezes-Blackburn, D., Jorquera, M. A., Gianfreda, L., Greiner, R., & de la Luz Mora, M. (2014). A novel phosphorus biofertilization strategy using cattle manure treated with phytase–nanoclay complexes. *Biology and fertility of soils, 50*(4), 583-592.

MEP, M. (2014). The communique of national investigation of soil contamination. *Ministry of Land and Resources of the People's Republic of China. Ministry of environmental protection of the People's Republic of China*.

Mogollón, J. M., Bouwman, A. F., Beusen, A. H., Lassaletta, L., van Grinsven, H. J., & Westhoek, H. (2021). More efficient phosphorus use can avoid cropland expansion. *Nature Food*, 1-10.

Murray, C. J., Müller-Karulis, B., Carstensen, J., Conley, D. J., Gustafsson, B. G., & Andersen, J. H. (2019). Past, present and future eutrophication status of the Baltic Sea. *Frontiers in Marine Science, 6*, 2.

Nassar, N. T., Brainard, J., Gulley, A., Manley, R., Matos, G., Lederer, G., . . . Gambogi, J. (2020). Evaluating the mineral commodity supply risk of the US manufacturing sector. *Science advances, 6*(8), eaay8647.

Nättorp, A., Remmen, K., & Remy, C. (2017). Cost assessment of different routes for phosphorus recovery from wastewater using data from pilot and production plants. *Water science and technology, 76*(2), 413-424.

Nino-Savala, A. G., ZHUANG, Z., MA, X., FANGMEIER, A., LI, H., TANG, A., & LIU, X. (2019). Cadmium pollution from phosphate fertilizers in arable soils and crops: an overview. *Frontiers of Agricultural Science and Engineering, 6*(4), 419-430.

Nižetić, S., Djilali, N., Papadopoulos, A., & Rodrigues, J. J. (2019). Smart technologies for promotion of energy efficiency, utilization of sustainable resources and waste management. *Journal of cleaner production, 231*, 565-591.

Nordberg, G. F. (2004). Cadmium and health in the 21st century–historical remarks and trends for the future. *Biometals, 17*(5), 485-489.

Nyenje, P., Foppen, J., Uhlenbrook, S., Kulabako, R., & Muwanga, A. (2010). Eutrophication and nutrient release in urban areas of sub-Saharan Africa—a review. *Science of the Total Environment, 408*(3), 447-455.

Ockenden, M. C., Hollaway, M. J., Beven, K. J., Collins, A., Evans, R., Falloon, P., . . . Macleod, C. (2017). Major agricultural changes required to mitigate phosphorus losses under climate change. *Nature communications, 8*(1), 1-9.

OCP. (2021). OCP Group. Retrieved from https://www.ocpgroup.ma/

Oleko Amivi, Fillol Clémence, Saoudi Abdessattar, Zeghnoun Abdelkrim, Bidondo Marie-Laure, & Gane Jessica, B. A. (2021). *Imprégnation de la population française par le cadmium. Programme national de biosurveillance, Esteban 2014-2016*. Sante publique France

Oloo, K. P., & Asbon, O. P. (2020). Depletion of phosphate rock reserves and world food crisis: Reality or hoax? *African Journal of Agricultural Research, 16*(9), 1223-1227.

Panagos, P., Borrelli, P., & Poesen, J. (2019). Soil loss due to crop harvesting in the European Union: A first estimation of an underrated geomorphic process. *Science of the Total Environment, 664*, 487-498.

Pedroso, M. M., Ely, F., Mitić, N., Carpenter, M. C., Gahan, L. R., Wilcox, D. E., . . . Schenk, G. (2014). Comparative investigation of the reaction mechanisms of the organophosphate-degrading phosphotriesterases from Agrobacterium radiobacter (OpdA) and Pseudomonas diminuta (OPH). *JBIC Journal of Biological Inorganic Chemistry, 19*(8), 1263-1275.

Pennock, D., McKenzie, N., & Montanarella, L. (2015). Status of the World's Soil Resources. *Technical Summary FAO, Rome, Italy*.

Pizzol, M., Smart, J. C., & Thomsen, M. (2014). External costs of cadmium emissions to soil: a drawback of phosphorus fertilizers. *Journal of cleaner production, 84*, 475-483.

Plaxton, W., & Lambers, H. (2015). *Annual plant reviews, phosphorus metabolism in plants* (Vol. 48): John Wiley & Sons.

Prăvălie, R., Patriche, C., Borrelli, P., Panagos, P., Roșca, B., Dumitraşcu, M., . . . Bandoc, G. (2021). Arable lands under the pressure of multiple land degradation processes. A global perspective. *Environmental research, 194*, 110697.

