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Our Phosphorus Future - an introduction

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The 'Our Phosphorus Future' project (OPF) responds to the critical need to provide direction from the global phosphorus scientific community to progress sustainable phosphorus use. The OPF project ran from 2017-2021. During this time over 100 scientists and industry experts came together to develop this report. The report identifies the priority issues, possible solutions and the capacity to address phosphorus sustainability from local to global scales.

Left: Lake Braies in the Prags Dolomites in South Tyrol, Italy. Ecotourism in this area is reliant on healthy aquatic ecosystems and high water quality. Photograph taken by Geoffrey Lucas on www.unsplash.com - www.geoffphotography.com/

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1.1 What is the Our Phosphorus Future project?

The 'Our Phosphorus Future' (OPF) project is a response from the scientific community to the need for direction on sustainable phosphorus (P) use (Focus Box 1.1). The OPF report identifies the priority issues, possible solutions and the potential to improve P sustainability from local to global scales. At the same time, it aims to prime the international scientific, practitioner and policy communities to co-develop the next steps towards a durable international process of scientific support for P policy. A principal aim has been to consolidate scientific evidence and use it to raise awareness of the need to improve P sustainability.

From 2017-2021, over 100 scientists and industry experts from around the world have combined efforts to develop the OPF Report. The project has been delivered through a partnership between the UK Centre for Ecology & Hydrology (UKCEH) and the University of Edinburgh, UK, and with funding from the UK Natural Environment Research Council (NERC), the European Sustainable Phosphorus Platform (ESPP), the United Nations Environment Programme (UNEP) and the Global Environment Facility (GEF) through the GEF/UNEP 'Towards the International Nitrogen Management System' (INMS) project.

This report is not designed to produce binding recommendations, but instead to inform discussions and raise awareness through appropriate fora. International teams of authors were invited to produce stand-alone chapters to cover the central components of P sustainability (Chapters 2-8). These components, referred to from here on as the 'OPF Pillars', were proposed by the Project Management Group and developed further by the co-authors of the chapters (Figure 1.1). Chapter 9 synthesises the key challenges and solutions identified across all OPF Pillars, integrating these across related sustainable nutrient management initiatives, from which it proposes a road map for improving future integration, targeted at encouraging wider community discussion.

This report represents hundreds of hours of scientific discussion and peer review and is underpinned by >2000 peer-reviewed publications and reports spanning more than 300 years of scientific research. The report has undergone an extensive review process (Figure 1.2), supported by more than 40 referees from both academia and industry bodies.

THE OPF PILLARS	CHAPTERS IN THE OPF REPORT
PHOSPHORUS ACCESS	**CHAPTER 2.** PHOSPHATE ROCK, RESERVES AND USES
FOOD SECURITY	**CHAPTER 3.** TRANSFORMING THE FOOD SYSTEM – IMPLICATIONS FOR PHOSPHORUS
AGRICULTURE AND FOOD PRODUCTION	**CHAPTER 4.** OPPORTUNITIES FOR BETTER PHOSPHORUS USE IN AGRICULTURE
WATER QUALITY	**CHAPTER 5.** PHOSPHORUS AND WATER QUALITY
PHOSPHORUS RECYCLING	**CHAPTER 6.** OPPORTUNITIES TO RECYCLE PHOSPHORUS-RICH ORGANIC MATERIALS
PHOSPHORUS RECOVERY	**CHAPTER 7.** OPPORTUNITIES TO RECOVER PHOSPHORUS FROM RESIDUE STREAMS
CONSUMPTION	**CHAPTER 8.** CONSUMPTION – THE MISSING LINK TOWARDS PHOSPHORUS SECURITY

Figure 1.1 The Seven Pillars of the OPF Report, which underpin the central components of phosphorus sustainability and corresponding chapter titles.

