02

Phosphorus reserves, resources and uses

Lead authors: Will J. Brownlie, Mark A. Sutton
Co-authors: Marissa A. de Boer, Lino Camprubí, Helen A. Hamilton, Kate V. Heal, Tibisay Morgandi, Tina-Simone Neset, Bryan M. Spears

Left: The Bou Craa phosphate mine, taken from the International Space Station. Bou Craa is one of the largest phosphate mines in the world, and one of the few human patterns visible from space in the western extremity of the Sahara Desert. Photograph courtesy of the Earth Science and Remote Sensing Unit, NASA Johnson Space Center, www.eol.jsc.nasa.gov.

Five countries hold 85% of the planet's phosphate rock reserves. High dependency on imported phosphate rock and/or mineral phosphorus fertiliser can contribute to national food system vulnerability. Geological depletion of phosphate rock is not an immediate threat, however geopolitical, institutional, economic, and managerial factors may impact phosphorus access. Improving the efficient use of phosphorus in agriculture and shifting reliance away from mined phosphorus sources by increasing phosphorus recycling may offer the greatest protection against potential phosphorus supply risks.

Suggested citation for this chapter: W.J. Brownlie, M.A. Sutton, M.A. de Boer, L. Camprubi, H.A. Hamilton, K.V. Heal, T. Morgandi, T.S. Neset, B.M. Spears. (2021). Chapter 2. Phosphate rock: resources, reserves and uses, in: W.J. Brownlie, M.A. Sutton, K.V. Heal, D.S. Reay, B.M. Spears (eds.), Our Phosphorus Future. UK Centre for Ecology & Hydrology, Edinburgh. doi: 10.13140/RG.2.2.25016.83209

Challenge 2.1: Few nations have phosphate rock reserves

Five countries hold around 85% of known phosphate rock reserves, with 70% found in Morocco and Western Sahara alone. Most countries do not have any phosphate rock reserves and are reliant on imports to supply their phosphorus demands to maintain food security. China, Morocco and Western Sahara, the USA and Russia currently produce around 80% of the planet's phosphate rock supply.

Challenge 2.2: Phosphate rock can contain contaminants harmful to human, animal and environmental health

Different phosphate rock ores vary in their composition between phosphates, impurities and contaminants. Phosphate rock contaminants can be transferred into fertiliser products, spread on soils, and end up in food. Cadmium is of particular concern as it can pose a risk to human, animal and environmental health when above threshold levels. The by-products of phosphate rock processing also include ~200 Mt year^{-1} of phosphogypsum, which can contain hazardous contaminants. Concerns have been raised that contaminant leaching from phosphogypsum stockpiles may pose a risk to the environment and the health of local communities.

Challenge 2.3: Geopolitics can impact phosphorus supply and demand, while slowing action on phosphorus sustainability

National and regional policies can have direct and indirect impacts on phosphorus access domestically or abroad. This includes taxes, tariffs, trade agreements and legislation. Political instability in countries mining phosphate rock can affect phosphate supply (e.g. Syria). Concerns over the legality and legitimacy of phosphate rock production in Western Sahara remain unresolved. Such issues also contribute to sensitivities that represent a barrier to effective dialogue and action on phosphorus.

Challenge 2.4: Phosphate rock price spikes remain an ongoing risk

In 2008, phosphate rock prices spiked by 800%, causing a subsequent increase in fertiliser prices that affected the livelihood of many of the world's poorest farmers. This price spike occurred in response to a combination of factors, including instability in energy prices, changing dynamics of supply/demand for agricultural and phosphorus products, and the influence of geopolitics on exports. The stability of phosphate rock prices remains vulnerable to such drivers.

Challenge 2.5: There is a lack of transparent, complete, and comparable phosphate rock data

Significant discrepancies in phosphate rock data are reported, making it difficult to assess accurately the risk of geographic depletion of reserves. Differing definitions for phosphate rock 'reserves' and 'resources' are a cause of discrepancies. Datasets on phosphate rock reserves and resources are commercially sensitive and are often not publicly available. Reserve estimates are dynamic and require regular updating, while conformity in data and reporting is needed. The United States Geological Survey estimates global phosphate rock reserves in 2020 at 70,000 Mt, indicating a current lifetime of >300 years, although a longer lifetime may be expected in practice due to innovation and price elasticity.

Solution 2.1: Reduce reliance on mineral phosphorus fertiliser

Replacing mineral phosphorus fertiliser with recycled phosphorus fertiliser would help to shift reliance away from mined phosphorus sources. Optimising capacity to recycle phosphorus throughout the food value chain in combination with societal change (e.g. diet change) would help to reduce phosphorus demand and losses. Enabling mainstream production of sustainable recycled phosphorus fertilisers containing low concentrations of contaminants is an essential prerequisite to upscaling operational recycling.

Solution 2.2: Establish safety levels for contaminants in fertilisers and agricultural products

Internationally agreed limits should be set for cadmium and harmful contaminants in mineral and recycled phosphorus fertilisers and food. Existing national cadmium limits require better enforcement. Optimising fertiliser use to match plant needs and practices to reduce phosphorus losses can also decrease inputs, thereby further lowering the application of fertiliser contaminants to soils, complementing the use of clean mineral and recycled phosphorus fertilisers.

Solution 2.3: Promote models of governance aimed at ensuring phosphorus security

Ensuring phosphorus security which supports all farmers to access sufficient phosphorus to grow crops, is a global responsibility and requires international cooperation. Balanced stakeholder participation in negotiations is necessary to ensure phosphate security and avoid domination of regulatory agencies by industries or private interests. An internationally agreed framework promoting sustainable phosphate rock mining and trading is currently missing and urgently needed.

Solution 2.4: Improve stakeholder capacity to deal with phosphate rock price volatility

Stakeholders need to plan for uncertainty by increasing adaptive capacity. Building national capacity to close the phosphorus loop in food production systems and shifting reliance from mined phosphorus to recycled phosphorus will help protect against phosphorus supply risk. Governments need to recognise phosphorus supply risks through appropriate policy and regulation.

Solution 2.5: Improve transparency and the independent assessment of phosphate rock data

There is a need for transparency and free access to accurate, current data on global reserves and resources of phosphate rock. An independent, international body is needed to assess data regularly and to disseminate findings through appropriate mechanisms, institutions and outreach programmes.

2.1 Introduction

For millions of years, the total amount of 'mobile' phosphorus (P) supporting the world's ecosystems remained largely unchanged. This 'mobile' P flowed between the various compartments of soil, plant, animal, wastes, waters, and sediments. Around 8000 years ago when farmers discovered that applying animal manures to croplands improved their harvests, humans started manipulating this system (Bogaard et al., 2013). In the 19th century, in addition to manures, P fertilisation of crops was commonly achieved by applying bone meal from slaughtered animals to soils (Plotegher and Ribeiro, 2016). However, as food demands increased, the low solubility of bone meal was not sufficient to provide an adequate supply of P to crops. In attempts to increase crop production, countries that could afford it replenished the P in their soils with P-rich guano (seabird and bat excrement accumulated over several millennia). A thriving industry quickly sprung up to export guano from Peru to Europe, complete with new infrastructure, overnight millionaires, and widespread worker exploitation (Melillo, 2012; Schnug et al., 2018). However, the guano deposits were quickly exhausted, and by the 1870s the guano industry had all but collapsed (Melillo, 2012; Schnug et al., 2018).

In parallel, by 1840, the agricultural scientist, Justus von Liebig had discovered the solubilisation of bone meal could be assisted through treatment with sulfuric acid (Ivell, 2012). Acid-treated bone meal released P more readily to soils and hence increased P uptake by crops (Plotegher and Ribeiro, 2016). In the same year, Liebig successfully applied the same chemical treatment to phosphate rock (PR) (Ivell, 2012). In the years that followed, John Bennet Lawes developed this process at an industrial scale, and renamed the product 'superphosphate fertiliser'; this was to be the first P fertiliser commercially produced worldwide (Ashley et al., 2011; Ivell, 2012). Since that time, with rapidly increasing production since World War II, PR has been the main source of P used by society, predominantly to provide fertilisers (Cordell et al., 2009; Ashley et al., 2011) (Figure 2.1). Over the past century, anthropogenic use of P, predominantly in agriculture, has increased by a factor of ~18 (from ~2 Mt year^{-1} in 1910 to a peak use of ~36 Mt year^{-1} in 2016) (Figure 2.1).

Globally, around 85% of phosphates produced for market are processed to make mineral P fertilisers, and 10% are used to make animal feed supplements. The remaining 5%, equivalent to ~2.5 Mt phosphorus pentoxide (P_2O_5) annually[i], is used across a range of chemical industries (de Boer et al., 2019). Of this ~2.5 Mt, around 38% is used for detergents and cleaning products, 25% for food and drink additives, 10% in metal production, 10% for water treatment to reduce dissolution of lead water pipes, 3% for specialised fertilisers (e.g. for use in aquaculture and aquaponics), and 3% for toothpaste, with the remaining 14% used for various purposes such as fuel cell electrolytes and medicines (Gantner et al., 2014; numbers rounded to nearest 1%) (Figure 2.2).

[i] Based on global consumption of ~50 Mt P_2O_5 as estimated for 2019 in Jasinski, (2020).

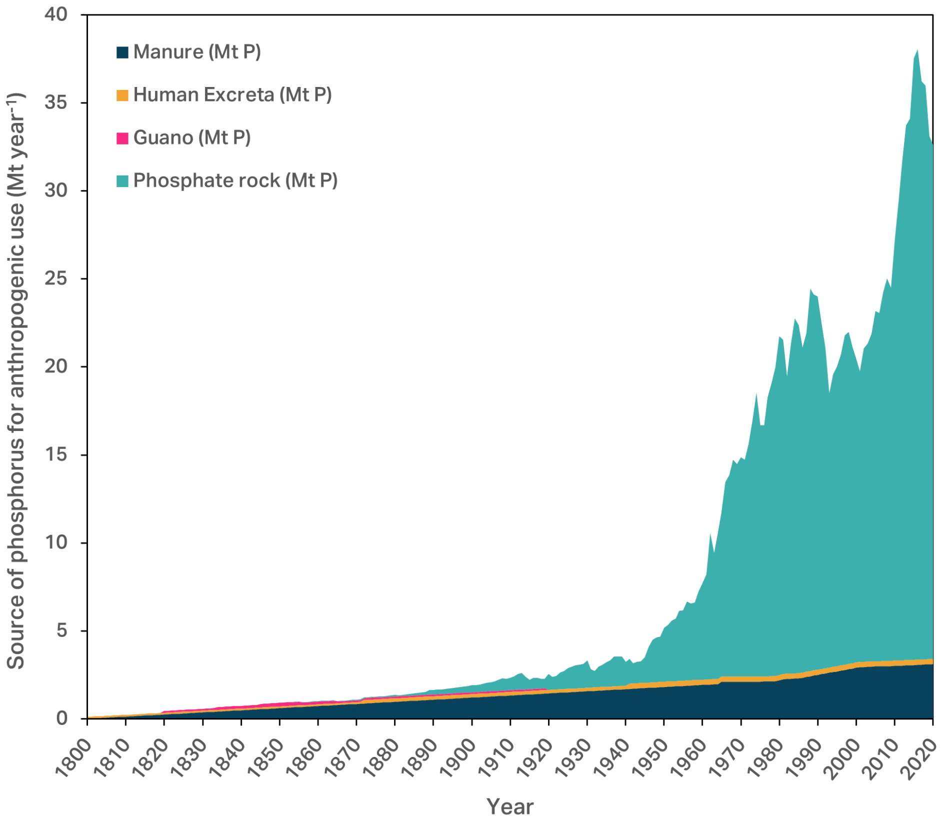

Figure 2.1 Sources of phosphorus (P) for anthropogenic use 1800–2020, including manure, human excreta, guano and P mined from phosphate rock (it is estimated ~85% of the phosphates produced from PR are used to produce mineral P fertilisers). The reliability of data sources varies; data points for human excreta, guano and manure should be interpreted as indicative rather than precise. Graph modified from Cordell et al., (2009) based on data from Smil, (2000); Cordell et al., (2009); U.S. Geological Survey, (2014); Chen and Graedel, (2016); Jasinski, (2021).

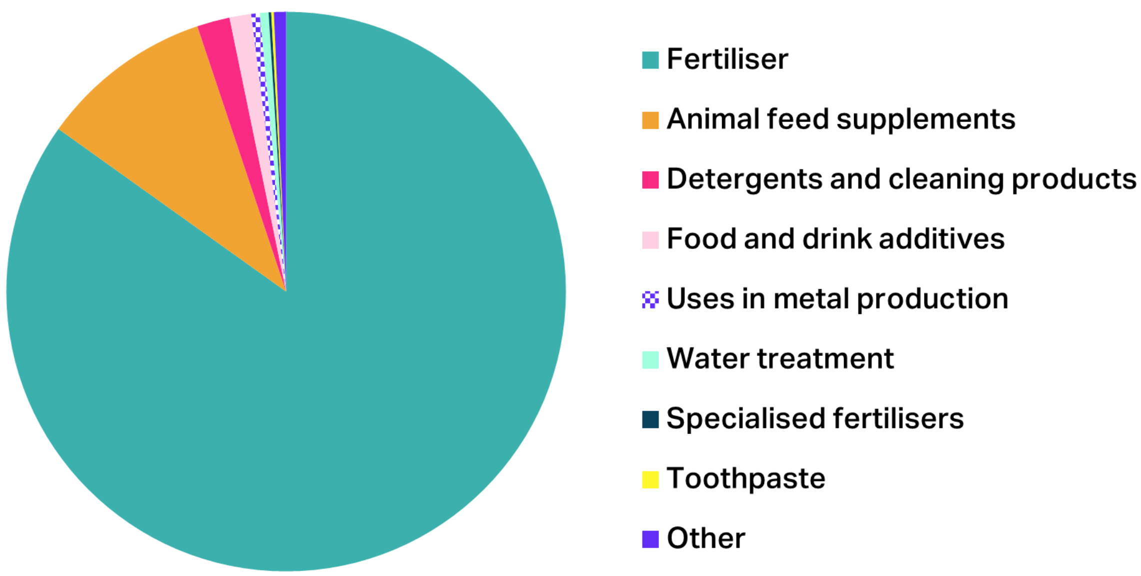

Figure 2.2 Global estimated uses of phosphorus mined from phosphate rock in 2014. 'Water treatment' refers to the addition of phosphate into potable water to reduce lead solvency from lead pipes, 'specialised fertilisers' refer to niche use fertilisers (e.g. for use in aquaculture and aquaponics). Based on data from Gantner et al. (2014) and de Boer et al. (2019).

2.2 Phosphorus sources and processing

2.2.1 Types of phosphate rock

There are three major types of PR: sedimentary, igneous and metamorphic. Each rock type has a different chemical composition, P content and range of impurities, and therefore physical characteristics (Table 2.1). Phosphate rock reserves are mined mostly at the surface, using bucket-wheel and dragline excavators and power shovels and earthmovers (Figure 2.3). The phosphate rock type has a significant impact on how easy it is to mine, the level of processing needed, and the energy requirements to complete mining and initial processing stages.

2.2.2 Processing phosphate rock and applications

Marketed PR is enriched to at least 28%, and often more than 30%, in P_2O_5. The process used to enrich PR is termed 'beneficiation' and refers to an initial processing stage, often consisting of grinding the rock, followed by flotation to separate non-P bearing minerals based on their densities and hydrophobic and hydrophilic properties.

The phosphates in untreated PR are not very water-soluble, and therefore not readily available to plants for uptake, though some plant types such as certain legumes and macadamia can mobilise the P from PR (Lyu et al., 2016; Zhao et al., 2019). Igneous deposits can provide PR with 35% to 40% P_2O_5 content after beneficiation.

Figure 2.3 Phosphate mining by the state company Société Nouvelle des Phosphates du Togo, in Togo. Photograph courtesy of Alexandra Pugachevsky.

Table 2.1 Description of the three main phosphate rock (PR) types mined for phosphorus (P), providing details on phosphate (PO_4^{3-}) concentrations (as a percentage of rock weight), mineral composition, and the location of key reserves, modified from de Boer et al. (2019) and van Kauwenbergh (2010).

Rock type	Description	Phosphate concentrations	Chemical composition	Geographic location of main global reserves
Sedimentary Rock	Sedimentary marine 'phosphorite' is the most common PR produced from accumulated fossilised shells and aquatic animals. More than 80% of mined phosphates originate from sedimentary rocks.	Phosphate concentrations in phosphatic shales and limestones range from 7.8% to 19.5% phosphate, whilst phosphorite contains above 19.5% phosphate.	Sedimentary rock contains the mineral apatite, which is calcium phosphate combined with either a hydroxide, fluoride, or chloride ion: $Ca5(PO_4)3(OH)$ or (F) or (Cl). Fluorapatite is the most common form. Whilst apatite is sparingly soluble in water, the different compositions influence its solubility.	China, Middle East, Northern Africa, USA
Igneous	Igneous deposits are associated with carbonatites and silica-deficient intrusions, formed through the crystallisation of cooling lava or magma.	Phosphate concentrations in igneous rocks are often lower than in sedimentary rocks, ranging from 0.005% to 0.4%, but higher values (i.e. up to 15% phosphate) can be found in strongly alkaline, low-silica igneous rocks.	Igneous rock mainly consists of carbonatite minerals consisting of more than 50% carbonate minerals and alkalic intrusions (e.g. diopside; $MgCaSi_2O_6$). The minerals calcite and dolomite can also be present in igneous rock.	Brazil, Canada, Finland, Russia, South Africa, Zimbabwe
Metamorphic	Both igneous and sedimentary rocks that have been subject to high temperature and pressure may form metamorphic phosphate rock.	Metamorphic rock often contains 0.01% to 1.3% phosphate.	Metamorphic rocks are created in high pressure and temperature conditions resulting in a less porous texture, more interlocked crystals, and higher induration compared to igneous and sedimentary rock. Consequently, the exploitation of metamorphic rock deposits is not currently economically viable.	China, India

The direct application of this 'granulated PR' with organic material can then be used as an alternative to mineral fertiliser, but this requires acidic soils and is not common practice (Sanchez, 2002; Chianu et al., 2012).

In most cases, the P in PR is processed into several intermediary products, including phosphoric acid and superphosphates, with less than 3% processed into (elemental) white phosphorus. Together these compounds provide the basis of industrial P chemistry (Figure 2.4).

2.2.3 Superphosphate

Superphosphate (SSP), double superphosphate (DSP) and triple superphosphate (TSP) is the term used in the P fertiliser industry for fertilisers containing monocalcium phosphate, also called calcium dihydrogen phosphate ($Ca(H_2PO_4)2.H_2O$). The key differences between SSP, DSP and TSP is their method of production and the P content of the final products. Single superphosphate is produced via the reaction between phosphate rock and sulfuric acid (H_2SO_4), whilst DSP and TSP are produced via the reaction between phosphate rock and phosphoric acid (H_3PO_4). Single, double and triple superphosphate have a P_2O_5 concentration of 7-9%, 32-36% and 44-46%, respectively.