Prober, S. M., O'Connor, M. H., & Walsh, F. J. (2011). Australian Aboriginal peoples' seasonal knowledge: a potential basis for shared understanding in environmental management. *Ecology and society, 16*(2).

Prokop, Z., Cupr, P., Zlevorova-Zlamalikova, V., Komárek, J., Dusek, L., & Holoubek, I. (2003). Mobility, bioavailability, and toxic effects of cadmium in soil samples. *Environmental research, 91*(2), 119-126.

Qi, F., Lamb, D., Naidu, R., Bolan, N. S., Yan, Y., Ok, Y. S., . . . Choppala, G. (2018). Cadmium solubility and bioavailability in soils amended with acidic and neutral biochar. *Science of the Total Environment, 610*, 1457-1466.

Rahman, Z., & Singh, V. P. (2019). The relative impact of toxic heavy metals (THMs)(arsenic (As), cadmium (Cd), chromium (Cr)(VI), mercury (Hg), and lead (Pb)) on the total environment: an overview. *Environmental Monitoring and Assessment, 191*(7), 1-21.

Randers, J., Rockström, J., Stoknes, P.-E., Goluke, U., Collste, D., Cornell, S. E., & Donges, J. (2019). Achieving the 17 Sustainable Development Goals within 9 planetary boundaries. *Global Sustainability, 2*.

Raniro, H. R., Teles, A. P. B., Adam, C., & Pavinato, P. S. (2022). Phosphorus solubility and dynamics in a tropical soil under sources derived from wastewater and sewage sludge. *Journal of environmental management, 302*, 113984.

Rashad, A. M. (2017). Phosphogypsum as a construction material. *Journal of cleaner production, 166*, 732-743.

Reijnders, L. (2014). Phosphorus resources, their depletion and conservation, a review. *Resources, Conservation and Recycling, 93*, 32-49.

Revuelta, M. B. (2018). Mineral Processing. In *Mineral Resources* (pp. 423-530): Springer.

Robles, Á., Aguado, D., Barat, R., Borrás, L., Bouzas, A., Giménez, J. B., . . . Serralta, J. (2020). New frontiers from removal to recycling of nitrogen and phosphorus from wastewater in the Circular Economy. *Bioresource technology, 300*, 122673.

Ruan, Y., He, D., & Chi, R. (2019). Review on beneficiation techniques and reagents used for phosphate ores. *Minerals, 9*(4), 253.

Ruys, T. (2019). The role of state immunity and act of state in the NM Cherry Blossom case and the Western Sahara dispute. *International & Comparative Law Quarterly, 68*(1), 67-90.

Sachs, J., Kroll, C., Lafortune, G., Fuller, G., & Woelm, F. (2021). *Sustainable Development Report 2021*: Cambridge University Press.

Sachs, J., Schmidt-Traub, G., Kroll, C., Lafortune, G., Fuller, G., & Woelm, F. (2020). The sustainable development goals and COVID-19. *Sustainable development report, 2020*.

Sachs, J., Schmidt-Traub, G., Mazzucato, M., Messner, D., Nakicenovic, N., & Rockström, J. (2019). Six transformations to achieve the sustainable development goals. *Nature Sustainability, 2*(9), 805-814.

Saeid, A. (2018). Phosphorus microbial solubilization as a key for phosphorus recycling in agriculture. *Phosphorus Recovery and Recycling*.

Salvia, A. L., Leal Filho, W., Brandli, L. L., & Griebeler, J. S. (2019). Assessing research trends related to Sustainable Development Goals: Local and global issues. *Journal of cleaner production, 208*, 841-849.

Santayana, G. (1910). *Reason in common sense* (Vol. 1): Constable.

Savchuk, O. P. (2018). Large-scale nutrient dynamics in the Baltic Sea, 1970–2016. *Frontiers in Marine Science, 5*, 95.

Schneider, K. D., Thiessen Martens, J. R., Zvomuya, F., Reid, D. K., Fraser, T. D., Lynch, D. H., . . . Wilson, H. F. (2019). Options for improved phosphorus cycling and use in agriculture at the field and regional scales. *Journal of Environmental Quality, 48*(5), 1247-1264.