THE REVIEW PROCESS OF CHAPTERS 2 - 8

- Authors and editors (i.e. Project Management Group) co-developed 2-page summaries outlining proposed chapter content.
- Authorship prepared 1st draft of full chapters.
- **1st draft reviewed by editors.**
- Authorship prepared 2nd draft of chapters.
- **2nd draft reviewed by the Scientific Advisory Committee.**
- Authorship prepared 3rd draft.
- **3rd drafts reviewed by Stakeholder Review Panel.**
- Authors addressed comments (over 80 pages of comments received) - this took over a year.
- The editors reviewed final chapters to ensure consistency and remove excess duplication with other chapters.
- The chapter text was sent for final approval and sign-off from all authors.
- Production team converted final text into chapter proofs, visual summaries and videos.
- Proofs, visual summaries and videos were shared for final sign-off from all authors.

Figure 1.2 The OPF review process. The review process involved three stages of review, with reviewers selected from academia, government and industry.

Focus Box 1.1 - Statements on the importance of sustainable phosphorus management in delivering global scale ambitions.

"A new global effort is needed to address 'The Nutrient Nexus', where reduced nutrient losses and improved nutrient use efficiency across all sectors simultaneously provide the foundation for a Greener Economy to produce more food and energy while reducing environmental pollution."

Sutton et al. (2013). Our Nutrient World.

"The accelerated use of nitrogen and phosphorus is at the centre of a complex web of development benefits and environmental problems. They are key to crop production and half of the world's food security is dependent on nitrogen and phosphorus fertiliser use. But excess nutrients from fertilizers, fossil fuel burning, and wastewater from humans, livestock, aquaculture and industry lead to air, water, soil and marine pollution, with loss of biodiversity and fish, destruction of ozone and additional global warming potential. The problems will intensify as the demand for food and bio-fuels increase, and growing urban populations produce more wastewater. This will be at a growing economic cost to countries in the undermining of ecosystems, notably in the coastal zone, and the services and jobs they provide."

Global Partnership on Nutrient Management (2011). The Nutrient Challenge.

"As the global population grows, the enormous problem of producing sufficient food in a sustainable manner will only intensify. Technological innovations and sustainable food production systems can decrease the sector's contribution to climate change, land-use change and ocean degradation; reduce environmentally damaging inputs and waste; improve production system resilience, through methods such as precision agriculture, integrated pest management and molecular breeding techniques; and are likely to have a positive economic impact, including the creation of jobs."

Dasgupta (2021) The Economics of Biodiversity: The Dasgupta Review.

"Action is needed: water quality needs to be politically prioritized, and it should be treated as an urgent concern for public health, the economy, and ecosystems. The findings from this report show that long-term costs have been underestimated and underappreciated. The threats that poor water quality presents are largely imperceptible, and as a result, policy inaction and procrastination are often convenient responses to an invisible problem. But this means that populations are subjected to hazards without their knowledge or their consent. With water scarcity expected to increase as populations grow and the climate changes, the world cannot afford to waste and contaminate its precious water resources."

Damania et al. (2019). Quality Unknown: The Invisible Water Crisis, World Bank.

"The fertilizer industry is aware of the role of fertilizers in nutrient losses to water (and more broadly to the environment) and is actively engaged in reducing such losses in partnership with farmers, their advisors and other relevant stakeholders. Nutrient losses can be minimized when best practices in farm and, more specifically, soil, water and nutrient management are applied."

International Fertiliser Association (2018). AGENDA 2030 Helping to Transform our World.

"The release of nutrients from agriculture and untreated wastewater poses the most widespread threat to environmental water quality globally. An in-depth analysis of submissions from countries that supplied parameter-level data showed that nitrogen and phosphorus failed to meet their

targets more often than the other water quality parameters of Level 1 reporting. This means that for these countries, and quite likely for most countries, reducing nutrient release and transport will have the greatest positive impact on water quality."

United Nations Environment Programme (2021a). Progress on ambient water quality. Tracking SDG 6 series: global indicator 6.3.2 updates and acceleration needs.