Production of SSP is a basic technique that has changed very little since its commercialisation in the 1800s (Ivell, 2012; IPNI, 2014a). Ground PR is treated with sulfuric acid to form a semi-solid, which is allowed to cool for several hours. This plastic-like substance is then cured for several weeks. The hardened material is then milled and screened to the required particle or granule size (IPNI, 2014a). Non-granular DSP and TSP are made by reacting ground PR with liquid phosphoric acid, commonly within a cone-type mixer (IPNI, 2014b). Granular DSP and TSP are made similarly, but the resulting slurry is sprayed as a coating onto small particles to build granules of the desired size. The products from both production methods then cure for several weeks as the chemical

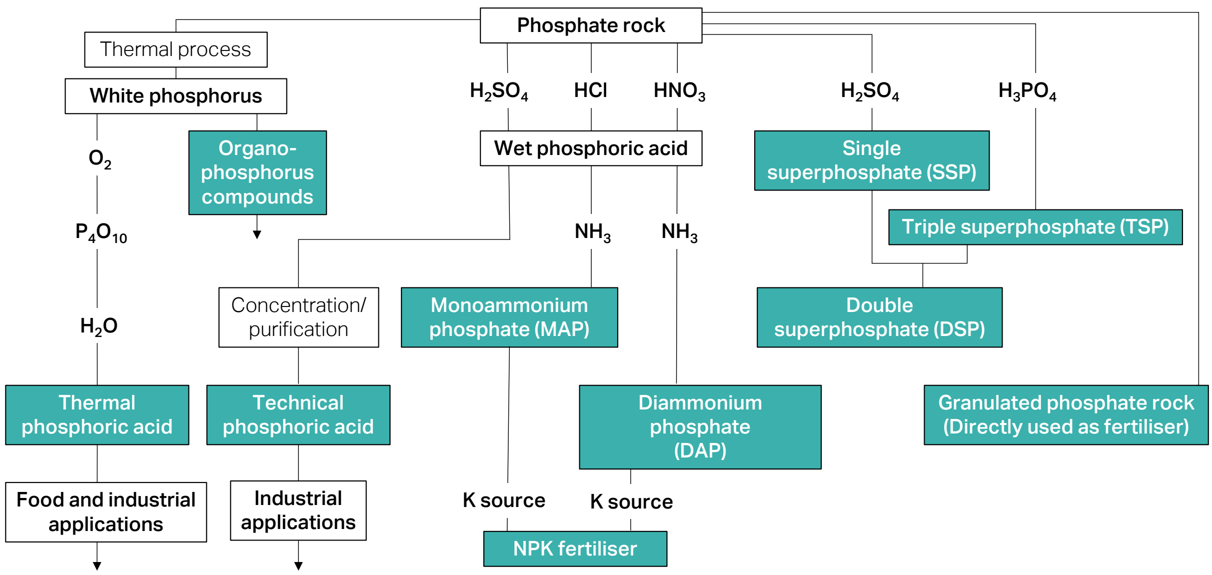

Figure 2.4 Typical processing pathways of phosphate rock to common P containing products, showing key reagents involved in the different stages. Modified from de Boer et al. (2019).

reactions are slowly completed. The chemistry and processes of these reactions vary somewhat depending on the properties of the phosphate rock.

The main fertilisers used in agriculture are monoammonium phosphate (MAP), diammonium phosphate (DAP), SSP, DSP and TSP. The ratio of nutrients differs among fertiliser types (Table 2.2).

Table 2.2 The ratio of nutrients nitrogen (N), phosphorus (P) and potassium (K) in a range of P fertilisers.

Fertiliser	Ratio of N:P:K
Monoammonium phosphate (MAP)	10:50:0
Diammonium phosphate (DAP)	18:46:0
Single superphosphate (SSP)	0:18:0
Single superphosphate (SSP)	0:36:0
Triple superphosphate (TSP)	0:46:0

2.2.4 Phosphoric acid

Two main commercial methods are used to produce phosphoric acid from PR, known as the wet process and the thermal process.

The wet process consists of three key stages: (1) digestion, (2) filtration and (3) concentration. In the first step, phosphate-containing apatite minerals (e.g. calcium hydroxyapatite or fluoroapatite) are treated in a reactor with a mineral acid (usually sulfuric acid). Nitric and hydrochloric acids (HNO_3, HCl) can also be used but are more expensive. This produces phosphoric acid and the by-product phosphogypsum (a thick slurry of solid particles containing gypsum ($CaSO_4 \cdot (nH_2O)$, where n=0, ½, or 2), unreacted residual PR and impurities. In the second stage, phosphogypsum is removed using a partial vacuum, leaving 'wet' phosphoric acid (23-33% P_2O_5). In the third step, the phosphoric acid is concentrated by reducing the liquid content, via evaporation with submerged combustion burners and vacuum circulation evaporators. 'Wet' phosphoric acid must be concentrated to 40-55% P_2O_5 for fertiliser/merchant grade, 50%-61.6% P_2O_5 for technical grade phosphoric acid, and above 61% P_2O_5 for semiconductor grade (de Boer et al., 2019).

Around 95% of the phosphoric acid produced globally is made using the wet process. An issue associated with the wet process is the production of large quantities of phosphogypsum, which can contain contaminants, depending on PR type (Tayibi et al., 2009). Impurities in PR can be carried into phosphoric acid products and/or phosphogypsum. A fourth stage can be added to remove impurities, but can represent a major challenge (Syers, 2001). The concentration and type of contaminants present are dependent on the PR origin as well as the digestion method. For example, phosphoric acid produced from igneous PR typically contains 5-10 mg l^{-1} of uranium, whilst 120-160 mg l^{-1} of uranium can be found in phosphoric acid produced from sedimentary PR (Cioroianu et al., 2001). The risk posed by impurities in fertilisers is discussed in more detail later in this chapter.

The thermal process is a less common method for producing phosphoric acid. Whilst methods differ between production plants, the thermal process can be described by three major steps: (1) combustion, (2) hydration, and (3) demisting (Speight, 2017). In the thermal process, the raw materials to produce phosphoric acid are elemental phosphorus, air and water. In the combustion step, the liquid elemental P is oxidised in a combustion chamber at temperatures of 1650–2760°C to form phosphorus pentoxide. The P_2O_5 is then hydrated with dilute phosphoric acid or water to produce a strong phosphoric acid liquid. The last stage is demisting, which removes the phosphoric acid mist from the combustion gas stream, before releasing it to the atmosphere, usually using high-pressure-drop demisters (Speight, 2017).

Because the thermal process is energy-intensive, purified wet-process phosphoric acid has replaced thermal phosphoric acid in many applications. However, phosphoric acid produced via the thermal process is of a much higher purity, which is often required to produce some organo-P compounds (often used in pesticides), such as phosphorus trichloride (PCl_3), and several other high-grade chemicals, pharmaceuticals, detergents, food products and beverages. The compounds that are produced using phosphoric acid are diverse, as summarised in Figure 2.5.

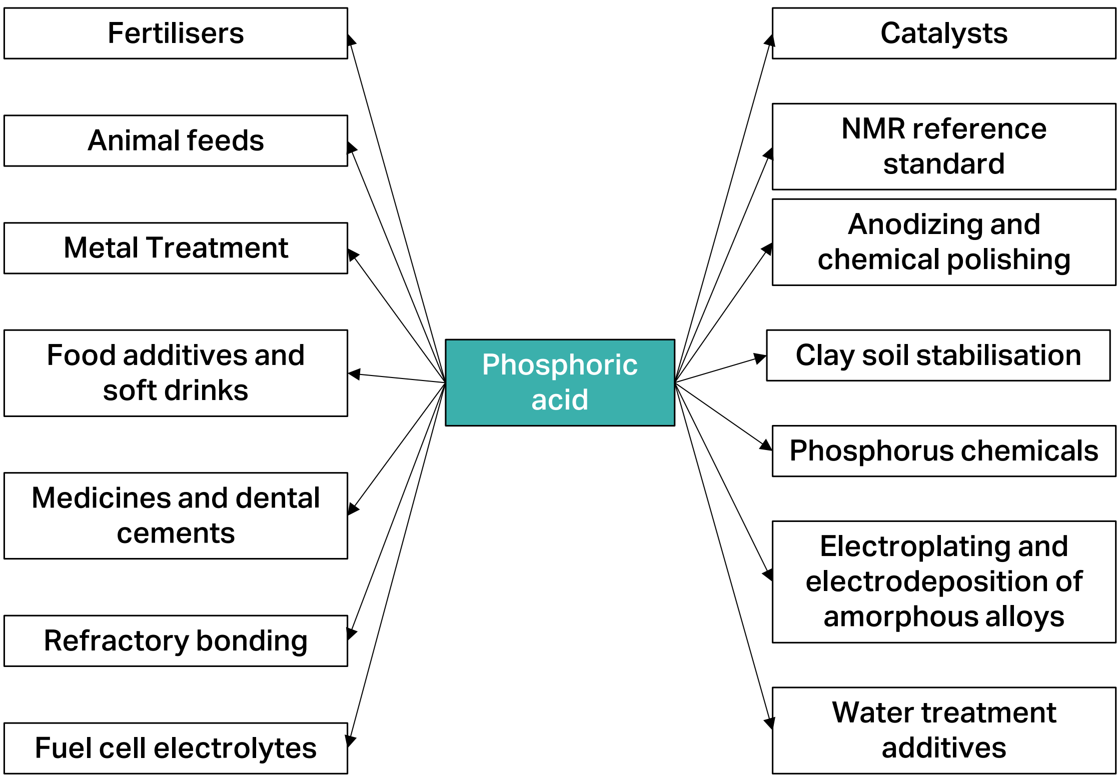

Figure 2.5 Common uses of phosphoric acid (H3PO4). NMR – Nuclear Magnetic Resonance Spectroscopy. Figure modified from de Boer et al. (2019).

2.2.5 White phosphorus

Several materials require elemental P in their production. Elemental P has ten allotropic forms, different structural modifications of an element, in which the atoms of the element are bonded together differently. The P allotrope 'white P' (P4) is used for 99% of elemental P demands, with ~0.85 Mt produced each year (de Boer et al., 2019).

White P is extremely reactive with oxygen, and as such must be stored underwater, with a layer of nitrogen above the surface. This aggressive reactivity has led to its limited and controversial use as a weapon (e.g. explosives and smoke grenades) (Macleod and Rogers, 2007). Most commonly, white P, which accounts for 1% of global P use, is a starting material to create other compounds, including those used in batteries, flame retardants, catalysts, anti-scale agents, plastic additives and the herbicide glyphosate (Figure 2.6). White P can also be further heated to make the much less reactive allotrope red P, which is stable in air and used as the striking contact on matchboxes.

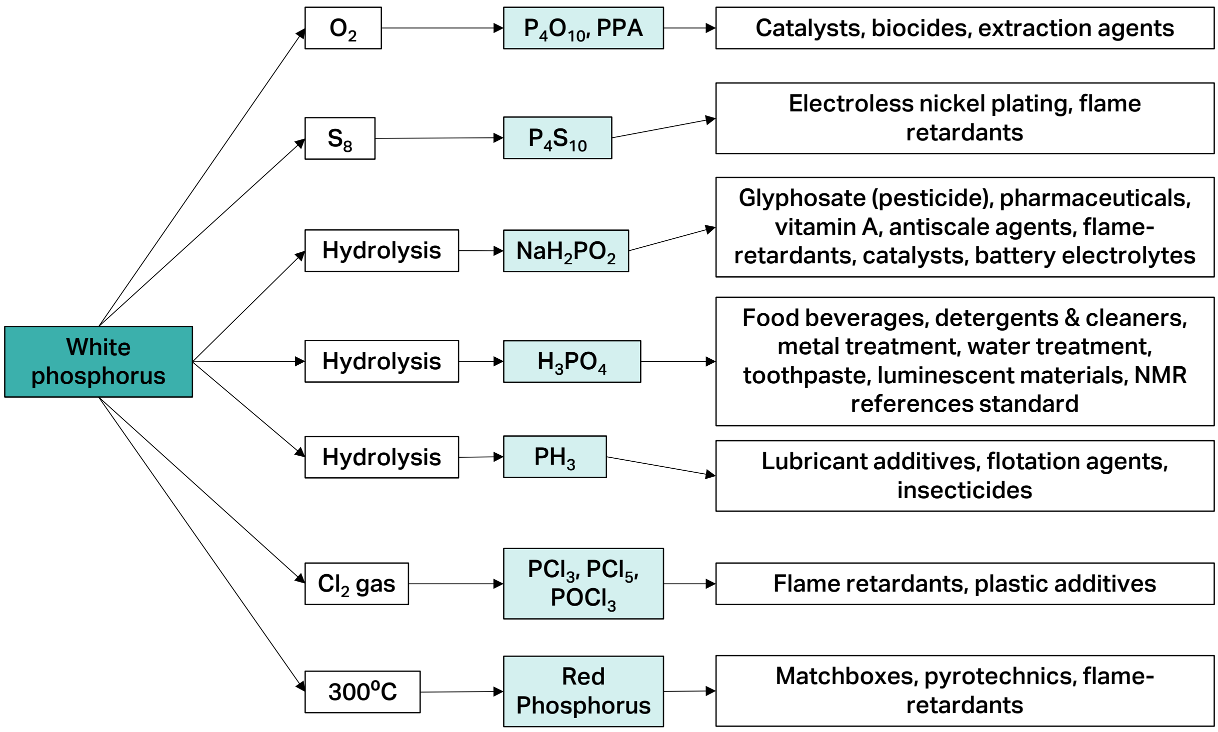

Figure 2.6 Common uses of white phosphorus, modified from de Boer et al. (2019) using data based on Gantner et al. (2014) and inputs from Willem Schipper.

2.3 Why do we need to improve the management of our phosphate rock reserves?

Demand for PR to supply fertiliser demands has increased rapidly since the 1950s, primarily due to the increase in fertilisers for agricultural production aiming to sustain a growing human population with an increasing demand for animal products (Metson et al., 2014), non-food products (Hamilton et al., 2018) and biofuel production (Jarvie et al., 2015) (Figure 2.7). A drop in production was observed between 2016 and 2020 but is still higher than at any point pre-2016 (Figure 2.7).

Besides the demand for fertiliser, there is also a steady increase in P demand for animal feed supplements, fizzy drinks, and flame-retardants (de Boer et al., 2019). Since the mid-1980s, an increasing number of countries have made reductions and/or banned the use of phosphates in domestic laundry and dishwasher detergents (but in some cases not industrial detergents) to reduce the amount of P entering waterbodies (van Drecht et al., 2009; van Puijenbroek et al., 2019). This has caused a drop in P demand for detergents over the last 3-4 decades, whilst demand in all other sectors has increased and is expected to continue to increase (de Boer et al., 2019). Drawing on data from Xu et al. (2020), Spears et al. (2022) estimate that the projected global demand for P to make $LiFePO_4$ batteries for electric cars (assuming a 60% $LiFePO_4$ market share), could increase to >3 Mt P per year by 2050.

Natural losses of P from soils to air and waters have been estimated at about 10 Mt year^{-1} (Smil, 2000). In contrast, in recent times (2000–2020), intensified erosion introduces an estimated additional 30 Mt year^{-1} P into the

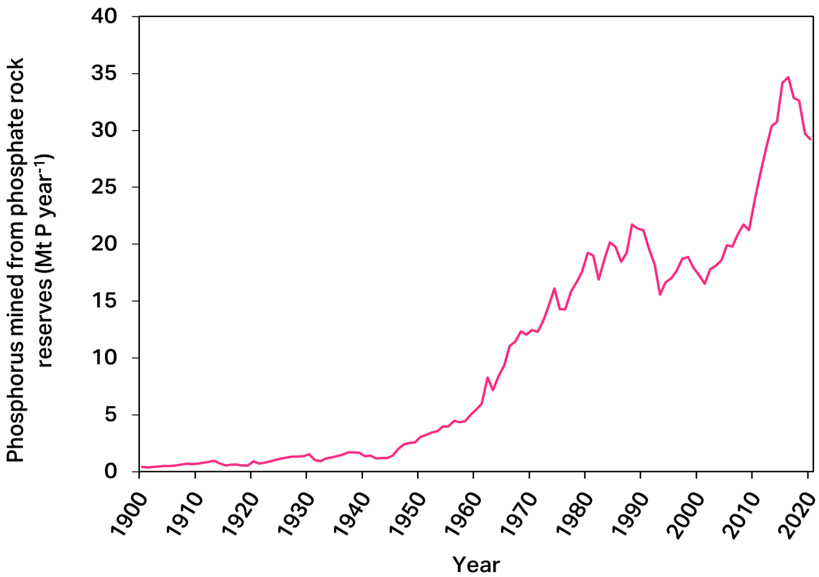

Figure 2.7 Annual mass of phosphorus mined from phosphate rock reserves globally between 1900 and 2020. Based on world production of phosphate rock (Mt) data as compiled by the U.S. Geological Survey (2014) and Jasinski (2021)[i].

[i]Data are based on the assumption that 30% of the mass of phosphate rock is P_2O_5, which was calculated as a global average of P_2O_5 content of PR mined from global PR reserves in 2017, as detailed in Jasinski (2017b). The phosphorus content of P_2O_5 was calculated by multiplying the mass of P_2O_5 by 0.4364.

global environment, mainly because human actions have approximately tripled the rate at which P reaches waters (Table 2.3). We highlight that wide variation in such estimates exists in the literature (e.g. Beusen et al., 2016). Further work is required to agree on standardised model parameters to assess P flows (see Chapter 9).

Poor P management has resulted in widespread P losses to waterbodies, causing significant damage to rivers, lakes, and coastal waters (Smith and Schindler, 2009) (see Chapter 5). Reliance on mined sources of P will continue to mobilise P that would otherwise be 'locked away', into a global mineral cycle where elevated P flows are having major impacts on freshwater and marine ecosystems around the world (see Chapter 5). The human-driven release of P has been estimated to exceed the "planetary boundary" for freshwater eutrophication (i.e., beyond levels deemed safe to avoid abrupt, irreversible environmental change) by a factor of three (Carpenter and Bennett, 2011; Steffen et al., 2015) (see Chapter 5). At the same time, current global reliance on mineral P for fertilisers to produce food means access to mineral P remains a critical requirement for food security at present (see Chapter 3). Actions to reduce the fraction of available P resources that are wasted by losses to the wider environment are necessary to address this dilemma (Chapter 6 and 7), thereby moving towards a more circular economy for phosphorus.

Table 2.3 Human intensification of the global phosphorus cycle (Mt year^{-1}), based on estimates from Smil (2000), updated from Chen and Graedel (2016)* and Jasinski, (2021)**. Note that estimates vary in the literature.

Flux type	Natural	Preindustrial (1800)	Recent (2000–2020)
Natural fluxes (including recent intensification by human actions)			
Erosion (wind)	<2	<3	>3
Erosion (water)	<8	>12	>27
River Transport	>7	>9	>22
Biomass combustion	<0.1	<0.2	<0.3
Anthropogenic fluxes			
Crop uptake	-	1	12
Animal wastes	-	>1	16*
Human wastes	-	0.5	3
Organic recycling	-	<0.5	15*
Mineral fertiliser	-	-	21**

2.4 Global phosphorus reserves and resources

Whilst estimates vary, in 2020, 29.2 Mt of P was mined from global PR reserves estimated to contain 9295 Mt of P (Jasinski, 2021)[i]. For the purpose of these estimates, PR 'reserves' are defined as PR deposits from which PR can be economically produced at the time of the determination using existing technology. This definition can be contrasted with P 'resources', which are defined as PR of any grade, including deposits that cannot be currently mined without significant economic and/or environmental cost (van Kauwenbergh, 2010).

Based on rates of PR production for 2020, the 'lifetime' of existing reserves is 318 years (Jasinski, 2021). However, this estimate fluctuates in response to changes in reported estimates (van Kauwenbergh et al., 2013; Blackwell et al., 2019). For example, annual PR production and PR reserves data for 2010 indicated PR reserves would last for 87 years. One year later this estimate rose to 325 years, largely due to an increase in reserve estimates in Morocco (discussed later in this chapter) (Jasinski, 2009) (Figure 2.8).

Estimated PR production can be compared with global consumption of phosphoric acid, fertilisers, and other uses, which in 2020 contained 21 Mt of P, 68% of the amount of PR mined (i.e. 47 Mt of P_2O_5 (Jasinski, 2021)). The remaining 32% is estimated to be lost to the environment as part of PR processing.