Schnug, E., & De Kok, L. J. (2016). *Phosphorus in agriculture: 100% zero*: Springer.
Schut, A. G., & Giller, K. E. (2020). Soil-based, field-specific fertilizer recommendations are a pipe-dream. *Geoderma, 380*, 114680.
Shahid, M., Dumat, C., Khalid, S., Niazi, N. K., & Antunes, P. M. (2016). Cadmium bioavailability, uptake, toxicity and detoxification in soil-plant system. *Reviews of Environmental Contamination and Toxicology Volume 241*, 73-137.
Sharma, B., Vaish, B., Singh, U. K., Singh, P., & Singh, R. P. (2019). Recycling of organic wastes in agriculture: an environmental perspective. *International Journal of Environmental Research, 13*(2), 409-429.
Shi, P., & Schulin, R. (2018). Erosion-induced losses of carbon, nitrogen, phosphorus and heavy metals from agricultural soils of contrasting organic matter management. *Science of the Total Environment, 618*, 210-218.
Shukla, P., Skea, J., Calvo Buendia, E., Masson-Delmotte, V., Pörtner, H., Roberts, D., . . . Van Diemen, R. (2019). IPCC, 2019: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems.
Sissine, F. (2007). *Energy Independence and Security Act of 2007: a summary of major provisions*.
Smol, M., Adam, C., & Krueger, O. (2020). Use of nutrients from wastewater for the fertilizer industry-approaches towards the implementation of the circular economy (CE).
Smolders, E. (2017). Scientific aspects underlying the regulatory framework in the area of fertilisers–state of play and future reforms. In *IP/A/IMCO/2016-19-PE 595.354*: European Union.
Smolders, E., & Six, L. (2013). Revisiting and updating the effect of phosphate fertilizers to cadmium accumulation in European agricultural soils. *Division of SoilandWater Management, Heverlee, Belgium*.
Steen, I. (1998). Phosphorus availability in the 21st century: management of a non-renewable resource. *Phosphorus Potassium, 217*, 25-31.
Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., . . . De Wit, C. A. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science, 347*(6223).
Steiner, G., Geissler, B., Watson, I., & Mew, M. C. (2015). Efficiency developments in phosphate rock mining over the last three decades. *Resources, Conservation and Recycling, 105*, 235-245.
Sud, M. (2020). Managing the biodiversity impacts of fertiliser and pesticide use: Overview and insights from trends and policies across selected OECD countries.
Svendsen, L. M., & Gustafsson, B. (2020). Waterborne nitrogen and phosphorus inputs and water flow to the Baltic Sea 1995-2018. *HELCOM Baltic Sea Environmental Fact Sheet. URL: https://helcom. fi/media/documents/BSEFS-Waterborne-nitrogen-a n d-phosphorus-inputs-and-water-flow-to-the-Baltic-Sea. pdf.(Accessed 5 November 2020)*.
Takolander, A., Cabeza, M., & Leskinen, E. (2017). Climate change can cause complex responses in Baltic Sea macroalgae: A systematic review. *Journal of Sea research, 123*, 16-29.
Talboys, P. J., Heppell, J., Roose, T., Healey, J. R., Jones, D. L., & Withers, P. J. (2016). Struvite: a slow-release fertiliser for sustainable phosphorus management? *Plant and soil, 401*(1-2), 109-123.
Taylor, M., Kim, N., Smidt, G., Busby, C., McNally, S., Robinson, B., . . . Schnug, E. (2016). Trace element contaminants and radioactivity from phosphate fertiliser. In *Phosphorus in Agriculture: 100% Zero* (pp. 231-266): Springer.

Tie-jun, R. (2008). World agriculture and fertilizer demand, global fertilizer supply and trade in 2007~ 2008 (Summary report). *Phosphate & Compound Fertilizer*, 04.

Tkaczyk, P., Mocek-Płóciniak, A., Skowrońska, M., Bednarek, W., Kuśmierz, S., & Zawierucha, E. (2020). The mineral fertilizer-dependent chemical parameters of soil acidification under field conditions. *Sustainability, 12*(17), 7165.

Ulrich, A. E. (2019). Cadmium governance in Europe's phosphate fertilizers: Not so fast? *Science of the Total Environment, 650*, 541-545.

Ulrich, A. E., & Frossard, E. (2014). On the history of a reoccurring concept: phosphorus scarcity. *Science of the Total Environment, 490*, 694-707.

UNEP. (2021). *Food Waste Index Report 2021*. Nairobi: United Nations

United Nations. (2019). *The Sustainable Development Goals Report 2019*. New York

United Nations. (2020). Guterres 'remains committed' to maintaining 1991 ceasefire in Western Sahara. *Peace and Security.* Retrieved from https://news.un.org/en/story/2020/11/1077672

USGS. (2011). *Mineral Commodity Summaries 2011*. U.S. Department of the Interior

USGS. (2021). *Mineral Commodity Summaries 2021*. Virginia: U.S. Department of the Interior

van der Kooij, S., van Vliet, B. J., Stomph, T. J., Sutton, N. B., Anten, N. P., & Hoffland, E. (2020). Phosphorus recovered from human excreta: A socio-ecological-technical approach to phosphorus recycling. *Resources, Conservation and Recycling, 157*, 104744.