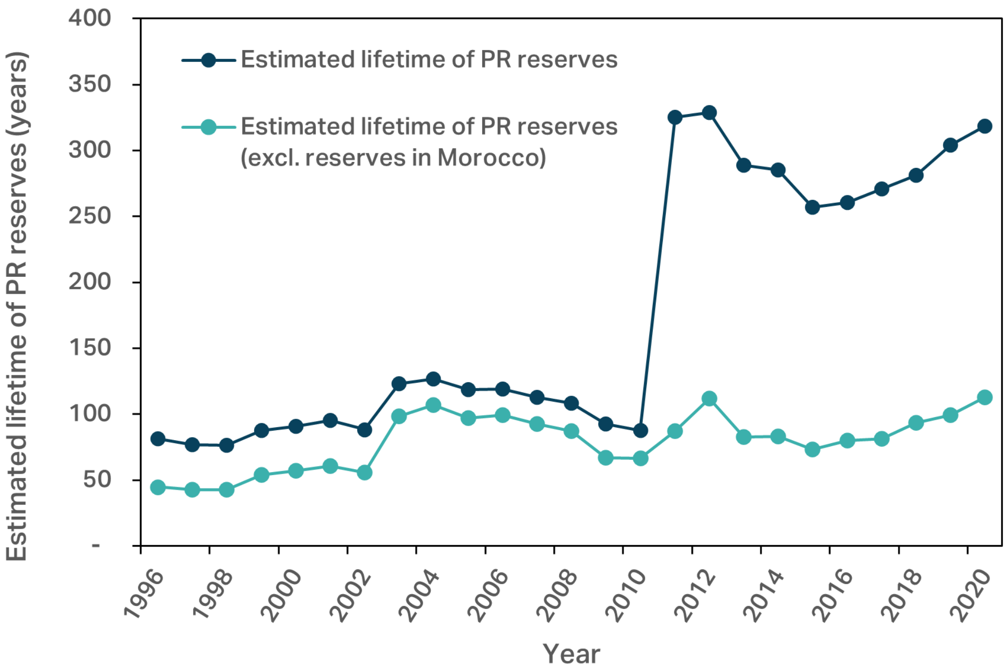

Figure 2.8 Estimated lifetime of global phosphate rock (PR) reserves (years) at current rates (2021) by year between 1996 to 2020, shown with and without Morocco. The estimated lifetime of reserves excluding Morocco is shown based on current total global production assuming that this is market driven.

[i] Calculated from Jasinski (2021) and assumption that 30% of the mass of phosphate rock (PR) is P_2O_5, as a global average, as detailed in Jasinski (2017b), i.e. in 2020, 223 Mt of PR, containing 67 Mt P_2O_5, was mined from global PR reserves of 71,000 Mt of PR, containing 21,300 Mt P_2O_5. Lifetime estimates also assume that remaining PR reserves are of homogeneous P_2O_5 content of 30% by weight. The phosphorus content of P_2O_5 is calculated by multiplying by the mass of P_2O_5 by 0.4364.

Steiner et al. (2015) showed that PR mining efficiency increased between 1983 and 2013, due to improved technologies to regain losses during the excavation and early PR processing stages. They also suggested that the average P content of PR mined globally increased from 513 Mt at 14.5% P_2O_5 in 1983, to 661 Mt at 17.5% P_2O_5 in 2013. However, PR reserves are finite, and concerns that high-quality PR reserves will diminish over time have been raised (Cordell and White, 2011; Scholz et al., 2013; Edixhoven et al., 2014).

Changes in estimated reserves have been observed for other commodities, for example, oil (Aleklett, 2012), rare earth elements, magnesium, tin and tantalum (Sutton et al., 2013; Scholz and Wellmer, 2013). However, unlike many other commodities where alternatives are available (e.g. renewable energy provides an alternative to fossil fuel combustion), nutrients are essential biological requirements; there are therefore no alternatives. Furthermore, nitrogen as a component of the air, is not constrained geographically.

Total global PR resources are estimated at 40,000 Mt of P (or 300,000 Mt of PR). As reserves are depleted and technological innovation occurs, some of these resources would be expected to be made available to increase the number of minable reserves. Based on current mining rates of 30 Mt P $year^{-1}$, the lifetime of estimated PR resources is 1330 years. There is therefore no risk of exhausting global P supplies within the next 100-300 years (Blackwell et al., 2019). However, Blackwell et al. (2019) demonstrate that, if mining production continues at the current rate (as of 2018 and based on current reserve estimates), domestic supplies in the three countries with the largest populations, China, India, and the USA, will be depleted within 40 years. A similar calculation for 2020 estimates (of PR reserves and production) shows that, within the next 46 years, three of the four countries that produce the highest quantities of PR globally (i.e. China, the USA and Russia), will have exhausted their PR reserves (Table 2.4). While some of these time horizons may appear long, it is evident that such a linear economy of mining followed by waste of lost P resources is ultimately unsustainable, with a major challenge to move toward a more circular system where recovery and reuse are central.

The calculated lifetimes of reserves summarised in Table 2.4 are unlikely to be accurate in practice. As demonstrated above, reserve estimates fluctuate, new reserves may be found, and market forces and technological advances may allow further resources to be economically mined (i.e. converting resources to reserves). However, Table 2.4 highlights that imminent, fundamental changes in global P trade, use and recycling efforts will be necessary. Whilst most now acknowledge that geological depletion of PR is not an immediate threat, factors that may impact P access go beyond physical reserves and include geopolitical, institutional, economic and managerial factors (Cordell and White, 2011).

In the following section, the challenges and solutions are discussed for managing our PR reserves in ways that are more sustainable, equitable and safe for human and environmental health. We highlight potential P access issues and risks to supply and suggest key actions that will help to improve 'Phosphorus Security'. As defined by Cordell, (2010), 'Phosphorus Security' allows the world's farmers to access sufficient P in the short and long term to grow enough food to feed a growing world population, while ensuring farmer livelihoods and minimising detrimental environmental and social impacts.

Table 2.4 Estimated phosphate rock (PR) reserves in 2020, PR production in 2019, with a lifetime of reserves calculated at 2020 production rates. The countries selected include the ten countries that produced the highest quantities of PR in 2019 and India. Based on data from Jasinski (2021).

Country/region	PR Reserves (Mt)	Annual PR Production (Mt)	Lifetime of reserves at 2019 production rates
China	3200	90.0	36
USA	1000	24.0	42
Morocco and Western Sahara	50000	37.0	1351
Russia	600	13.0	46
Jordan	800	9.2	87
Tunisia	100	4.0	25
Brazil	1600	5.5	291
Egypt	2800	5.0	560
Israel	57	2.8	20
Australia	1100	2.7	407
India	46	1.5	31
World	**71,000**	**223**	**318**

2.5 Challenges

Challenge 2.1: Few nations have phosphate rock reserves

Five countries hold around 85% of known phosphate rock reserves, with 70% found in Morocco and Western Sahara alone. Most countries do not have any phosphate rock reserves and are reliant on imports to supply their phosphorus demands to maintain food security. China, Morocco and Western Sahara, the USA and Russia currently produce around 80% of the planet's phosphate rock supply.

Phosphate rock reserves are not equally distributed in the world (Jasinski, 2021) (Figure 2.9). Around 85% of the world's known PR reserves are found in only five countries, with 70% in Morocco and Western Sahara alone (Jasinski, 2021).

Mining in China, Russia, the USA, Morocco and Western Sahara accounted for around 80% of global PR production in 2019 (Jasinski, 2021). Since 2006, the production of PR in China has increased significantly, from 30.7 Mt to a peak of 144 Mt in 2017 (Jasinski, 2009, 2019) (Figure 2.10).

Whilst China contains less than 5% of the global PR reserves, it is the largest producer (and consumer) of PR in the world, accounting for 52% of global PR production in 2019 (Jasinski, 2021) (Figure 2.11). However, with ongoing investments in PR mining in Morocco it is anticipated that Morocco will become the largest producer in the coming years (Rosemarin and Ekane, 2016).

In 2019, the global phosphate fertilisers market was worth US$66 billion, with growth projected at a compound annual rate of 7% to reach US$84 billion by 2023 (The Business Research Company, 2020). The global market is dominated by a few key companies (Rosemarin and Ekane, 2016). In 2021, major players in the phosphate fertilisers market included Agrium Inc. (Canada), Coromandel International Ltd. (India), EuroChem Group A (EU), Guizhou (China), Israel Chemicals Limited (Israel), Ma'aden (Saudi Arabia), The Mosaic Company (USA), Nutrien Ltd. (Canada), OCP S.A (Morocco), PhosAgro (Russia) and Yunthianhua (China).

A high dependency on imported PR and/ or mineral P fertiliser can contribute to national food system vulnerability. For example, South Asia is almost completely reliant on P imports (Subba Rao et al., 2015; Jasinski, 2018). In 2015, India imported 8.27 Mt of PR, mainly from Jordan (39%), Egypt (22%) and Morocco (17%), whilst 85% of India's mineral P fertilisers came from China (Indian Bureau of Mines, 2016). Similarly, European countries rely heavily on P imports for mineral fertiliser and animal feed supplements (Ott and Rechberger, 2012; van Dijk et al., 2016). In 2010, the EU imported 7.5 Mt (de Ridder et al., 2012), whilst the remaining ~10% was produced in Finland (the only active PR mining country in Europe). Similarly, Australia is heavily reliant on imports, which have been estimated to supply 80% of its P use (Cordell et al., 2013).

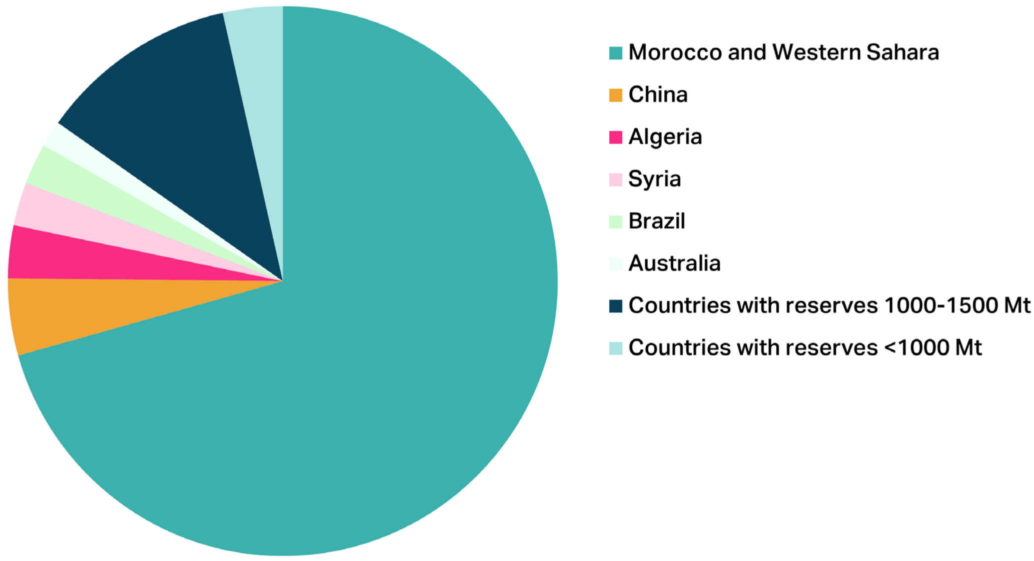

Figure 2.9 Distribution between countries of known phosphate rock (PR) reserves in 2019, equal to 69,000 Mt. Countries with reserves 1000-1500 Mt are Finland, Jordan, and the USA. Countries with <1000 Mt include Russia, Peru, India, Senegal, Kazakhstan, Tunisia, Uzbekistan, Vietnam, Mexico, Israel, and Togo. (Data source: (Jasinski, 2021)). Phosphate rock 'reserve' is defined here as the part of the reserve base which could be economically extracted or produced at the time of determination but need not signify that extraction facilities are in place and operative.

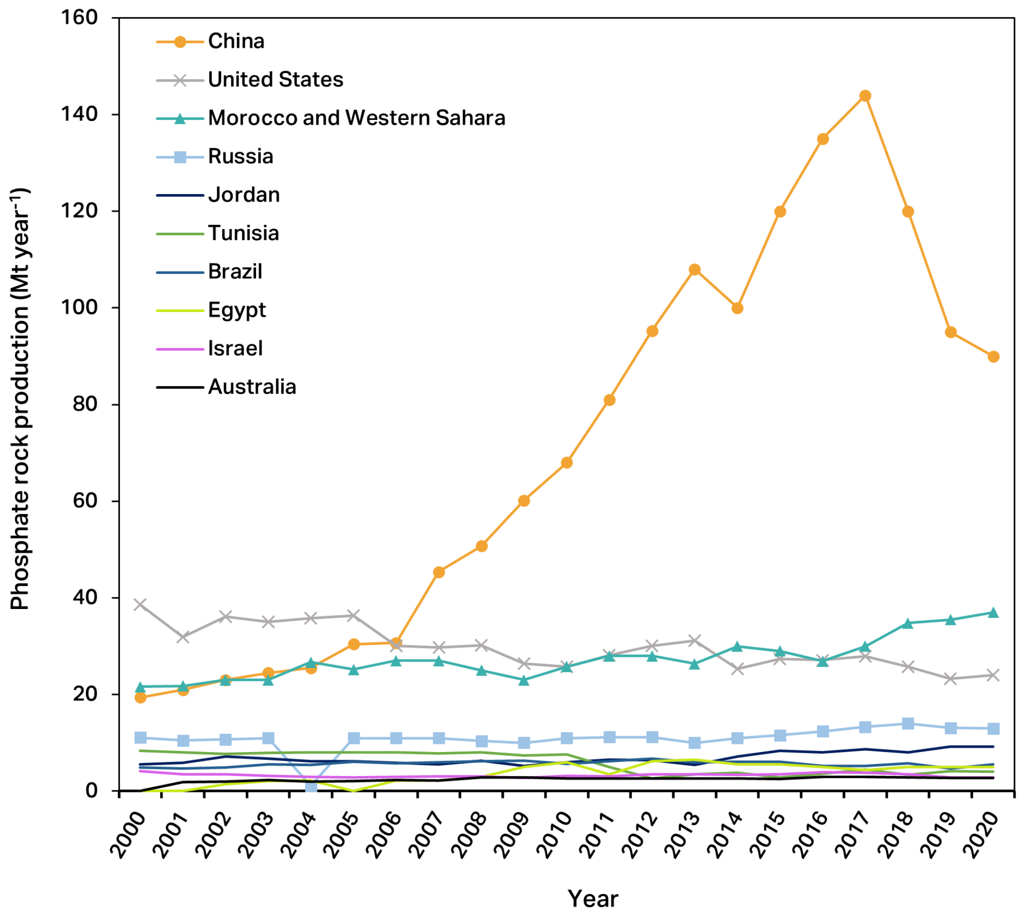

Figure 2.10 Phosphate rock (PR) production between 2000 and 2020 in the ten countries that produced the highest quantities of PR in 2020. Based on data from the annual U.S. Geological Survey reports from 2003-2021 (Jasinski, 2003 through to 2021).

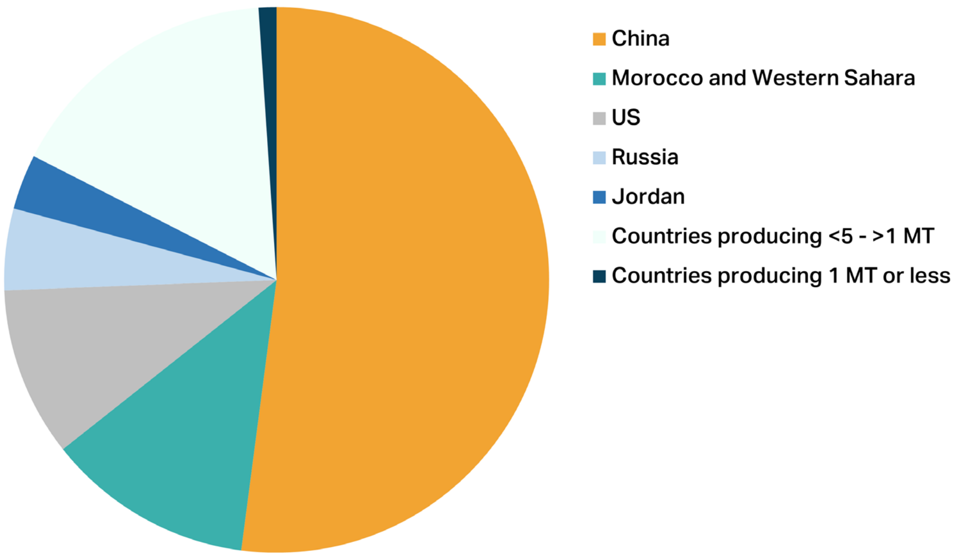

Figure 2.11 Distribution between countries of global PR production in 2019 (Data source: Jasinski, 2021).

China, the USA, Russia, Saudi Arabia and Morocco are among the few countries that contain large PR reserves and fertiliser production facilities, and hence are less reliant on imported phosphorus.

For P, the concept that 'the few' own the supply needed by 'the many' is an oversimplification. Not all countries with PR deposits mine them, while not all countries that mine PR can produce fertilisers. In addition, some countries that lack PR reserves are producers of P fertilisers (Table 2.5). For example, phosphate rock resources are located across Europe in Belgium, Germany, Spain, France, Italy, Greece and the UK. However, under current markets, these resources are not economically viable to mine and/or have been closed due to environmental concerns (Notholt et al., 2005). Brazil contains 2.4% of known global PR reserves, producing 2.0% of global PR annually (FAO, 2017). However, Brazilian PR reserves are mainly poor quality igneous fluorapatites, with low P solubility and high processing costs.

Although Brazil has been expanding its PR production, it is insufficient to supply domestic requirements, and thus imported P supplies about 70% of Brazil's mineral P fertiliser demands (Withers et al., 2018b).

Some countries may contain PR reserves but lack the infrastructure to produce fertilisers. For example, Sub-Saharan African countries (SSA) hold an estimated 2% of global PR reserves (Jasinski, 2021), but manufacture little fertiliser (Chianu et al., 2012). Phosphate rock is instead exported from SSA, often to EU countries that do not have PR reserves but do have fertiliser production capacity. In some cases, fertiliser produced in the EU is re-imported back into SSA (de Ridder et al., 2012), where it is sold at prices reported to be too expensive for most farmers to access (Chianu et al., 2012). By contrast, despite having no significant PR reserves, Japan produces ~36% of the fertiliser it uses for domestic agriculture and even exports a small amount of mineral P fertiliser (FAO, 2017).

Table 2.5 Phosphate Rock (PR) reserves and PR mine production for 2018 (Jasinski, 2021) and the estimated P imported and produced and contained in all P products in 2016 (FAO, 2017) for different regions/countries. Percentage of P supplied by imports (I), or produced (Pr) within the country, followed by the percentage of the total supply that was used in the agricultural sector (A), used outside of the agricultural sector (O) or exported (E). FAO data assume I + Pr = A + O + E. Discrepancies in the equation balance may reflect a change in P stock within the county or the available data was collected from different years. For further details see supporting documents for data provided by FAOSTAT.

Region	PR Reserve (% of global reserves)	PR Mine production (% of global production)	Import (I) + Production (Pr) = Agricultural Use (A) + Other Uses (O) + Export (E)						
			I	Pr	I+Pr (Mt P)	A	O	E	A+O+E (Mt P)
European Union	1%	<1%	75%	25%	2.84	40%	23%	37%	2.80
Brazil	2%	2%	68%	32%	2.08	95%	4%	1%	2.28
US	1%	10%	20%	80%	4.44	51%	26%	23%	4.45
Australia	2%	1%	63%	37%	0.64	79%	0%	21%	0.64
India	<1%	1%	32%	68%	2.92	99%	0%	1%	2.94
SSA	2%	2%	36%	64%	0.81	38%	34%	28%	0.81
China	5%	52%	2%	98%	7.75	76%	0%	24%	9.10
Japan	0%	0%	64%	36%	0.24	98%	0%	2%	0.15
Syria	3%	<1%	10%	90%	0.01	34%	0%	66%	0.01
Morocco	71%	12%	0%	100%	0.85	4%	0%	96%	2.31

The European Commission has formally acknowledged that PR is a commodity with a high supply risk, adding PR to the EU 'Critical Raw Materials list' in 2014 (European Commission, 2014) and white P in 2017 (European Commission, 2017). The EU Critical Raw Materials list is composed of 30 materials (after 2020 revision) of high importance to the EU economy and with a high risk associated with their supply (European Commission, 2020). These decisions were made because:

- limited PR reserves in the EU make it highly dependent on imports,
- P demand is expected to increase (due to the growing world population), and
- there are no alternatives to P in fertilisers or animal feeds (European Commission, 2014).