Van Kauwenbergh, S. J., Stewart, M., & Mikkelsen, R. (2013). World reserves of phosphate rock… a dynamic and unfolding story. *Better Crops, 97*(3), 18-20.

Van Vuuren, D. P., Bouwman, A. F., & Beusen, A. H. (2010). Phosphorus demand for the 1970–2100 period: a scenario analysis of resource depletion. *Global Environmental Change, 20*(3), 428-439.

Vogliano, C., Murray, L., Coad, J., Wham, C., Maelaua, J., Kafa, R., & Burlingame, B. (2021). Progress towards SDG 2: Zero hunger in melanesia–A state of data scoping review. *Global Food Security, 29*, 100519.

Wackernagel, M., Hanscom, L., Jayasinghe, P., Lin, D., Murthy, A., Neill, E., & Raven, P. (2021). The importance of resource security for poverty eradication. *Nature Sustainability*, 1-8.

Walsh, P. P. (2021). The Political Economy of Sustainable Development. *The Economy of Ireland: Policy Making in a Global Context*, 136.

Wang, L., Cui, X., Cheng, H., Chen, F., Wang, J., Zhao, X., . . . Pu, X. (2015). A review of soil cadmium contamination in China including a health risk assessment. *Environmental Science and Pollution Research, 22*(21), 16441-16452.

Wang, Q., Zhang, J., Zhao, B., Xin, X., Zhang, C., & Zhang, H. (2014). The influence of long-term fertilization on cadmium (Cd) accumulation in soil and its uptake by crops. *Environmental Science and Pollution Research, 21*(17), 10377-10385.

Wang, Y., & Lambers, H. (2020). Root-released organic anions in response to low phosphorus availability: recent progress, challenges and future perspectives. *Plant and soil, 447*(1), 135-156.

Warne, M., George, R., Brent, P., Drew, N., Klim, E., Mclaughlin, M., . . . Sparrow, L. (2007). *Final Report of the National Cadmium Management Committee (NCMC)*. National Cadmium Committee Retrieved from https://csiropedia.csiro.au/wp-content/uploads/2017/08/NCMC-Final-Report-web.pdf

WHO. (2000). *Air quality guidelines for Europe*. (9289013583). Copenhagen: WHO Regional Office for Europe

WHO. (2019a). *Preventing disease through healthy environments: exposure to highly hazardous pesticides: a major public health concern*. (WHO/CED/PHE/EPE/19.4.2). World Health Organization
WHO. (2019b). *Safer water, better health*. (9241516895). World Health Organization
WHO. (2021). *Levels and trends in child malnutrition: UNICEF/WHO/The World Bank Group joint child malnutrition estimates: key findings of the 2021 edition*: World Health Organization.
Wingate, E., & Kohmuench, J. (2016). An optimized approach to phosphate recovery. *Beneficiation of Phosphates: Comprehensive Extraction, Technology Innovations, Advanced Reagents*, 43.
Withers, P. J. (2019). Closing the phosphorus cycle. *Nature Sustainability, 2*(11), 1001-1002.
Withers, P. J., Vadas, P. A., Uusitalo, R., Forber, K. J., Hart, M., Foy, R. H., . . . Burkitt, L. L. (2019). A global perspective on integrated strategies to manage soil phosphorus status for eutrophication control without limiting land productivity. *Journal of Environmental Quality, 48*(5), 1234-1246.
Wooldridge, S. A. (2020). Excess seawater nutrients, enlarged algal symbiont densities and bleaching sensitive reef locations: 1. Identifying thresholds of concern for the Great Barrier Reef, Australia. *Marine pollution bulletin, 152*, 107667.
World Bank. (2020). *Poverty and Shared Prosperity 2020: Reversals of Fortune*. The World Bank
WWAP. (2017). *The United Nations World Water Development Report 2017. Wastewater: The Untapped Resource*. Paris: UNESCO
Zabel, F., Delzeit, R., Schneider, J. M., Seppelt, R., Mauser, W., & Václavík, T. (2019). Global impacts of future cropland expansion and intensification on agricultural markets and biodiversity. *Nature communications, 10*(1), 1-10.
Zhang, T. (2019). *Phosphorus: Recovery and Recycling*: IntechOpen.
Zhao, Q., Du, C., Jia, Y., Yuan, J., Song, G., Zhou, X., . . . Yang, S. (2020). Solar-powered Janus membrane for one-step conversion of sewage to clean water. *Chemical Engineering Journal, 387*, 124131.