Challenge 2.2: Phosphate rock can contain contaminants harmful to human, animal and environmental health

Different phosphate rock ores vary in their composition between phosphates, impurities and contaminants. Phosphate rock contaminants can be transferred into fertiliser products, spread on soils, and end up in food. Cadmium is of particular concern as it can pose a risk to human, animal and environmental health when above threshold levels. The by-products of phosphate rock processing also include ~200 Mt year^{-1} of phosphogypsum, which can contain hazardous contaminants. Concerns have been raised that contaminant leaching from phosphogypsum stockpiles may pose a risk to the environment and the health of local communities.

Contaminants of PR include non-P bearing minerals and potentially toxic elements, such as heavy metals and metalloids. Heavy metals found in PR include arsenic, cadmium, chromium, uranium, mercury, lead, iron and copper (Al-Shawi and Dahl, 1999; Corbridge, 2000). Phosphate rock can also contain the radionuclides uranium and thorium. The recovery of uranium from PR can have value for nuclear power production. The USA recovered uranium from PR processing from the 1970s to the 1990s, but the production facilities were dismantled when prices for uranium from other sources dropped (Merkel and Hoyer, 2012). Processing PR into fertiliser can increase the concentration of potentially toxic elements by 1.5 times compared to the original ore (Sattouf, 2007). Cadmium concentrations in fertilisers have been reported between 1 and >640 mg kg^{-1} (Mclaughlin et al., 1996; Ulrich et al., 2014). The concentration of contaminants depends on the origins of the PR and is also highly variable between and within the same PR reserve. Typically, concentrations of heavy metals and radioactive elements are much higher in sedimentary phosphate rock. However, whilst igneous rock deposits have lower contaminant concentrations, they also contain less phosphate. The PR reserves in Finland and Russia are igneous and relatively contaminant-free, whereas most PR ores in Africa, the Middle East and Israel are sedimentary and contain higher concentrations of contaminants (e.g. cadmium) that are largely exported, transferred into fertiliser products and spread on soils (Hermann et al., 2018). Russia is the only major PR producing country with mainly igneous rock reserves. Differences in the content of cadmium and phosphate in PR ores between the major PR producing countries, China, Russia, the USA and Morocco, are summarised in Table 2.6.

Cadmium, uranium, chromium and arsenic tend to bio-accumulate (Al-Shawi and Dahl, 1999; Sabiha-Javied et al., 2009; Ertani et al., 2017) and can be toxic to humans and animals if ingested above certain levels (Kratz et al., 2011). Cadmium is efficiently retained in the kidney and liver in the human body, with a very long biological half-life ranging from 10 to 30 years (EFSA, 2012). Cadmium is classified as a class 1 carcinogen (Group B1) by the International Agency of Research on Cancer and the World Health Organization (World Health Organization & International Programme on Chemical Safety, 1992; IARC, 1993). Phosphate fertilisers are the main source of uranium enrichment of topsoil globally (Schnug and Lottermoser, 2013). Although little uranium is incorporated into crops, it can bind to root vegetables, and thus enter the food chain, and also be transported by groundwater and surface waters. The intake of uranium by humans from plant products is considered negligible, with ingestion through drinking water suggested as the main exposure route (Schnug et al., 2005). Whilst it is dependent on the region, uranium in drinking water may derive from the bedrock geology or from fertiliser use (Smedley et al., 2006; Brindha et al., 2011; Smidt, 2011).

Concentrations of cadmium and other metals in soils vary and depend on natural background levels, but increasingly also on human activities, including mineral

Table 2.6 Concentrations of cadmium (Cd) and phosphate in phosphate rock (PR) ore types of the major PR producers, China, Morocco, US and Russia. Modified from de Boer et al. (2019b), with cadmium data based on Mar and Okazaki (2012) and Geissler et al. (2019).

Origin of PR reserves	PR ore type	Cadmium content (mg Cd kg $rock^{-1}$)	Phosphate content
China	Sedimentary	4	High
Morocco	Sedimentary	3-186	High
USA	Sedimentary	3-186	High
Russia	Igneous	0.1-<13	Low-moderate

fertiliser use (Römkens et al., 2018). From analysis of mineral P fertilisers used in Germany and Southern Brazil, (Smidt et al., (2011) estimated that annually, 42 and 611 t of cadmium, and 228 and 1614 t of uranium, are applied to agricultural soils in mineral P fertilisers in Germany and Brazil, respectively. This is equivalent to 2.9 g cadmium ha^{-1} $year^{-1}$ and 11.8 g uranium ha^{-1} $year^{-1}$ applied to agricultural soils in Brazil, and 1.4 g cadmium ha^{-1} $year^{-1}$ and 8.2 g uranium ha^{-1} $year^{-1}$ applied to agricultural soils in Germany (Smidt et al., 2011). With repeated application of fertilisers containing cadmium, levels of cadmium can accumulate to undesirable concentrations in agricultural topsoil, dependent on multiple factors including fertiliser application rates, crop rotation, soil properties and weather conditions (Bigalke et al., 2017). Cadmium sequestration by some crops can be high, depending on soil pH, organic matter, and leaching losses to deeper soil layers or in run-off (Smolders, 2001; Rizwan et al., 2017). FitzGerald and Roth (2015) concluded that cadmium in fertilisers used in Switzerland should be controlled to reduce human exposure as much of the population already ingests close to the tolerable limit. The European Food Safety Authority (EFSA) has shown that children and adults that consume higher amounts of vegetables grown in soils containing cadmium frequently exceed the tolerable weekly intake of 2.5 µg cadmium kg^{-1} body weight (EFSA, 2012). Although the risk of adverse effects on kidney function at an individual level at dietary exposures across Europe is very low, it was concluded that the current exposure to cadmium at the population level should be reduced (EFSA, 2012). A study by de Vries and McLaughlin (2013) suggested that cadmium inputs in fertilisers in Australia exceed the long-term critical loads in heavy-textured soils for dryland cereals, although all other systems are at low risk. de Vries and co-authors concluded that current cadmium inputs in fertilisers in the EU27 countries are nearly always below critical thresholds for toxic impacts on food quality (ETC/ULS, 2016) and soil organisms (de Vries and Römkens, 2017), but exceedance may occur locally. Similarly, Römkens et al. (2018) predicted small absolute changes at the EU level in soil cadmium concentration of less than 0.02 mg kg^{-1} after 100 years application of P fertilisers with cadmium concentrations of 20 and 60 mg cadmium kg^{-1} P_2O_5. However, regional differences were substantially larger varying from -0.15 mg kg^{-1} to 0.07 mg kg^{-1} (compared to the EU average soil cadmium content).

As mentioned earlier, phosphogypsum is a by-product of the digestion stage in PR processing. Production of 1.0 t of phosphoric acid yields around 5.0 t of phosphogypsum, equivalent to a global annual production of 100-280 Mt phosphogypsum $year^{-1}$ (Tayibi et al., 2009; Saadaoui et al., 2017). The construction industry uses gypsum ($CaSO_4$) as a component of cement amongst other uses. For example, in Russia, between 2008 and 2019, hemi-hydrate phosphogypsum was used in road building (Levin et al., 2020). However, impurities in phosphogypsum, such as thorium, radium, cadmium and uranium, can prevent such uses depending on the regulatory threshold levels for contaminants within the operating country. Hilton (2020) provides an expansive list of regulatory and commercial barriers related to phosphogypsum use, by country. 'Flotation', which is mainly used to separate P from igneous rock deposits (see Section 2.2.2 above), is increasingly used to extract P from 'low grade' sedimentary ores, that were traditionally discarded as waste, thus reducing stockpiling of phosphogypsum (Steiner et al., 2015). However, currently, around 85% of phosphogypsum produced in the wet process is disposed of without treatment (de Boer et al., 2019), and discharged into the sea and watercourses, or stored in large stockpiles. The stockpiling of large quantities of potentially hazardous phosphogypsum generates concerns over impacts to the environment and health risks for communities living close to stockpiles (Rutherford et al., 1994; Tayibi et al., 2009; Saadaoui et al., 2017; Attallah et al., 2019). The composition and characterisation of phosphogypsum depend mainly on the ore source (Hilton, 2020). Where phosphogypsum is free from or contains insignificant amounts of contaminants, it may have much fewer negative impacts on the environment.

The leaching of toxic elements and radionuclides from phosphogypsum stockpiles shows variation been multiple sites that have been assessed. For example, minimal environmental impacts were observed from stockpiles in Poland (Olszewski et al., 2016), Jordan (Al-Hwaiti, 2005) and Greece (Papageorgiou et al., 2016), whilst more significant impacts were observed from stockpiles in India (Haridasan et al., 2001) and Portugal (Corisco et al., 2017). The method used to assess the impacts of different stockpiles will influence comparability between results. However, differences can be largely attributed to the variation in impurity concentrations of the phosphogypsum stockpiled, and the local conditions (e.g. weather, soil types, hydrology, species impacted), suggesting that thorough and individual site-level assessments will always be needed to reduce risks.

Challenge 2.3: Geopolitics can impact phosphorus supply and demand while slowing action on phosphorus sustainability

National and regional policies can have direct and indirect impacts on phosphorus access domestically or abroad. This includes taxes, tariffs, trade agreements and legislation. Political instability in countries mining phosphate rock can affect phosphate supply (e.g. Syria). Concerns over the legality/legitimacy of phosphate rock production in Western Sahara remain unresolved. Such issues also contribute to sensitivities that represent a barrier to effective dialogue and action on phosphorus.

Geopolitics (i.e. the interaction between politics and international relations and dynamic geographical settings) can have significant impacts on P supply and demand. Countries with the capacity to export PR or P fertiliser can implement export restrictions in the form of export taxes, quantitative restrictions, or export bans of P products (PR and fertilisers) (Karapinar, 2011). Such export restrictions are often subject to extensive public attention and heated debate as they can impact food security (Karapinar, 2011).

For example, in 2008, China introduced an export tax of 100-135% on fertilisers to ensure that fertilisers produced in China were used domestically (Huang, 2009). This was driven by an increase in domestic fertiliser demand to match increased national agricultural production, and by concerns that easily extracted and processed Chinese PR reserves were being overexploited (van Kauwenbergh, 2010; de Ridder et al., 2012; Li et al., 2015). In relation to P specifically, this led to legal proceedings under the World Trade Organisation (WTO). China is permitted under its WTO obligations to impose an export duty of up to 20% on yellow phosphorus. In early 2009, it had imposed an additional duty of 50% on yellow P, as well as certain other measures, including minimum export prices. Because of this, and related restrictions on other raw materials, including PR (de Ridder et al., 2012), the EU, Mexico and the USA commenced legal proceedings in the WTO against China in 2009. China withdrew the special duty of 50% on yellow P on 1 July 2009 before the dispute commenced and so the WTO panel made no findings on this point, but China lost its case in relation to minimum export prices for yellow P (World Trade Organization, 2009). In the end, China succeeded on appeal on a technicality, namely that the three complaining countries had not specified the legal basis of their claim with sufficient precision (World Trade Organization, 2009). In January 2019, China dropped all taxes on all fertiliser exports, including phosphate ore and phosphoric acid.

Policies in P-importing countries can also affect supply. In late 2018, the European Parliament agreed on the revision of Fertilisers Regulation (EC) No 2003/2003, originally proposed in 2016. The revised 'Fertilising Products Regulation' (EU) 2019/1009, which repealed Regulation (EC) No 2003/2003 and harmonised the requirements for phosphate fertilisers including by setting harmonised cadmium limits (Fertilising Products Regulation, Part II), may increase the EU's dependence on countries that can provide low cadmium PR or fertilisers (discussed in more detail in Solution 2.1 below).

Instability in the Middle East and North African countries after the 'Arab Spring' has been noted to impact P trade, with issues over sovereignty, labour disputes and civil war cited as factors impacting PR production (Webeck et al., 2014; Smith, 2015). In Tunisia, annual PR production decreased from 7.6 to 2.6 Mt between 2010 and 2012 (Jasinski, 2013), related to unrest among industrial workers, due to employment disputes, involving miners, as well as rail workers, who obstructed the transport of PR from mines (Gobe, 2010; de Ridder et al., 2012; Al Jazeera, 2020). Previously, the Syrian PR industry, which held 1800 Mt in PR reserves produced 3.9 Mt of PR in 2006 (Jasinski, 2009). However, the phosphate rock mines in Iraq and Syria were closed in late 2015 because of ongoing conflicts (Jasinski, 2009). Conversely, during the same period, other countries in the Middle East increased PR production, including Egypt and Saudi Arabia, where production doubled between 2011 and 2013 (Jasinski, 2013). It could be argued that this reflects an automatic rebalancing mechanism on the supply side: when production in one area falls, it is compensated by a rise elsewhere. Disruption in Syria and Tunisia had effectively no impact on the global price of phosphate rock. However, this is expected since the highest PR production levels in the period 2000-2020 for Tunisia (8.0 Mt in 2000) and Syria (3.9 Mt in 2006) represented less than 3% and 2% of global PR production (in 2020), respectively (data based on annual reports of Jasinski, (2002-2021).

Phosphate rock production in Morocco between 2000 and 2020 has steadily increased from 22 to 37 Mt year^{-1} (Jasinski, 2002-2021). However, the controversy surrounding PR mining in Western Sahara by Moroccan mining operations is widely documented (Chernoff and Orris, 2002; Leite et al., 2006; Arts and Leite, 2007; Mundy and Zunes, 2010; Boukhars and Roussellier, 2014; Camprubí, 2015; White, 2015; Smith, 2015; Hagen, 2015; Allan, 2016; Kingsbury, 2018; Omar, 2018). A summary of issues associated with the political context of Western Sahara is given in Focus Box 2.1.

Focus Box 2.1 - The conflict in Western Sahara

The ongoing conflict in Western Sahara is one of the more intractable legacies of European colonisation (Boukhars and Roussellier, 2014). Following the withdrawal of Spain in 1975, forces from Morocco and Mauritania moved in to occupy much of the territory. In 1975, the International Court of Justice issued a landmark ruling (The International Court of Justice, 2017)[i], that found no convincing historical evidence that Western Sahara belonged to anyone but the indigenous Sahrawi inhabitants.

The territory has a native population of less than half a million ethnic Sahrawis, 170,000 of whom have lived as refugees in Algeria since 1976 (UNHCR, 2018). In 1976, the Frente POLISARIO[ii] (also known as the Polisario Front) in the representation of Sahrawi, proclaimed the Sahrawi Arab Democratic Republic (SADR) as a sovereign State over the Territory of Western Sahara (Omar, 2018). Boukhars and Roussellier (2014) explain that this territorial dispute escalated into a war of independence between the POLISARIO, who were backed by Algeria, and the states of Mauritania (who withdrew in 1996), and Morocco who claim sovereignty.

It is widely accepted by legal scholars and under international law that Morocco has no legal title to Western Sahara (Chernoff and Orris, 2002; Leite et al., 2006; Arts

[i] The International Court of Justice stated "the Court's conclusion was that the materials and information presented to it did not establish any tie of territorial sovereignty between the territory of Western Sahara and the Kingdom of Morocco or the Mauritanian entity" https://www.icj-cij.org/en/case/61

[ii] Frente Popular para la Liberación de Saguía el Hamra y de Río de Oro (Frente POLISARIO).

and Leite, 2007; Mundy and Zunes, 2010; Boukhars and Roussellier, 2014; Camprubí, 2015; Smith, 2015; Kingsbury, 2018; Omar, 2018). Similar positions have been taken by the African Union (2017), the European Union (High Court of Justice (England & Wales), 2016) and the United Nations General Assembly (1980). For example, the European Court of Justice has ruled that treaties between the EU and Morocco do not cover Western Sahara, as this is not considered to be Moroccan 'territory' within the meaning of those treaties (The European Court of Justice, 2016).

It follows that Morocco remains an occupying power subject to international obligations concerning the exploitation of natural resources in that territory. These obligations prevent Morocco from exploiting these resources for its own benefit. By the same token, Morocco is constrained in granting exploitation licences to state-owned foreign companies. In a letter from the United Nations Under-Secretary-General for Legal Affairs and the Legal Counsel to the President of the Security Council in 2002 (in response to a request for legal advice), the UN Legal Counsel considered that it was not per se illegal for Morocco to conclude contracts with foreign companies to exploit mineral resources in Western Sahara, as has been done, but it would be illegal to do so if this was done 'in disregard of the needs and interests of the people of that Territory" (UN Legal Counsel, 2002).

A long-term solution to the issue does not appear to be in sight. In 1991, the United Nations Mission for the Referendum in Western Sahara (MINURSO) was established under the 'Security Council resolution 690 (1991) [Western Sahara]' settlement plan (United Nations Security Council, 1991). MINURSO was mandated to monitor a cease-fire and to organise an independence referendum. To date (2021) a referendum has not been held.

The Sahrawi Arab Democratic Republic (SADR), whilst not admitted into the United Nations, by 2021 has been recognised at some point in time by 84 of its member states and South Ossetia (45 of which have "suspended", "frozen" or "withdrawn" recognition)[i]. The African Union recognises both Morocco and Western Sahara as full member states. The United Nations observe Western Sahara as the last 'non-self-governing territory' in Africa (United Nations, 2020). Recent opinions of the European Court of Justice have reinforced that so long as Western Sahara is denied its right to self-determination, it is a non-self-governing territory (Court of Justice of the European Union, 2018). In 2020, in a change from 45 years of US policy, the Trump administration announced US recognition of Moroccan sovereignty over Western Sahara (Mundy, 2020) and this policy does not seem set for reversal under the Biden administration (Kasraoui, 2021).

[i] A full list of UN member states that have recognised the Sahrawi Arab Democratic Republic from 1975 to 2020, is provided on Wikipedia with relevant references included: https://en.wikipedia.org/wiki/International_recognition_of_the_Sahrawi_Arab_Democratic_Republic

Despite major interruptions of supply due to the Morocco-Polisario war (1976-1991), between 1976 and 2015, Moroccan investment in PR mining in the town of Bou Craa in Western Sahara has resulted in the export of over US$4 billion worth of PR (Smith, 2015). The Bou Craa reserves are mined by 'Phosphates de Boucraa S.A.' (Phosboucraa), a fully-owned subsidiary of the Moroccan state-owned phosphate mining company OCP. Phosboucraa also markets the PR from the Bou Craa mine and operates the loading dock and treatment plant located on the Atlantic coast at El Aaiún (or Laayoune). Whilst the Bou Craa mines represent 2% of Morocco's PR reserves (OCP, 2021), in 2016, 22% of Morocco's exported PR departed from El Aaiún (OCP SA, 2018). The average exports from Bou Craa over the last years have generated an annual income of around US$200 million (OCP, 2021). Phosboucraa is engaged in a development programme of approximately US$2.2 billion to move its operations up the value chain from raw materials to intermediate products and phosphate fertilisers by 2022 (OCP, 2015). OCP claim Phosboucraa is a major provider of economic viability and well-being of the region's inhabitants (OCP, 2015). Phosboucraa has around 2,195 employees, of which 75% are "locals" (without specifying whether they are Sahrawis or settlers). Zunes (2015) argues "the benefits of such 'development' have largely gone to Moroccan settlers and occupation authorities, not the indigenous population".

Disruption to supply from Bou Craa will not impact global P access significantly since around 1-2% of annual global PR production is in Western Sahara (based on PR production rate in 2019; see Jasinski, 2021). However, Camprubí (2015) argues that such quantities are significant enough to disrupt prices, and that countries currently and historically involved in exploiting the PR reserves in Western Sahara are not only interested in mining the resources, but also preventing others from doing so. Moreover, ethical questions for countries receiving PR supply from Bou Craa have been raised by several authors (including: Chernoff and Orris, 2002; Leite et al., 2006; Arts and Leite, 2007; Mundy and Zunes, 2010; Boukhars and Roussellier, 2014; Camprubí, 2015; Smith, 2015; Kingsbury, 2018; Omar, 2018). This controversy has been acknowledged by international courts (United Nations Security Council, 2002; Leite et al., 2006; White, 2015). For example, in December 2016, the Court of Justice of the European Union issued its decision in the appeal case of the POLISARIO against the European Council, concerning the EU's free trade arrangements with Morocco in Western Sahara (The European Court of Justice, 2016). The Court of Justice ruled that Morocco had no territorial right to make agreements covering Western Sahara with respect to free trade in this context.

Furthermore, ships carrying Western Saharan PR were detained in South Africa (OCP, 2018; WSRW, 2018) and Panama in 2017, with local courts asked to rule on the legality of their cargo. The High Court in South Africa ruled that the vessel NM Cherry Blossom carried PR that had been illegally exported from the territory, and was owned by SADR (High Court of South Africa, 2017). Conversely, the court in Panama ruled it did not have the right to hear the case, and the vessel was able to continue on its journey (Reuters, 2017a, b; Dudley, 2018).

Such concerns have not only been a matter of international dispute over resources but have also affected investment in PR production and import (Hagen, 2015; Allan, 2016; WSRW, 2020). The Western Sahara Resource Watch (WSRW)[i] report that the Danske Bank, the Norwegian Government Pension Fund, Luxembourg Pension Fund, KLP (the Norwegian insurance company), MP Pension (Denmark), the Norwegian Pension Fund, AP Fonden (the Swedish government pension fund), Nykredit Realkredit Group (Denmark) and PGB Pensioenfonds (the Netherlands), are among those to divest shares from OCP, and/or companies importing PR from Western Sahara (WSRW, 2018, 2020). They claim reasons for divestment[ii] are based on concerns of human rights breaches, international law violations and political controversy (WSRW, 2020). In 2018, the Canadian company Nutrien stopped importing PR from Western Sahara, stating this decision was based on a restructuring of the company (Nutrien, 2019). The WSRW report this caused a 50% drop in exports from the Bou Craa port of El Aaiún between 2018 and 2019 (WSRW, 2020). Notwithstanding this, in 2019, companies in New Zealand, India, Brazil and China imported PR from Western Sahara (WSRW, 2020).

For the present report, we do not focus on the legitimacy or otherwise of any territorial claims (including claims over natural resources) by Morocco or the SADR over land and mineral rights, nor on the determination of the European Court of Justice or other courts in regarding the merits or otherwise of any claim. Our role as sustainability researchers is rather to draw attention to these issues as part of providing a comprehensive picture of the challenges for sustainable P management.

Importantly, we note that this topic has become taboo for certain stakeholders. This section of the report has been subject to intense scrutiny as part of a peer review process linked to the UNEP-affiliated Global Partnership on Nutrient Management. The comparison of stakeholder engagement in sustainability discussions around P and nitrogen is particularly informative. Discussion about P is extremely sensitive. For example, a Policy Brief led by SCOPE identifying P as an emerging issue for food production (Syers et al., 2011) was reported by SCOPE staff as being exceptionally difficult to negotiate. Later, a policy brief for UNEP, prepared by some of the present authors, proved equally difficult, taking three years to finalise what was essentially a two-page brief (Brownlie et al., 2017). Experience in developing the International Nitrogen Management System by some of the authors (e.g. Sutton et al. 2021) has clearly shown that, if fast progress should be achieved with nitrogen, then P should be excluded from the stakeholder and intergovernmental discussion.

It is difficult to apportion the relative contribution of possible reasons for this extreme sensitivity about P, which we term here 'phosphorus hypersensitivity'. For example, is P sensitive to producers and relevant industry associations because of the way that any public discussion might

[i] The Western Sahara Resource Watch (WSRW) is an independent international non-governmental organisation that works "in solidarity with the people of Western Sahara, researching and campaigning against Morocco's resource exploitation of the territory".
[ii] The WSRW provides quotes from divesting companies justifying their decisions to divest shares from OCP, and/or companies importing phosphates from Western Sahara on page 5 of WSRW, (2020) – www.wsrw.org/files/dated/2020-02-24/p_for_plunder_2020-web.pdf

affect resource value and market confidence of a commodity that has already been seen to be vulnerable to price instability? (See Figure 2.12 and Challenge 2.4 below). Or are the geopolitical interactions between companies and the relevant governments more important? Here it is possible to envisage that certain company interests would not wish to be in conflict with specific governments controlling access to PR reserves. In both cases, it can easily be seen how conflict surrounding PR in Western Sahara could spill over to make the whole topic of P extremely sensitive for certain stakeholders.

For this report, it is therefore not our purpose either to justify or to defend any party. Rather, we draw attention to the critical message from a global perspective: that P hypersensitivity associated with such geopolitical conflicts makes P difficult to discuss in the international arena. Consequently, it becomes even harder to make effective progress towards sustainable P management. Much more work is needed to better understand the complex geopolitical-business-sustainability dynamics at play. Future efforts should focus on finding governance models which, while considering the complexities involved, would enable relevant stakeholders to address the underlying issues and provide the confidence needed to accelerate the global conversation about phosphorus. Ultimately, this will be essential to mobilise the global adoption of sustainable P practices.

Challenge 2.4: Phosphate rock price spikes remain an ongoing risk

In 2008, phosphate rock prices spiked by 800%, causing a subsequent increase in fertiliser prices that affected the livelihood of many of the world's poorest farmers. This price spike occurred in response to a combination of factors, including instability in energy prices, changing dynamics of supply/demand for agricultural and phosphorus products, and the influence of geopolitics on exports. The stability of phosphate rock prices remains vulnerable to such drivers.

Two major PR price spikes have been observed in the last 30 years, in 1974 and 2008 (Rosemarin and Ekane, 2016) (Figure 2.12). Mew (2016) predicted that PR price spikes should be expected in the future. After the 1974 price spike, the price of PR remained reasonably stable at around US\$50 t^{-1}. In 2008, PR prices increased by 800%, impacting P fertiliser prices accordingly (de Ridder et al., 2012), with a further modest spike in 2012. Spiralling fertiliser prices eventually led to a crash in demand for P, and the PR price dropped. However, as observed by Mew (2016), although the PR price dropped after each price spike, it has dropped to double the baseline preceding the increase (Figure 2.12).

The cause of the 2008 PR price spike is complex and likely driven by a combination of factors including

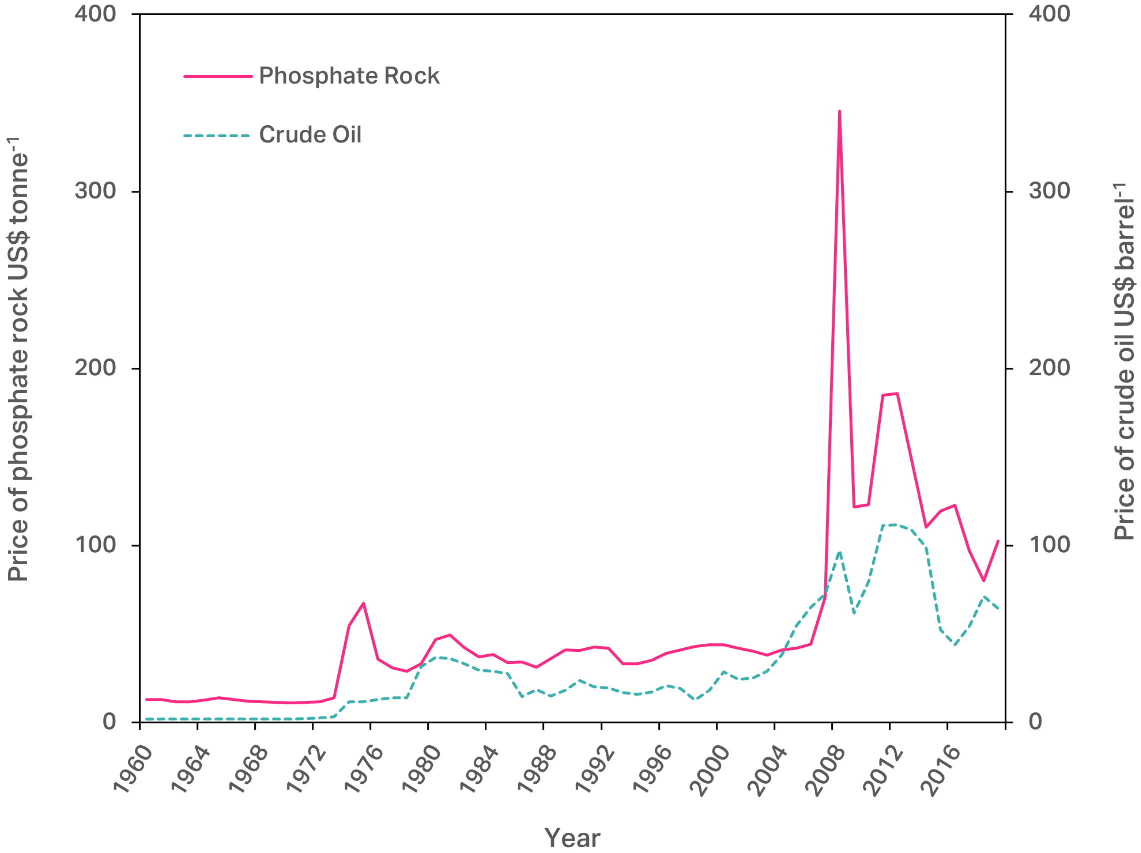

Figure 2.12 Phosphate rock (PR) and crude oil prices 1960–2019, indicating a PR price spike in 1974 and an 800% price spike in 2008, with another spike following in 2012. After each price spike, the cost drops and stabilises at a higher cost. Other commodities experienced price spikes in 2008, including crude oil. Data source: World Bank Commodity Price data.

changing the market supply/demand dynamics for agricultural and P products, instability in energy prices and geopolitical control on exports. Indeed, the price spike in 2008 was not unique to PR and affected almost all commodities, including oil, minerals, and grains (Martin and Anderson, 2012). An International Fertiliser Association (IFA) bulletin suggested the 2008 volatility in agricultural and fertiliser prices reflected a combination of long- and short-term factors (IFA, 2011). Long-term factors included:

- income growth and dietary changes in emerging economies;
- competing objectives for agriculture, in addition to food and feed production (e.g. production of fibre, biofuel feedstock and bio-chemicals);
- global grain market conditions (i.e. low cereal stocks); and
- regular increases in energy prices.

Contributing short-term factors included economic weakness in many countries, export restriction measures and extreme weather conditions and natural disasters (IFA, 2011). Some reports suggested the introduction of a US ethanol policy and increases in food prices were the major contributors to the increases in P demand (Cordell et al., 2009; Childers et al., 2011). However, Khabarov and

Obersteiner (2017) argue that fertiliser market policies in India, which led to India doubling its import of P-fertiliser in 2008 at a time when prices doubled, were the major contributor to the global PR price spike.

The 2008 price spike affected the livelihood of many of the world's poorest farmers, resulting in farmer debt and reports of farmer riots, for example, in Haiti and India (Cordell and White, 2014). Mew (2016) states "these price spike events can be seen to be related to the escalating investment cost required by new mine capacity, and as such can be expected to be repeated in future…[and] ...phosphate rock price volatility is likely to have more impact on food prices than rising phosphate rock production costs." In 2021, the PR price began to rise steeply again.

Challenge 2.5: There is a lack of transparent, complete and comparable phosphate rock data

Significant discrepancies in phosphate rock data are reported, making it difficult to assess accurately the risk of geographic depletion of reserves. Differing definitions for phosphate rock 'reserve' and 'resource' are a cause of discrepancies. Datasets on phosphate rock reserves and resources are commercially sensitive and are often not publicly available. Reserve estimates are dynamic and require regular updating, while conformity in data and reporting is needed. The United States Geological Survey estimates global phosphate rock reserves in 2020 at 70,000 Mt, indicating a current lifetime of >300 years, although a longer lifetime may be expected in practice due to innovation and price elasticity.

The current rate of PR mining far outweighs the geological replacement of reserves and resources. Geological deposits of PR take millions of years to form, such as via the decomposition of marine organisms. In 2020, 223 Mt of PR (containing 67 Mt P_2O_5) were mined from global PR reserves estimated at 71,000 Mt of PR (containing 21,300 Mt of P_2O_5) (Jasinski, 2021). In the same year, 47 Mt of P_2O_5 was consumed in the anthropogenic global P cycle, in phosphoric acids, fertilisers and other products (Jasinski, 2021). Even if only currently-identified reserves are considered (excluding P resources which are a factor of 4 larger), this indicates that there is little risk of scarcity of PR in the coming decades (Ulrich and Frossard, 2014). However, access to P for many smallholder farmers, especially in parts of Africa, remains a significant issue, impacted by factors other than geological scarcity associated with total P reserves and resources (Cordell and White, 2014) (see Chapter 3).

Concerns over the depletion of PR reserves are not only a contemporary issue (Ulrich and Frossard, 2014), as illustrated on the front cover of 'The Fertiliser Review' from 1938, which depicts concern in North America over depletion of reserves (i.e. Eastern Field) against a backdrop of considerable 'resources' (i.e. Western Field) (Figure 2.13).

In 2009, there were renewed concerns about the geological depletion of P reserves under the term 'Peak Phosphorus' (Déry and Anderson, 2007) resulting in contention in accounting reserves (Déry and Anderson, 2007; Cordell et al., 2009) and debates on how long PR reserves may last (e.g. Cordell and White, 2011; Scholz et al., 2013; Ulrich and Frossard, 2014; Geissler et al., 2018). As Ulrich and Frossard (2014) explain, however, concerns about P scarcity, when framed as geologic depletion alone, have been repeatedly disproven by resource appraisals from industry or government experts.

Authors who have conducted estimates in the past share frustration that PR reserve data are unsatisfactory and call for conformity in reporting (Brobst and Pratt, 1973; McKelvey, 1974; Bender, 1986). Currently, estimates are constrained by a lack of available information and

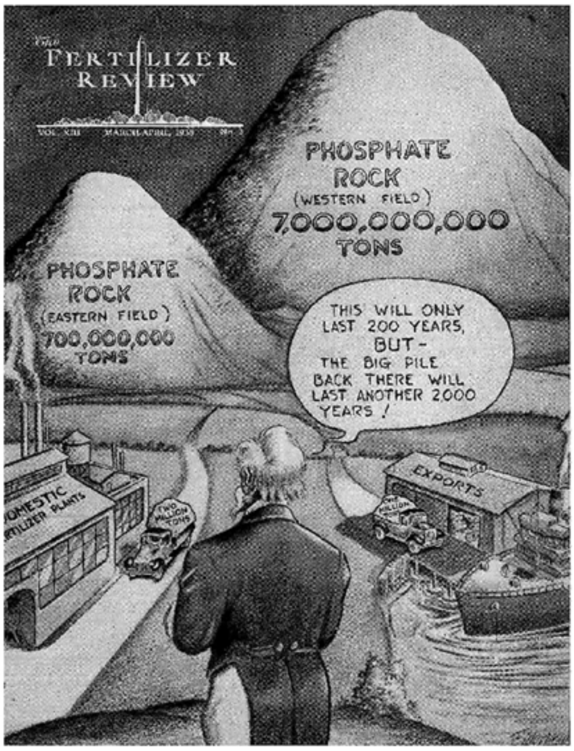

Figure 2.13 Cover of The Fertiliser Review Vol. XIII, No. 2, March–April 1938. The small pile of phosphate rock (PR) represents 200 years left of supplies in Florida, with the larger pile representing 2000 years left of other US PR resources, illustrating the role of the undeveloped western PR deposits in USA phosphorus supply considerations (image featured in Ulrich, 2016).

often based on data collected using different methodologies (Ulrich and Frossard, 2014). Notable publicly available datasets include:

- USGS PR reports (the major data source for global scientific publications on mineral resources) (https://www.usgs.gov/centers/nmic/phosphate-rock-statistics-and-information).
- FAO fertiliser datasets, available at its FAOSTAT data portal (http://www.fao.org/faostat/en/).
- IFA data portal (IFASTAT) (http://ifastat.org) which provides limited publicly available data, with extensive data for members.

- World Bank 'pink sheets' (https://www.worldbank.org/en/research/commodity-markets) providing long-term price series for PR and various mineral fertiliser types.

However, since estimates are not reported in the same units (i.e. P_2O_5 or P content, or amount of PR) comparable analyses have to rely on assumptions that may not be accurate (e.g. concentration of P in PR, which differs between rock type). There is no independent source of data or governance at the international level to set standards and norms for reporting on PR (Rosemarin and Ekane, 2016). A review of the commonly used data sources on PR by Geissler et al. (2018a) identified current and significant discrepancies in global PR production data.

A major source of discrepancies has been variation in the definitions of PR 'reserve' and 'resource' (Nedelciu et al., 2020). Phosphate rock 'reserves' can be considered PR resources that can be economically produced. However, 'economic' is contextual, dependent on changing socio-economic conditions and technological capacity. Currently, a classification method for monitoring reserves is not universally agreed upon, or required by law (Edixhoven et al., 2014), which can lead to uncertainty in reserve and resource speculations.

For example, in 2010, reserves and resources as reported by the USGS were reassessed by the International Fertiliser Development Centre (IFDC). The USGS reported the global PR reserves in 2010 of 16,000 Mt, 36% of which were in Morocco and Western Sahara. In the same year, the IFDC issued a report (van Kauwenbergh, 2010) in which global PR reserves were estimated at 60,000 Mt, with 85% in Morocco and Western Sahara. In the USGS report, reserves were defined as an upgraded concentrate (when the information is available), a term used by the mining industry for ore processed to remove tailings to give a concentrate with phosphate content of at least 30%, ready for sale on the market. In the IFDC report (van Kauwenbergh, 2010), the term 'PR deposit' is used for both unprocessed rock and beneficiated concentrates, although it is not detailed how the weight of beneficiated ore is converted to the weight of PR. The USGS subsequently adopted the reserve estimation of the IFDC (de Boer et al., 2019), resulting in significant increases in the estimated PR reserves from 2009 to 2010 in Morocco and Western Sahara and in the Middle East (Figure 2.14).

Reserves estimates are dynamic and require regular updating. Currently, there is a high degree of uncertainty on the extent of PR reserves (Edixhoven et al., 2014). As with oil reserves, the effort to discover new reserves is not static and will increase with impending shortages, and technological development. Furthermore, some PR resources may become economically profitable to exploit as prices of PR rise or through innovation to increase P yield or reduce processing costs.

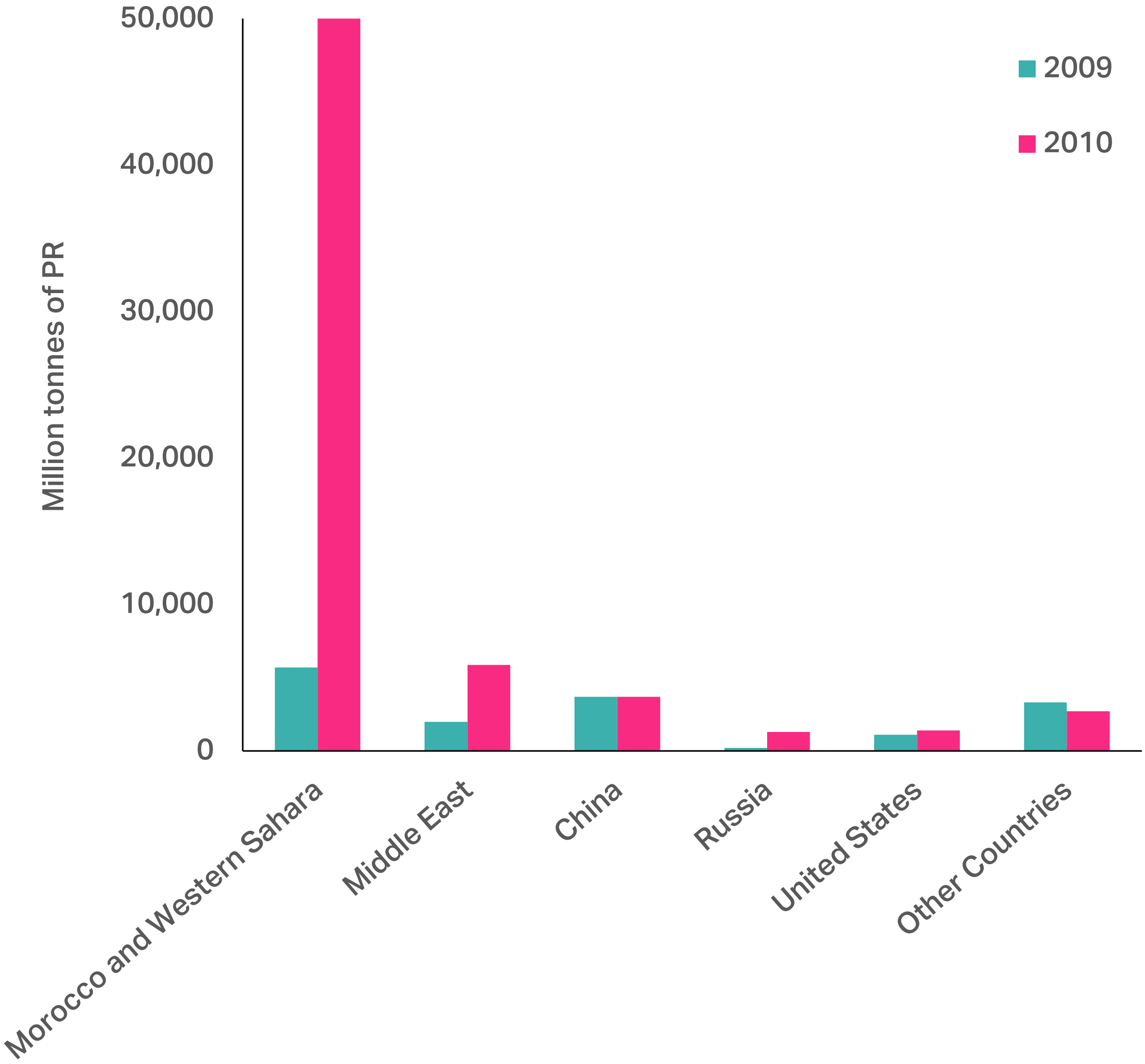

Figure 2.14 Estimated world reserves of Phosphate Rock (PR) in Mt in 2009 and 2010, according to USGS (Jasinski, 2009). In 2011, following a reassessment of PR reserves by the International Fertiliser Development Centre (van Kauwenbergh, 2010), the USGS adopted a different definition for 'PR reserve' (as used by the IFDC). This resulted in the USGS reporting a significant increase in the estimated size of PR reserves in Morocco and Western Sahara, from 5700 Mt in 2009 to 50,000 Mt in 2010, despite no new PR reserves being identified (compare with Figure 2.8). The definition of 'PR reserve' has a significant impact on PR reserve reports and our understanding of P scarcity.

2.6. Solutions

Solution 2.1: Reduce reliance on mineral phosphorus fertiliser

Replacing mineral phosphorus fertiliser with recycled phosphorus fertiliser would help to shift reliance away from mined phosphorus sources. Optimising capacity to recycle phosphorus throughout the food value chain in combination with societal change (e.g. diet change) would help to reduce phosphorus demand and losses. Enabling mainstream production of sustainable recycled phosphorus fertilisers containing low concentrations of contaminants is an essential prerequisite to upscaling operational recycling.

National and international resilience to mineral P fertiliser supply risk can be increased by implementing a more circular approach to P use (Withers et al., 2015a). A framework to address inefficient P use throughout the food value chain is outlined in the 5R stewardship framework (Withers et al., 2015a). The 5R framework promotes Re-aligning P inputs, Reducing P losses, Recycling P in bioresources, Recovering P in wastes, and Redefining P in food systems. Through consideration of these elements, it can help identify and deliver a range of integrated, cost-effective and feasible technological innovations to improve Phosphorus Use Efficiency (PUE, defined and discussed in Chapter 4) in society and reduce dependence on mined P imports (Withers et al., 2015a). For most regions, this will require a combination of actions highlighted in later chapters in this report, including significantly improving PUE in agriculture (Chapter 4), reducing societal P demand (Chapter 8), and shifting reliance from PR to recycled P from both domestic and international sources (Chapters 6 and 7).

National policies that optimise P recycling, and hence reduce reliance on mineral P fertilisers, are acknowledged as pivotal to a transition to a more sustainable P future (Koppelaar and Weikard, 2013; Reijnders, 2014; Cordell and White, 2014; Withers et al., 2015b; van Dijk et al., 2016; Chowdhury et al., 2017; Withers et al., 2018a; van Kernebeek et al., 2018). Switzerland, Sweden, Austria and Germany are pioneering policies to recover P from waste streams (Günther et al., 2018). Furthermore, the revision of the Fertilisers Regulation (EC) No 2003/2003, aimed to increase market opportunities for recycled P fertilisers to give farmers and consumers a wider choice of more sustainable products, promote green innovation and help to develop the circular economy while reducing dependence on imported nutrients (European Parliament, 2018).

Currently, the use of recovered P to produce fertiliser cannot compete financially against phosphate rock. To make a significant increase in the use of the recovered P, the mineral fertiliser industry must make a substantial shift to increase its use of recovered P as a raw material (see Chapter 7). Increasing national capacity and further research and development to support mainstreaming of fertiliser production using recovered P materials is essential as a foundation to reduce costs, although issues of contaminants should also be addressed (Kratz et al., 2016; Kumpiene et al., 2016; Bigalke et al., 2017) (see Chapters 6 and 7). Marketing opportunities for using recycled P sources may also merit consideration by the fertiliser industry. For example, a goal for fertiliser products to contain a minimum of 20% recycled P by 2030 could set a benchmark that demonstrates green commitment across the industry.

Solution 2.2: Establish safety levels for contaminants in fertilisers and agricultural products

Internationally agreed limits should be set for cadmium and harmful contaminants in mineral and recycled phosphorus fertilisers and food. Existing national cadmium limits require better enforcement. Optimising fertiliser use to match plant needs and practices to reduce phosphorus losses can also decrease inputs, thereby further lowering the application of fertiliser contaminants to soils, complementing the use of clean mineral and recycled phosphorus fertilisers.

Implementing safe limits for cadmium and other potentially harmful contaminants in all P fertilisers and feed supplements should be applied globally, especially when considering the global trade in agricultural produce (Bigalke et al., 2017; Hooser, 2018). National limits on cadmium in mineral P fertilisers exist in 21 EU countries and to a lesser extent around the world (Ulrich, 2019), though Bigalke et al. (2017a) argue that existing cadmium limits need to be better enforced. In addition to reducing contaminant inputs, a reduction in the recycling of contaminants in manure and other organic resources may be necessary. Optimising fertiliser practices to match plant needs, reducing fertiliser losses and increasing the use of clean and high-quality mineral and recycled P fertilisers are all important in reducing the load of fertiliser-borne contaminants to the environment (Bigalke et al., 2017; Hermann et al., 2018). Furthermore, contaminants can be removed during PR processing and fertiliser production through existing measures such as blending (mixing of PRs with varying levels of cadmium) and decadmiation (i.e. processes to remove cadmium) (Syers, 2001; Benredjem and Delimi, 2009). However, such processes can be expensive and, given limited regulatory requirements in many territories, they are not currently used at industry scales.

Whilst there has long been a lack of global policy or regional legislation on cadmium levels in fertiliser products, this is starting to change. In 2019, the European Parliament and Council adopted Regulation 2019/1009 which set harmonised cadmium limits for CE marked phosphate fertilisers (European Parliament & the Council of the European Union, 2019). Whilst cadmium limits are currently unrestricted, by 2022 P fertilisers must contain less than 60 mg cadmium kg^{-1} P_2O_5 (European Parliament & the Council of the European Union, 2019). Further tightening of this limit to 40 mg kg^{-1} (by 2025) and 20 mg kg^{-1} over the next 12-16 years has been proposed (Ulrich, 2019), but was not accepted by the European Commission.

Solution 2.3: Promote models of governance aimed at ensuring phosphorus security

Ensuring phosphate security which supports all farmers to access sufficient phosphorus to grow crops, is a global responsibility and requires international cooperation. Balanced stakeholder participation in negotiations is necessary to ensure phosphate security and avoid domination of regulatory agencies by industries or private interests. An internationally agreed framework promoting sustainable phosphate rock mining and trading is currently missing and urgently needed.

Ensuring all farmers (in particular, on small-scale farms in less economically developed countries) have access to sufficient P to grow crops and are buffered from fertiliser price fluctuations is a global responsibility and requires international cooperation (Teah and Onuki, 2017). There are several dimensions to this from a legal perspective. Under international law, states are entitled to control the natural resources located in their territory and maritime areas. This is an attribute of their sovereignty and stems from the well-recognised principle of permanent sovereignty over natural resources. As such, states are entitled to freely decide whether to exploit their resources (even, if they wish, to the point of depletion) or instead to leave them in situ. In light of the unequal distribution of PR reserves and the growing need for all states to have access to P, it would be sensible for states to explore models of governance driven by a benefit-sharing approach, following examples adopted for other natural resources (De Jonge, 2011; Morgera, 2016).

Two other areas of international law are also relevant. First, international trade obligations prohibit export bans (but not production bans) on products, unless this is justified on good grounds, e.g. environmental considerations. Second, human rights law requires states, in certain circumstances, not to harm persons in other states. In this respect, it is relevant that access to P is an essential step towards reaching the objectives of SDG 2 - Zero Hunger (Gil et al., 2019; El Wali et al., 2021). The right to food is recognised in the 1948 Universal Declaration of Human Rights as part of the right to an adequate standard of living and is enshrined in the 1966 International Covenant on Economic, Social and Cultural Rights (United Nations, 2010). This does not mean that states with P are necessarily under an obligation to allow exports of P to states in need of fertiliser, but it is a relevant consideration in any negotiated solution, and also plays a role in the interpretation of other relevant international rules.

Balanced stakeholder participation in negotiations is necessary to ensure P security and avoid 'regulatory capture' by industry. The concept of 'regulatory capture' has been introduced to reflect situations where the decisions of regulatory agencies are dominated by the industries or interests they are charged with regulating (De Jonge, 2011). There is also a need to recognise socio-political power differences between different stakeholders, both nationally and internationally. This may require engagement to go beyond governments and international organisations to include indigenous communities and their respective rights over specific resources, including healthy ecosystems, access to agricultural lands and access to clean water (De Jonge, 2011; de Ridder et al., 2012; Smith, 2015). Indeed, PR mining can require large amounts of water, which may challenge the needs of local communities. Furthermore, potential adverse environmental effects and human health risks associated with the discharge of phosphate mining waters have been reported (Chraiti et al., 2016; Reta et al., 2019). It is appropriate that assessment of social impacts be informed through consultation with all stakeholders, and careful analysis of the complex relationships between all stakeholders involved in the mining, trade and use of P from PR reserves (Nedelciu et al., 2020). Two initiatives in the mining sector have relevance here: the Extractive Industries Transparency Initiative (EITI) and the Due Diligence Guidance for Responsible Mineral Supply Chains from Conflict-Affected and High-Risk Areas (DDG) of the Organisation for Economic Co-operation and Development (OECD). The EITI Standard (EITI, 2019) requires the disclosure of information along the extractive industry value chain, such as how extraction rights are awarded, how revenues make their way through the government and how these revenues benefit the public. Whilst currently implemented in 55 countries, it would be appropriate for the EITI standard to be extended to all nations that mine PR reserves. The OECD DDG provides detailed recommendations to help companies respect human rights. The OECD DDG cultivates transparent mineral supply chains and sustainable corporate engagement in the mineral sector. It aims at enabling countries to benefit from their mineral resources, whilst preventing the extraction and trade of minerals from becoming a source of conflict, human rights abuses, and insecurity. The OECD DDG is available for use by any company potentially sourcing minerals or metals from conflict-affected and high-risk areas (OECD, 2016).

Ultimately, it is up to the international community to agree on the exact terms and provisions of a fair and equitable PR sharing mechanism. The World Trade Organization and the United Nations are perhaps best positioned to take a leading role in facilitating these processes. It is recommended that states should seek to adopt a multilateral legal framework promoting 'sustainable PR mining and trading'. Although PR mining cannot be fully sustainable, as it depletes a natural resource, it can be optimised and made more efficient (Nedelciu et al., 2020). Such a framework would need to consider environmental impacts, socioeconomics, fairness for local communities and intergenerational equity. Its activities would need to consider reasonable export/import taxation of PR and trade agreements that are not exploitive (e.g. addressing potential concerns about favouring rich countries and affecting access of poorer nations to P reserves).

It is recommended that progress in P sustainability would be advanced by the establishment of an appropriate United Nations body entrusted with making a global assessment of all PR reserves (Rosemarin and Ekane, 2016; Nedelciu et al., 2020) and developing harmonised criteria for 'sustainable PR mining and trading'. A potential framework to address these needs is suggested in Chapter 9, and in Brownlie et al. (2021). Significant investments and compromises from all governments and other stakeholders are needed to move forward successfully. The approach of addressing common but differentiated responsibilities as used in climate change negotiations could provide a suitable model. In this way, the parties with more means (e.g. high-income countries) might take the lead in promoting PR security and equitable access to phosphorus.

Solution 2.4: Improve stakeholder capacity to deal with phosphate rock price volatility

Stakeholders need to plan for uncertainty by increasing adaptive capacity. Building national capacity to close the phosphorus loop in food production systems and shifting reliance from mined phosphorus to recycled phosphorus will help protect against phosphorus supply risk. Governments need to recognise phosphorus supply risks through appropriate policy and regulation.

Understanding the drivers of PR price spikes is important as a foundation to anticipate and mitigate the impacts of future volatility. Given PR price spikes are expected in the future (Mew, 2016), P stakeholders need to plan for uncertainty by increasing adaptive capacity. Ultimately, improving nutrient management to ensure the most efficient use of P in agriculture (as discussed in Chapter 5), and improving circularity in national P cycles will provide the greatest protection. Progress towards this goal requires a shift in reliance away from mined P sources to recycled P sources and the reuse of organic sources of P on farmland (see Chapters 6 and 7). Implementing strategies to optimise P demand and investing in innovations to access legacy P from soil stores and reduce P losses to the environment are also required. However, for most nations 'phosphate independence' is unrealistic, even impossible; governments, therefore, need to recognise P supply risks within national policy. To assess supply risk, governments and stakeholders require accurate and comparable data on reserves, resources, supply and demand at the national scale. Approaches have been developed to produce these data to inform analyses of P supply resilience (Rosemarin and Ekane, 2016; Geissler et al., 2018).

Governments need to recognise P supply risks through appropriate policy and regulation. The 2008 fertiliser price spike was certainly a trigger for the European Union to place PR on the EU list of critical raw materials (European Commission, 2014), which has in part led to innovative legislation in Germany and Switzerland to increase P recycling from wastes. Whilst current processes to recover P and manufacture recovered P fertilisers can be expensive (see Chapter 7), legislation to support innovation and growth in P recycling industries can help to bring down prices of recycled P fertilisers.

Finally, the international financial sector can play a crucial role in shaping the behaviours of the industry with respect to reducing the financial impact of P losses through the food system and in realising the financial benefits of new investment in companies developing sustainable P approaches. There is an opportunity to dovetail and build upon the progress currently being made in climate change responses across the international financial sector, recognising that unsustainable nutrient use is a key driver of climate change and environmental degradation. These impacts carry large financial costs, for example, to the drinking water sector, whereas the emergence of more sustainable nutrient use technologies and approaches (e.g. the recycling industry) represents an opportunity for future investment. An example of the type of approach that could be utilised is the Task Force on Climate-related Financial Disclosure (TCFD, 2017), which was established by the Financial Stability Board of the G20 group of countries. Nutrient-related financial information could be developed to help support investors and companies make evidence-based decisions on their response to environmental change, new regulations, and customer behaviour associated with a transition towards a more sustainable P future.

Solution 2.5: Improve transparency and the independent assessment of phosphate rock data

There is a need for transparency and free access to accurate, current data on global reserves and resources of phosphate rock. An independent, international body is needed to assess data regularly and to disseminate findings through appropriate mechanisms, institutions, and outreach programmes.

The need for transparency on global reserves and resources of PR and estimated quality of supply is recognised widely (e.g. Ulrich and Frossard, 2014; Rosemarin and Ekane, 2016; Wellmer and Scholz, 2017; Geissler et al., 2018; Nedelciu et al., 2020). Increasing transparency will require the collaborative efforts of governments, industry stakeholders, geological surveys, academia and inter/-national organisations (van Kauwenbergh, 2010; Ulrich and Frossard, 2014).

Strategies for P management often rely on quantitative models to underpin decision-making and policy development. Independent of the modelling approach, robust data is essential. With the lack of available data, decisions taken by governments may not be correct, and predictions by scientists uncertain (Geissler et al., 2018). Currently, private consulting firms collect data, which are then available to paying members. For example, CRU is a business intelligence company that collects data (e.g. mineral P fertiliser production costs, prices, supply and demand) and uses IFA data to cross-check its numbers, whilst scientists usually depend on access to publicly available data from national geological surveys. Geissler et al. (2018) suggest IFA data on global PR production is likely to be the most accurate, and covers 98% of global production, but points out that only limited reports and data are available to non-members.

The establishment of an independent and international body to regularly assess data and to promote and disseminate findings/ results through appropriate mechanisms, institutions and outreach programmes is urgently needed (Rosemarin and Ekane, 2016; Geissler et al., 2018; Nedelciu et al., 2020; Brownlie et al., 2021) (see Chapter 9). This could serve a similar function for P supply and demand, as the UN World Water Quality Alliance does for water quality, by providing governments and other stakeholders with relevant evidence-based assessment, scenarios, solutions, and services. It is recommended that such activities be accompanied by efforts to agree on the definitions of reserves and deposits, and conversion of all phosphate data to a common base, such as 100% P_2O_5 ("total tonnes of P_2O_5 nutrients") (Geissler et al., 2018). In the meantime, policymakers should be made aware of the discrepancies and uncertainties in PR data when making policy decisions.

References

African Union. 2017. Decisions, Declarations, Resolution and Motion - Assembly of the Union. Twenty-eighth ordinary session, 30 - 31 January 2017, Addis Ababa, Ethiopia session.

Al-Hwaiti, M. 2005. Heavy Metal Assessment of Phosphogypsum Waste Stockpile Material from Jordan. J. Am. Soc. Min. Reclam. 2005(1): 1–22. doi: 10.21000/JASMR05010001.

Al-Shawi, A.W., and R. Dahl. 1999. Determination of total chromium in phosphate rocks by ion chromatography. J. Chromatogr. A 850(1–2): 137–141. doi: 10.1016/S0021-9673(99)00543-9.

Aleklett, K. 2012. Peeking at Peak Oil. Springer New York, New York, NY.

Allan, J. 2016. Natural resources and intifada : oil, phosphates and resistance to colonialism in Western Sahara. J. North African Stud. 21(4): 645–666. doi: 10.1080/13629387.2016.1174586.

Arts, K., and P.P. Leite. 2007. International Law and the Question of Western Sahara. Autonomy, Leiden, The Netherlands.

Ashley, K., D. Cordell, and D. Mavinic. 2011. A brief history of phosphorus: From the philosopher's stone to nutrient recovery and reuse. Chemosphere 84(6): 737–746. doi: 10.1016/j.chemosphere.2011.03.001.

Attallah, M.F., S.S. Metwally, S.I. Moussa, and M.A. Soliman. 2019. Environmental impact assessment of phosphate ws and phosphogypsum waste: Elemental and radiological effects. Microchem. J. 146: 789–797. doi: 10.1016/j.microc.2019.02.001.

Bender, F. 1986. Mineral resources availability and global change. Episodes 9(3): 150–154.

Bigalke, M., A. Ulrich, A. Rehmus, and A. Keller. 2017. Accumulation of cadmium and uranium in arable soils in Switzerland. Environ. Pollut. 221: 85–93. doi: 10.1016/j.envpol.2016.11.035.

Blackwell, M., T. Darch, and R. Haslam. 2019. Phosphorus use efficiency and fertilizers: future opportunities for improvements. Front. Agric. Sci. Eng. 6(4): 332–340. doi: 10.15302/J-FASE-2019274.

Beusen, A.H.W., A.F. Bouwman, L.P.H. Van Beek, J.M. Mogollón, and J.J. Middelburg. 2016. Global riverine N and P transport to ocean increased during the 20th century despite increased retention along the aquatic continuum. Biogeosciences 13(8): 2441–2451. doi: 10.5194/bg-13-2441-2016.

de Boer, M.A., L. Wolzak, and J.C. Slootweg. 2019. Phosphorus: Reserves, Production, and Applications. In: Ohtake, H. and Tsuneda, S., editors, Phosphorus Recovery and Recycling. Springer, Singapore. p. 75–100

Bogaard, A., R. Fraser, T.H.E. Heaton, M. Wallace, P. Vaiglova, et al. 2013. Crop manuring and intensive land management by Europe's first farmers. Proc. Natl. Acad. Sci. 110(31): 12589–12594. doi: 10.1073/pnas.1305918110.

Boukhars, A., and J. Roussellier, editors. 2014. Perspectives on Western Sahara: Myths, Nationalisms, and Geopolitics. Rowman and Littlefield Publishers, Inc, Lanham, Maryland.

Brindha, K., L. Elango, and R.N. Nair. 2011. Spatial and temporal variation of uranium in a shallow weathered rock aquifer in southern India. J. Earth Syst. Sci. 120(5): 911–920.

Brobst, D.A., and W.P. Pratt. 1973. Geological Survey Professional Paper 820. Washington, US.

Brownlie, W.J., D. Cordell, M.A. Sutton, T.S. Neset, and B.M. Spears. 2017. Phosphorus: critical for food production and water quality - Prepared for UNEP, by the Centre for Ecology & Hydrology on behalf of the Global Partnership on Nutrient Management.

Brownlie, W.J., M.A. Sutton, D.S. Reay, K.V. Heal, L. Hermann, et al. 2021. Global actions for a sustainable phosphorus future. Nat. Food 2: 71–74.

Camprubí, L. 2015. Resource Geopolitics: Cold War Technologies, Global Fertilizers, and the Fate of Western Sahara. Technol. Cult. 56(3): 676–703. doi: 10.1353/tech.2015.0077.

Carpenter, S.R., and E.M. Bennett. 2011. Reconsideration of the planetary boundary for phosphorus. Environ. Res. Lett 6: 14009–14021. doi: 10.1088/1748-9326/6/1/014009.

Chen, M., and T.E. Graedel. 2016. A half-century of global phosphorus flows, stocks, production, consumption, recycling, and environmental impacts. Glob. Environ. Chang. 36: 139–152. doi: 10.1016/j.gloenvcha.2015.12.005.

Chernoff, C.B., and G.J. Orris. 2002. Data Set of World Phosphate Mines, Deposits, and Occurrences—Part A. Geologic Data. U.S. Geol. Surv.

Chianu, J.N., J.N. Chianu, and F. Mairura. 2012. Mineral fertilizers in the farming systems of sub-Saharan Africa. A review. Agron. Sustain. Dev. 32(2): 545–566. doi: 10.1007/s13593-011-0050-0.

Childers, D.L., J. Corman, M. Edwards, and J.J. Elser. 2011. Sustainability Challenges of Phosphorus and Food: Solutions from Closing the Human Phosphorus Cycle. Bioscience 61(2): 117–124. doi: 10.1525/bio.2011.61.2.6.

Chowdhury, R.B., G.A. Moore, A.J. Weatherley, and M. Arora. 2017. Key sustainability challenges for the global phosphorus resource, their implications for global food security, and options for mitigation. J. Clean. Prod. 140: 945–963. doi: 10.1016/J.JCLEPRO.2016.07.012.

Chraiti, R., M. Raddaoui, and A. Hafiane. 2016. Effluent Water Quality at Phosphate Mines in M'Dhilla, Tunisia and its Potential Environmental Effects. Mine Water Environ. 35(4): 462–468. doi: 10.1007/s10230-016-0400-x.

Cioroianu, T.M., F. Bunus, D. Filip, and G. Filip. 2001. Environmental considerations on uranium and radium from phosphate fertilizers. Int. Energy Agency IAEA-TECDO: 215–224. https://inis.iaea.org/collection/NCLCollectionStore/_Public/32/051/32051590.pdf.

Corbridge, D.E.C. 2000. Phosphorus 2000. Chemistry, Biochemistry and Technology. Elsevier, New York.

Cordell, D. 2010. The Story of Phosphorus: S ustainability implications of global phosphorus scarcity for food security. Ph.D. Thesis, Linköping Univ. Linköping, Sweden. http://liu.diva-portal.org/smash/get/diva2:291760/FULLTEXT01.pdf (accessed 18 October 2021).

Cordell, D., J.O. Drangert, and S. White. 2009. The story of phosphorus: Global food security and food for thought. Glob. Environ. Chang. 19(2): 292–305. doi: 10.1016/j.gloenvcha.2008.10.009.

Cordell, D., M. Jackson, and S. White. 2013. Phosphorus flows through the Australian food system: Identifying intervention points as a roadmap to phosphorus security. Environ. Sci. Policy 29: 87–102. doi: 10.1016/J.ENVSCI.2013.01.008.

Cordell, D., and S. White. 2011. Peak Phosphorus: Clarifying the Key Issues of a Vigorous Debate about Long-Term Phosphorus Security. Sustainability 3(12): 2027–2049. doi: 10.3390/su3102027.

Cordell, D., and S. White. 2014. Life's Bottleneck: Sustaining the World's Phosphorus for a Food Secure Future. Annu. Rev. Environ. Resour. 39(1): 161–188. doi: 10.1146/annurev-environ-010213-113300.

Corisco, J.A.G., J. Mihalík, M.J. Madruga, M.I. Prudêncio, R. Marques, et al. 2017. Natural Radionuclides, Rare Earths and Heavy Metals Transferred to the Wild Vegetation Covering a Phosphogypsum Stockpile at Barreiro, Portugal. Water, Air, Soil Pollut. 228(235): 1–9. doi: 10.1007/s11270-017-3413-6.

Court of Justice of the European Union. 2018. The Queen, on the application of Western Sahara Campaign UK v Commissioners for Her Majesty's Revenue and Customs and Secretary of State for Environment, Food and Rural Affairs. (Judgment in Case C-266/16).

Déry, P., and B. Anderson. 2007. Peak phosphorus.

van Dijk, K.C., J.P. Lesschen, and O. Oenema. 2016. Phosphorus flows and balances of the European Union Member States. Sci. Total Environ. 542: 1078–1093. doi: 10.1016/j.scitotenv.2015.08.048.

van Drecht, G., A.F. Bouwman, J. Harrison, and J.M. Knoop. 2009. Global nitrogen and phosphate in urban wastewater for the period 1970 to 2050. Global Biogeochem. Cycles 23(GB0A03): 1–19. doi: 10.1029/2009GB003458.

Dudley, D. 2018. European Court Rules Against Morocco Again, Barring Western Sahara's Waters From EU Fisheries Deal. Forbes. https://www.forbes.com/sites/dominicdudley/2018/02/27/ecj-morocco-western-sahara-fisheries/?sh=602b251327f3 (accessed 1 March 2021).

Edixhoven, J.D., J. Gupta, and H.H.G. Savenije. 2014. Recent revisions of phosphate rock reserves and resources: A critique. Earth Syst. Dyn. 5(2): 491–507. doi: 10.5194/esd-5-491-2014.

EFSA. 2012. Cadmium dietary exposure in the European population. Eur. Food Saf. Auth. 10(1): 2551. doi: 10.2903/j.efsa.2012.2551.

EITI. 2019. The EITI Standard 2019, The global standard for the good governance of oil, gas and mineral resources. EITI International Secretariat, Oslo, Norway.

Ertani, A., A. Mietto, M. Borin, and S. Nardi. 2017. Chromium in Agricultural Soils and Crops: A Review. Water. Air. Soil Pollut. 228(190): 1–12. doi: 10.1007/s11270-017-3356-y.

ETC/ULS. 2016. Assessment of critical load exceedances of nitrogen, phosphorus and cadmium in view of food, soil and water quality. Deliverable 1.8.2.3 KD2.

European Commission. 2014. Report on Critical Raw Materials for the EU - Critical Raw Materials Profiles.

European Commission. 2017. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on the 2017 list of Critical Raw Materials for the EU. COM/2017/0.

European Commission. 2020. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the regions. Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability. COM/2020/4.

European Parliament. 2018. Fertilisers/cadmium: Parliament and Council negotiators reach provisional deal. Eur. Parliam. Press Release - REF. 20181119IPR19407. http://www.europarl.europa.eu/news/nl/press-room/20181119IPR19407/fertilisers-cadmium-parliament-and-council-negotiators-reach-provisional-deal (accessed 10 January 2020).

European Parliament & the Council of the European Union. 2019. Laying down rules on the making available on the market of EU fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003. Off. J. Eur. Union L 170/1. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32019R1009 (accessed 15 June 2020).

FAO. 2017. FAOSTAT. Food Agric. Data. http://www.fao.org/faostat/en/#data.

FitzGerald, R., and N. Roth. 2015. Cadmium in Mineral Fertilizers - Human and Environmental Risk Update. Basel.

Gantner, O., W. Schipper, and J. Weigand. 2014. Technological use of phosphorus: the non-fertilizer, non-feed and non-detergent domain. In: Scholz, R.W., Roy, A.H., Brand, F.S., Hellums, D.H., and Ulrich, A.E., editors, Sustainable phosphorus management – A sustainable roapmap. Springer, Berlin

Geissler, B., M.C. Mew, and G. Steiner. 2019. Phosphate supply security for importing countries: Developments and the current situation. Sci. Total Environ. 677: 511–523. doi: 10.1016/j.scitotenv.2019.04.356.

Geissler, B., G. Steiner, and M.C. Mew. 2018. Clearing the fog on phosphate rock data – Uncertainties, fuzziness, and misunderstandings. Sci. Total Environ. 642: 250–263. doi: 10.1016/j.scitotenv.2018.05.381.

Gil, J.D.B., P. Reidsma, K. Giller, L. Todman, A. Whitmore, et al. 2019. Sustainable development goal 2: Improved targets and indicators for agriculture and food security. Ambio 48(7): 685–698. doi: 10.1007/s13280-018-1101-4.

Gobe, E. 2010. The Gafsa Mining Basin between Riots and a Social Movement: meaning and significance of a protest movement in Ben Ali's Tunisia. halshs-005(July). https://halshs.archives-ouvertes.fr/halshs-00557826.

Günther, S., M. Grunert, and S. Müller. 2018. Overview of recent advances in phosphorus recovery for fertilizer production. Eng. Life Sci. 18(7): 434–439. doi: 10.1002/elsc.201700171.

Hagen, E. 2015. Saharawi conflict phosphates and the Australian dinner table. Glob. Chang. Peace Secur. 27(3): 377–393. doi: 10.1080/14781158.2015.1083541.

Hamilton, H.A., D. Ivanova, K. Stadler, S. Merciai, J. Schmidt, et al. 2018. Trade and the role of non-food commodities for global eutrophication. Nat. Sustain. 1: 314–321. doi: 10.1038/s41893-018-0079-z.

Haridasan, P.P., A.C. Paul, and M.V.M. Desai. 2001. Natural radionuclides in the aquatic environment of a phosphogypsum disposal area. J. Environ. Radioact. 53(2): 155–165. doi: 10.1016/S0265-931X(00)00121-1.

Hermann, L., F. Kraus, and R. Hermann. 2018. Phosphorus Processing—Potentials for Higher Efficiency. Sustainability 10(5): 1482. doi: 10.3390/su10051482.

High Court of Justice (England & Wales). 2016. In Case C-266/16: Western Sahara Campaign UK v Commissioners for Her Majesty's Revenue and Customs, Secretary of State for Environment, Food and Rural Affairs. http://curia.europa.eu/juris/document/document.jsf;jsessionid=4E8B93C565CDC31B4E8669F2057F6A62?text=-canada%2Bpnr&docid=199683&pageIndex=0&doclang=EN&mode=req&dir=&occ=-first&part=1&cid=16352757#ctx1 (accessed 27 February 2021).

High Court of South Africa. 2017. In the High Court of South Africa (Eastern Cape Local Division, Port Elizabeth). Case No 14. https://wsrw.org/files/dated/2018-02-23/20180223_south_africa_ruling.pdf.

Hilton, J. 2020. Phosphogypsum Leadership, Innovation, Partnership: Report for the International Fertiliser Association. IFA, Paris, France.

Hooser, S.B. 2018. Cadmium. In: Gupta, R.C., editor, Veterinary Toxicology. Elsevier. p. 417–421.

Huang, W. 2009. Factors Contributing to the Recent Increase in US Fertilizer Prices, USDA Outlook, AR-33. United States Dep. Agric.

IARC. 1993. Beryllium, cadmium, mercury, and exposures in the glass manufacturing industry. IARC Monogr. Eval. Carcinog. Risks to Hum. their Suppl. 58.

IFA. 2011. Feeding the Earth: Food Prices and Fertiliser Markets Factors influencing variations in fertiliser market conditions. https://www.fertilizer.org/images/Library_Downloads/2011_ifa_food_prices.pdf.

Indian Bureau of Mines. 2016. Indian Minerals Yearbook 2016 (Part-III: Mineral Reviews). 55th Edition. Apatite and Rock Phosphate. https://ibm.gov.in/writereaddata/files/05152018161445Apatiteandrockphophate2016.pdf.

IPNI. 2014a. Nutrient Source Specifics No. 14 - Single Superphosphate. https://www.cropnutrition.com/resource-library/single-superphosphate (accessed 17 February 2021).

IPNI. 2014b. Nutrient Source Specifics No. 21 - Triple Superphosphate. https://www.cropnutrition.com/resource-library/triple-superphosphate (accessed 17 February 2021).

Ivell, D.M. 2012. Phosphate Fertilizer Production – From the 1830's to 2011 and Beyond. Procedia Eng. 46: 166–171. doi: 10.1016/j.proeng.2012.09.461.

Jarvie, H.P., A.N. Sharpley, D. Flaten, P.J.A. Kleinman, A. Jenkins, et al. 2015. The Pivotal Role of Phosphorus in a Resilient Water–Energy–Food Security Nexus. J. Environ. Qual. 44(4): 1049–1062. doi: 10.2134/jeq2015.01.0030.

Jasinski, S.M. 2009. Mineral Commodity Summaries: Phosphate Rock. U.S. Geol. Surv.

Jasinski, S.M. 2014. 2014 Minerals Yearbook - Phosphate Rock. U.S. Geol. Surv.

Jasinski, S.M. 2017. 2017 Minerals Yearbook - Phosphate Rock [advance release]. U.S. Geol. Surv. https://www.crugroup.com/. (accessed 16 December 2020).

Jasinski, S.M. 2019. Mineral Commodity Summaries: Phosphate Rock. U.S. Geol. Surv.

Jasinski, S.M. 2021. Mineral Commodity Summaries: Phosphate Rock. U.S. Geol. Surv.

Al Jazeera. 2020. Protesters in Tunisia halt key phosphate production. https://www.aljazeera.com/news/2020/11/25/protesters-in-tunisia-halt-key-phosphate-production (accessed 2 March 2021).

De Jonge, B. 2011. What is Fair and Equitable Benefit-sharing? J. Agric. Environ. Ethics 24(2): 127–146. doi: 10.1007/s10806-010-9249-3.

Karapinar, B. 2011. China's export restriction policies: complying with 'WTO plus' or undermining multilateralism. World Trade Rev. 10(03): 389–408. doi: 10.1017/S1474745611000218.

Kasraoui, S. 2021. State Department Human Rights Report Lists Western Sahara in Morocco. Morocco World News. https://www.moroccoworldnews.com/2021/03/338588/state-department-human-rights-report-lists-western-sahara-in-morocco.

van Kauwenbergh, S. 2010. World Phosphate Rock Reserves and Resources, IFDC Technical Bulletin, 75. Washington, DC and Muscle Shoals, DC and Muscle Shoals.

van Kauwenbergh, S., M. Stewart, and R. Mikkelsen. 2013. World Reserves of Phosphate Rock… a Dynamic and Unfolding Story. Better Crop. with Plant Food 97(3): 18–20. http://insors.de/index.php/de/licht-und-jalousiemanagement.

Kelly, T.D., and G.R. Matos. 2014. Phosphate rock statistics. Historical statistics for mineral and material commodities in the United States: U.S. Geological Survey Data Series 140

van Kernebeek, H.R.J., S.J. Oosting, M.K. van Ittersum, R. Ripoll-Bosch, and I.J.M. de Boer. 2018. Closing the phosphorus cycle in a food system: insights from a modelling exercise. Animal 12(8): 1755–1765. doi: 10.1017/S1751731118001039.

Khabarov, N., and M. Obersteiner. 2017. Global Phosphorus Fertilizer Market and National Policies: A Case Study Revisiting the 2008 Price Peak. Front. Nutr. 4(22): 1–8. doi: 10.3389/fnut.2017.00022.

Kingsbury, D. 2018. Western Sahara: International Law, Justice and Natural Resources. Routledge, New York.

Koppelaar, R.H.E.M.H.E.M., and H.P.P. Weikard. 2013. Assessing phosphate rock depletion and phosphorus recycling options. Glob. Environ. Chang. 23(6): 1454–1466. doi: 10.1016/j.gloenvcha.2013.09.002.

Kratz, S., F. Godlinski, and E. Schnug. 2011. Heavy Metal Loads to Agricultural Soils in Germany from the Application of Commercial Phosphorus Fertilizers and Their Contribution to Background Concentration in Soils. In: Merkel, B. and Schipek, M., editors, The New Uranium Mining Boom. Springer, Berlin, Heidelberg. p. 755–762.

Kratz, S., J. Schick, and E. Schnug. 2016. Trace elements in rock phosphates and P containing mineral and organo-mineral fertilizers sold in Germany. Sci. Total Environ. 542: 1013–1019. doi: 10.1016/J.SCITOTENV.2015.08.046.

Kumpiene, J., E. Brännvall, M. Wolters, N. Skoglund, S. Čirba, et al. 2016. Phosphorus and cadmium availability in soil fertilized with biosolids and ashes. Chemosphere 151: 124–132. doi: 10.1016/j.chemosphere.2016.02.069.

Leite, P., C. Olsson, M. Schöldtz, T. Shelley, P. Wrange, et al. 2006. The Western Sahara Conflict: The Role of Natural Resources in Decolonization (C. Olsson, editor).

Levin, B.V., V.V. Kochetkov, S.A. Talalay, A.V. Korotkovsky, A.V. Shibnev, et al. 2020. Road innovation using phosphogypsum. In: Hilton, J., editor, Phosphogypsum Leadership, Innovation, Partnership: Report for the International Fertiliser Association. IFA, Paris, France. p. 79–84.

Li, H., J. Liu, G. Li, J. Shen, L. Bergström, et al. 2015. Past, present, and future use of phosphorus in Chinese agriculture and its influence on phosphorus losses. Ambio 44: 274–85. doi: 10.1007/s13280-015-0633-0.

Lyu, Y., H. Tang, H. Li, F. Zhang, Z. Rengel, et al. 2016. Major Crop Species Show Differential Balance between Root Morphological and Physiological Responses to Variable Phosphorus Supply. Front. Plant Sci. 7(1939). doi: 10.3389/fpls.2016.01939.

Macleod, I.J., and A.P.V. Rogers. 2007. The Use of White Phosphorus and the Law of War. Yearb. Int. Humanit. Law 10: 75–97. doi: 10.1017/S138913590700075X.

Mar, S.S., and M. Okazaki. 2012. Investigation of Cd contents in several phosphate rocks used for the production of fertilizer. Microchem. J. 104: 17–21. doi: 10.1016/j.microc.2012.03.020.

Martin, W., and K. Anderson. 2012. Export Restrictions and Price Insulation During Commodity Price Booms. Am. J. Agric. Econ. 94(2): 422–427. doi: 10.1093/ajae/aar105.

McKelvey, V.E. 1974. Potential mineral reserves. Resour. Policy 1(2): 75–81. doi: 10.1016/0301-4207(74)90016-6.

Mclaughlin, M.J., K.G. Tiller, R. Naidu, and D.P. Stevens. 1996. Review: the behaviour and environmental impact of contaminants in fertilizers. Aust. J. Soil Res. 34(1): 1–54.

Melillo, E.D. 2012. The First Green Revolution: Debt Peonage and the Making of the Nitrogen Fertilizer Trade, 1840–1930. Am. Hist. Rev. 117(4): 1028–1060. doi: 10.1093/ahr/117.4.1028.

Merkel, B.J., and M. Hoyer. 2012. Remediation of sites contaminated by radionuclides. In: Poinssot, C. and Geckeis, H., editors, Radionuclide Behaviour in the Natural Environment: Science, Implications and Lessons for the Nuclear Industry. Elsevier Ltd. p. 601–645.

Metson, G.S., V.H. Smith, D.J. Cordell, D.A. Vaccari, J.J. Elser, et al. 2014. Phosphorus is a key component of the resource demands for meat, eggs, and dairy production in the United States. Proc. Natl. Acad. Sci. 111(46): E4906–E4907. doi: 10.1073/pnas.1417759111.

Mew, M.C. 2016. Phosphate rock costs, prices and resources interaction. Sci. Total Environ. 542: 1008–1012. doi: 10.1016/j.scitotenv.2015.08.045.

Morgera, E. 2016. The Need for an International Legal Concept of Fair and Equitable Benefit Sharing. Eur. J. Int. Law 27(2): 353–383. doi: 10.1093/ejil/chw014.

Mundy, J. 2020. The U.S. recognized Moroccan sovereignty over the disputed Western Sahara. Here's what that means. Washington Post. https://www.washingtonpost.com/politics/2020/12/11/us-recognized-moroccan-sovereignty-over-disputed-western-sahara-heres-what-that-means/.

Mundy, J., and S. Zunes. 2010. Western Sahara: War, Nationalism, and Conflict Irresolution. Syracuse University Press, New York.

Nedelciu, C.E., K.V. Ragnarsdóttir, I. Stjernquist, and M.K. Schellens. 2020. Opening access to the black box: The need for reporting on the global phosphorus supply chain. Ambio 49(4): 881–891. doi: 10.1007/s13280-019-01240-8.

Notholt, A., R. Sheldon, and D. Davidson, editors. 2005. Phosphate Deposits of the World: Volume 2, Phosphate Rock Resources (Cambridge Earth Science Series). Cambridge Univeristy Press, Cambridge.

Nutrien. 2019. Revamping Nutrien's Phosphate Operations, Now Self-Sufficient in Phosphate Rock . https://www.nutrien.com/what-we-do/stories/revamping-nutriens-phosphate-operations (accessed 2 March 2021).

OCP. 2015. Annual Report - 2015. OCP Gr. https://corpo.ocpgroup.ma/en/annual-report-2015 (accessed 1 March 2021).

OCP. 2018. South Africa – NM Cherry Blossom: OCP Group recovers its phosphate cargo. https://corpo.ocpgroup.ma/en/south-africa-nm-cherry-blossom-ocp-group-recovers-its-phosphate-cargo (accessed 2 March 2021).

OCP. 2021. PHOSBOUCRAA | About Phosboucraa. https://phosboucraa.ma/company/about-phosboucraa (accessed 1 March 2021).

OCP SA. 2018. SUMMARY OF THE PROSPECTUS. Emission obligataire subordonnée perpétuelle avec options de remboursement anticipé et de différé de paiement d'intérêt. http://www.casablanca-bourse.com/BourseWeb/UserFiles/File/2018/niocp resumeanglais 23042018.pdf.

OECD. 2016. OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas. 3rd ed. OECD Publishing, Paris.

Olszewski, G., A. Boryło, and B. Skwarzec. 2016. The radiological impact of phosphogypsum stockpile in Wiślinka (northern Poland) on the Martwa Wisła river water. J. Radioanal. Nucl. Chem. 307(1): 653–660. doi: 10.1007/s10967-015-4191-5.

Omar, S. 2018. The African Union policies towards the Western Sahara. Africana Stud. 29: 91–102.

Ott, C., and H. Rechberger. 2012. The European phosphorus balance. Resour. Conserv. Recycl. 60: 159–172. https://www.sciencedirect.com/science/article/pii/S0921344911002540 (accessed 16 January 2019).

Papageorgiou, F., A. Godelitsas, T.J. Mertzimekis, S. Xanthos, N. Voulgaris, et al. 2016. Environmental impact of phosphogypsum stockpile in remediated Schistos waste site (Piraeus, Greece) using a combination of γ-ray spectrometry with geographic information systems. Environ. Monit. Assess. 188(133): 1–14. doi: 10.1007/s10661-016-5136-3.

Plotegher, F., and C. Ribeiro. 2016. Characterization of single superphosphate powders - A study of milling effects on solubilization kinetics. Mater. Res. 19(1): 98–105. doi: 10.1590/1980-5373-MR-2015-0401.

van Puijenbroek, P.J.T.M., A.H.W. Beusen, and A.F. Bouwman. 2019. Global nitrogen and phosphorus in urban waste water based on the Shared Socio-economic pathways. J. Environ. Manage. 231: 446–456. https://www.sciencedirect.com/science/article/pii/S0301479718311824 (accessed 6 September 2019).

Rao, A., S. Srivastava, A. Subba Rao, S. Srivastava, and A.N. Ganeshamurty. 2015. Phosphorus supply may dictate food security prospects in India. Curr. Sci. 108(7): 1253–1261. https://www.researchgate.net/publication/280572144 (accessed 24 April 2020).

Reijnders, L. 2014. Phosphorus resources, their depletion and conservation, a review. Resour. Conserv. Recycl. 93: 32–49. doi: 10.1016/j.resconrec.2014.09.006.

Reta, G.L., X. Dong, B. Su, X. Hu, H. Bo, et al. 2019. The Influence of Large Scale Phosphate Mining on the Water Quality of the Huangbaihe River Basin in China: Dominant Pollutants and Spatial Distributions. Mine Water Environ. 38(2): 366–377. doi: 10.1007/s10230-019-00604-6.

Reuters. 2017a. Morocco phosphate ship held in Panama over Western Sahara challenge: officials. https://www.reuters.com/article/us-westernsahara-morocco-idUSKCN18E2YA (accessed 2 March 2021).

Reuters. 2017b. Panama court dismisses Western Sahara phosphate claim: Morocco's OCP. https://www.reuters.com/article/us-westernsahara-morocco-panama-idUSKBN18Z2SC (accessed 2 March 2021).

de Ridder, M., S. de Jong, J. Polchar, and S. Lingemann. 2012. Risks and Opportunities in the Global Phosphate Rock Market. Robust Strategies in Times of Uncertainty. Hague Cent. Strateg. Stud. No 17 | 12 | 12. www.hcss.nl (accessed 4 February 2019).

Rizwan, M., S. Ali, M. Adrees, M. Ibrahim, D.C.W. Tsang, et al. 2017. A critical review on effects, tolerance mechanisms and management of cadmium in vegetables. Chemosphere 182: 90–105. doi: 10.1016/j.chemosphere.2017.05.013.

Römkens, P., R. Rietra, H. Kros, J.C. Voogd, and W. de Vries. 2018. Impact of cadmium levels in fertilisers on cadmium accumulation in soil and uptake by food crops.

Rosemarin, A., and N. Ekane. 2016. The governance gap surrounding phosphorus. Nutr. Cycl. Agroecosystems 104(3): 265–279. doi: 10.1007/s10705-015-9747-9.

Rutherford, P.M., M.J. Dudas, and R.A. Samek. 1994. Environmental impacts of phosphogypsum. Sci. Total Environ. 149(1–2): 1–38. doi: 10.1016/0048-9697(94)90002-7.

Saadaoui, E., N. Ghazel, C. Ben Romdhane, and N. Massoudi. 2017. Phosphogypsum: potential uses and problems–a review. Int. J. Environ. Stud. 74(4): 558–567. doi: 10.1080/00207233.2017.1330582.

Sabiha-Javied, T. Mehmood, M.M. Chaudhry, M. Tufail, and N. Irfan. 2009. Heavy metal pollution from phosphate rock used for the production of fertilizer in Pakistan. Microchem. J. 91(1): 94–99. doi: 10.1016/J.MICROC.2008.08.009.

Sanchez, P.A. 2002. Soil Fertility and Hunger in Africa. Science (5562): 2019–2020. doi: 10.1126/science.1065256.

Sattouf, M. 2007. Identifying the origin of rock phosphates and phosphorus fertilisers using isotope ratio techniques and heavy metal patterns. Ph.D. Thesis, Braunschweig, Techn. Univ. http://agris.fao.org/agris-search/search.do?recordID=US201300124575 (accessed 26 March 2019).

Schnug, E., F. Jacobs, and K. Stöven. 2018. Guano: The White Gold of the Seabirds. In: Mikkola, H., editor, Seabirds. InTech, London, UK. p. 81–100.

Schnug, E., and B.G. Lottermoser. 2013. Fertilizer-derived uranium and its threat to human health. Environ. Sci. Technol. 47(6): 2433–2434. doi: 10.1021/es4002357.

Schnug, E., H. Steckel, and S. Haneklaus. 2005. Contribution of uranium in drinking waters to the daily uranium intake of humans - a case study from Northern Germany.

Scholz, R.W., A.E. Ulrich, M. Eilittä, and A. Roy. 2013. Sustainable use of phosphorus: A finite resource. Sci. Total Environ. 461–462: 799–803. doi: 10.1016/j.scitotenv.2013.05.043.

Scholz, R.W., and F.W. Wellmer. 2013. Approaching a dynamic view on the availability of mineral resources: What we may learn from the case of phosphorus? Glob. Environ. Chang. 23(1): 11–27. doi: 10.1016/j.gloenvcha.2012.10.013.

Smedley, P.L., B. Smith, C. Abesser, and D. Lapworth. 2006. Uranium occurrence and behaviour in British groundwater. Br. Geol. Surv. Comm. Rep. (CR/06/050N): 60 pp. www.bgs.ac.uk (accessed 16 June 2020).

Smidt, G.A. 2011. Mobility of fertiliser-derived uranium in arable soils and its contribution to uranium concentrations in groundwater and tap water. PhD thesis. Jacobs Univ. Breman. http://nbn-resolving.org/urn:nbn:de:101:1-201305294841 (accessed 16 June 2020).

Smidt, G.A., F.C. Landes, L. Machado de Carvalho, A. Koschinsky, and E. Schnug. 2011. Cadmium and Uranium in German and Brazilian Phosphorous Fertilizers. In: Merkel, B. and Schipek, M., editors, Springer Geology. Springer. p. 167–175

Smil, V. 2000. Phosphorus in the environment: Natural Flows and Human Interfences. Annu. Rev. Energy Environ. 25: 53–88.

Smith, J.J. 2015. The taking of the Sahara: the role of natural resources in the continuing occupation of Western Sahara. Glob. Chang. Peace Secur. 27(3): 263–284. doi: 10.1080/14781158.2015.1080234.

Smith, V.H., and D.W. Schindler. 2009. Eutrophication science: where do we go from here? Trends Ecol. Evol. 24(4): 201–207. doi: 10.1016/j.tree.2008.11.009.

Smolders, E. 2001. Cadmium uptake by plants. Int. J. Occup. Med. Environ. Health 14(2): 177–183.

Spears, B.M., W.J. Brownlie, D. Cordell, L. Hermann, J. Mogollón (2022) Concerns about global phosphorus demand for lithium-iron phosphate batteries in the light electric vehicle sector. Nat. Comms. Materials.

Speight, J.G. 2017. Environmental Inorganic Chemistry for Engineers. Elsevier.

Steffen, W., K. Richardson, J. Rockström, S.E. Cornell, I. Fetzer, et al. 2015. Planetary boundaries: Guiding human development on a changing planet. Science 347(1259855). doi: 10.1126/science.1259855.

Steiner, G., B. Geissler, I. Watson, and M.C. Mew. 2015. Efficiency developments in phosphate rock mining over the last three decades. Resour. Conserv. Recycl. 105: 235–245. doi: 10.1016/j.resconrec.2015.10.004.

Sutton, M.A., A. Bleeker, C.M. Howard, M. Bekunda, M. Grizzetti, et al. 2013. Our Nutrient World: The challenge to produce more food and energy with less pollution. Global Overview of Nutrient Management. Centre of Ecology and Hydrology, Edinburgh on behalf of the Global Partnership on Nutrient Management and the International Nitrogen Initiative.

Sutton, M.A., C.M. Howard, D.R. Kanter, L. Lassaletta, A. Móring, et al. 2021. The nitrogen decade: mobilizing global action on nitrogen to 2030 and beyond. One Earth 4(1): 10–14. doi: 10.1016/j.oneear.2020.12.016.

Syers, J.K. 2001. Progress in the development of decadmiation of phosphorus fertilizers. Fertilizer Industry Federation of Australia, Inc., Conference "Fertilizers in Focus." p. 101–106.

Syers, K., M. Bekunda, D. Cordell, J. Corman, J. Johnston, et al. 2011. Phosphorus and food production. UNEP Year Book 2011. Emerging issues in our global environment. United Nations Environment Programme, Nairobi. p. 34–45

Tayibi, H., M. Choura, F. López, F.J. Alguacil, and A. López-Delgado. 2009. Environmental impact and management of phosphogypsum. J. Environ. Manage. 90: 2377–2386. doi: 10.1016/j.jenvman.2009.03.007.

TCFD. 2017. Recommendations of the Task Force on Climate-related Financial Disclosures. Financial Stability Board, Basel, Switzerland.

Teah, H.Y., and M. Onuki. 2017. Support phosphorus recycling policy with social life cycle assessment: A case of Japan. Sustain. 9(1223). doi: 10.3390/su9071223.

The Business Research Company. 2020. Phosphate Fertilizers Global Market Report 2020. https://www.prnewswire.com/news-releases/global-phosphate-fertilizers-market-report-2020—-rapid-increase-in-production-and-exports-of-phosphates-from-china-301026227.html (accessed 26 February 2021).

The European Court of Justice. 2016. Appeal — External relations — Agreement between the European Union and the Kingdom of Morocco concerning liberalisation measures on agricultural and fishery products — Decision approving the conclusion of an international agreement — Action for annulment. (Case C-104/16 P). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:62016CJ0104_SUM.

The International Court of Justice. 2017. Western Sahara. OVERVIEW OF THE CASE. https://www.icj-cij.org/en/case/61.

Ulrich, A. 2016. Taking Stock: Phosphorus Supply from Natural and Anthropogenic Pools in the 21st Century. Sci. Total Environ. 542: 1005–1007. doi: 10.1016/j.scitotenv.2015.10.036.

Ulrich, A.E. 2019. Cadmium governance in Europe's phosphate fertilizers: Not so fast? Sci. Total Environ. 650: 541–545. doi: 10.1016/j.scitotenv.2018.09.014.

Ulrich, A., and E. Frossard. 2014. On the history of a reoccurring concept: Phosphorus scarcity. Sci. Total Environ. 490: 694–707. doi: 10.1016/j.scitotenv.2014.04.050.

Ulrich, A.E., E. Schnug, H. Prasser, and E. Frossard. 2014. Uranium endowments in phosphate rock. Sci. Total Environ. 478: 226–234. doi: 10.1016/j.scitotenv.2014.01.069.

UN. Legal Counsel. 2002. Letter dated 29 January 2002 from the Under-Secretary-General for Legal Affairs, the Legal Counsel, addressed to the President of the Security Council. United Nations Secur. Counc. (S/2002/161). https://digitallibrary.un.org/record/458183?ln=en.

UNHCR. 2018. Sahrawi Refugees in Tindouf, Algeria: Total In-Camp Population - Official report for the United Nations High Commissioner for Refugees.

United Nations. 2010. UN Office of the High Commissioner for Human Rights (OHCHR), Fact Sheet No. 34, The Right to Adequate Food. Geneva.

United Nations. 2020. The United Nations and Decolonization - Non-Self-Governing Territories. https://www.un.org/dppa/decolonization/en/nsgt (accessed 1 March 2021).

United Nations General Assembly. 1980. Resolutions adopted on the reports of the Fourth Committee - General Assembly Thirty-fifth Session - "35/19 Question of Western Sahara" - 56th Plenary meeting. https://www.securitycouncilreport.org/atf/cf/%7B65BFCF9B-6D27-4E9C-8CD3-CF6E4FF96FF9%7D/a_res_35_19.pdf.

United Nations Security Council. 1991. Security Council resolution 690 (1991) [Western Sahara] 29 April 1991, S/RES/690 (1991). https://www.refworld.org/docid/3b00f16818.html (accessed 1 June 2021).

United Nations Security Council. 2002. Letter dated 29 January 2002 from the Under-Secretary-General for Legal Affairs, the Legal Counsel, addressed to the President of the Security Council. : S/2002/161. https://digitallibrary.un.org/record/458183?ln=en.

de Vries, W., and M.J. McLaughlin. 2013. Modeling the cadmium balance in Australian agricultural systems in view of potential impacts on food and water quality. Sci. Total Environ. 461–462: 240–257. doi: 10.1016/j.scitotenv.2013.04.069.

de Vries, W., and P.F.A.M. Römkens. 2017. Impact of nitrogen, phosphorus and metals on food, soil and water quality: Comparison of current and critical metal inputs and soil metal concentrations in agricultural soils in EU-27 in view of ecotoxicological impacts on soil organisms.

El Wali, M., S.R. Golroudbary, and A. Kraslawski. 2021. Circular economy for phosphorus supply chain and its impact on social sustainable development goals. Sci. Total Environ. 777: 146060. doi: 10.1016/j.scitotenv.2021.146060.

Webeck, E., K. Matsubae, K. Nakajima, K. Nansai, and T. Nagasaka. 2014. Analysis of phosphorus dependency in Asia. Sociotechnica 11: 119–126. http://shakai-gijutsu.org/vol11/11_119.pdf (accessed 4 February 2019).

Wellmer, F.-W., and R.W. Scholz. 2017. Putting Phosphorus First: The Need to Know and Right to Know Call for a Revised Hierarchy of Natural Resources. Resources 6(2): 20. doi: 10.3390/resources6020020.

White, N. 2015. Conflict Stalemate in Morocco and Western Sahara: Natural Resources, Legitimacy and Political Recognition. Br. J. Middle East. Stud. 42(3): 339–357. doi: 10.1080/13530194.2014.949220.

Withers, P.J.A., K. van Dijk, T.S. Neset, T. Nesme, O. Oenema, et al. 2015a. Stewardship to tackle global phosphorus inefficiency: The case of Europe. Ambio 44: 193–206. doi: 10.1007/s13280-014-0614-8.

Withers, P.J.A., D. Doody, and R. Sylvester-Bradley. 2018a. Achieving Sustainable Phosphorus Use in Food Systems through Circularisation. Sustainability 10(6): 1804. doi: 10.3390/su10061804.

Withers, P.J.A., J.J. Elser, J. Hilton, H. Ohtake, W.J. Schipper, et al. 2015b. Greening the global phosphorus cycle: how green chemistry can help achieve planetary P sustainability. Green Chem. 17(4): 2087–2099. doi: 10.1039/C4GC02445A.

Withers, P.J.A., M. Rodrigues, A. Soltangheisi, T.S. De Carvalho, L.R.G. Guilherme, et al. 2018b. Transitions to sustainable management of phosphorus in Brazilian agriculture. Sci. Rep. 8(2537): 1–13. doi: 10.1038/s41598-018-20887-z.

World Health Organization & International Programme on Chemical Safety. 1992. Cadmium : environmental aspects.

World Trade Organization. 2009. China - Measures related to the exportation of various raw materials. Reports of the Panel. WT/DS394/R. https://docs.wto.org/dol2fe/Pages/FE_Search/FE_S_S009-DP.aspx?language=E&CatalogueIdList=55573,108753,96753&CurrentCatalogueIdIndex=1&FullTextHash=&HasEnglishRecord=True&HasFrenchRecord=True&HasSpanishRecord=True.

WSRW. 2018. P is for plunder - Morocco's exports of phosphates from occupied Western Sahara. 2018 with data from 2017.

WSRW. 2020. P is for plunder - Morocco's exports of phosphates from occupied Western Sahara. 2020 with data from 2019.

Xu, C., Q. Dai, L. Gaines, M. Hu, A. Tukker, et al. 2020. Future material demand for automotive lithium-based batteries. Commun. Mater. 1(99). doi: 10.1038/s43246-020-00095-x.

Zhao, X., Q. Dong, S. Ni, X. He, H. Yue, et al. 2019. Rhizosphere processes and nutrient management for improving nutrient-use efficiency in macadamia production. HortScience 54(4): 603–608. doi: 10.21273/HORTSCI13643-18.

Zunes, S. 2015. Western Sahara, resources, and international accountability. Glob. Chang. Peace Secur. 27(3): 285–299. doi: 10.1080/14781158.2015.1080233.