"Sustainable food systems work with nature, adapt to a warming world, minimize environmental impacts, eliminate hunger and improve human health. Sustainable food production is vital to protecting nature and human well-being. It can be achieved through a range of overlapping approaches, including conservation agriculture, organic farming, agroecology, integrated pest and nutrient management, soil and water conservation, conservation aquaculture, sustainable grazing, agroforestry, silvopastoral systems, irrigation management, small or patch systems and practices to improve animal welfare. Sustainable agriculture requires a reduction in nitrogen and phosphorus imbalances to reduce pollution of freshwater, groundwater and coastal zones."

United Nations Environment Programme (2021b). Making Peace with Nature: A scientific blueprint to tackle the climate, biodiversity and pollution emergencies.

"It is clear from this study that land-based activities generate multiple natural and non-natural stressors that impact the condition of coastal resources. Particularly impactful stressors were increasing concentrations of sediment (such as those from infrastructure development or poor land management), increasing concentrations of persistent toxins (including from mining runoff), increasing concentrations of plastic (for instance, from poor industrial production processes) and increasing concentrations of nitrogen and phosphorus (from, inter alia, poor agricultural practices). Agriculture, ports/harbours and aquaculture were the land-based activities with the greatest cumulative impacts on coastal resources, and should therefore be governance priorities."

IRP (2021). Governing Coastal Resources: Implications for a Sustainable Blue Economy.

"Phosphorus is essential for food production, but its global supply is limited. Better insight is needed into the availability of this non-renewable resource and the environmental consequences associated with its use. Optimizing agricultural practices while exploring innovative approaches to sustainable use can reduce environmental pressures and enhance the long-term supply of this important plant nutrient."

Syers et al. (2011) UNEP Year Book 2011: Emerging issues in our global environment, United Nations Environment Programme

"Noting with concern that excessive levels of nutrients, in particular reactive nitrogen and phosphorus, have significant impacts on species composition in terrestrial, freshwater and coastal ecosystems, with cascading effects on biodiversity, soil, water and air quality, ecosystem function and human well-being"

UNEA. 2022. UNEP/EA.5/L.12/Res.1. Draft resolution on sustainable nitrogen management.

1.2 A brief history of phosphorus

1.2.1 Discovery of phosphorus

Hennig Brand, in 1669, Hamburg, is widely credited in contemporary popular texts with the discovery of the first known element, phosphorus. The discovery, often romanticised, is depicted by an alchemist at his craft in search of the philosopher's stone (e.g. Focus Box 1.2). However, references to the discovery in modern literature suggest some contention in the details of the discovery, as addressed by Partington (1936). Kragh (2003) presents the case for Brand based on the conditions of credible discovery, where a substance is confirmed as being elemental and where details of the element are presented publicly for scrutiny. Indeed, it appears that Brand did neither, but instead disclosed the details of his experiments to contemporaries, Johann Kunckel and Daniel Kraft. Homberg (1692) described Brand as an uneducated person in search of the philosophers' stone, who, in his desire for secrecy, did not fully disclose his experiments to contemporaries such as Kunckel. Homberg (1692) claimed that Kunckel rediscovered phosphorus in his own laboratories following Brand's death. Leibniz (1710) having worked directly with Brand to replicate the process under the patronage of John Frederick, Duke of Brunswick-Calenberg, concluded that Homberg's account "departs from matter of fact". Leibniz goes on to give his account, based on having worked extensively with Brand:

"The invention of the phosphorus happen'd thus; Brand had fallen on a certain chemical process, extant in a printed book, which taught how to prepare from urine a liquor fit to ripen a particle off silver into gold; And in labouring on this he found out his phosphorus. He had some acquaintance with Daniel Kraft, then of the council of commerce to the [George III] Elector of Saxony; and by his means with Kunkel, one of the said Prince's bed-chamber; but who under that character perform'd chemical processes. On persuading Brand that this arcanum might be sold to the Great at a high price; and offering him their assistance, they obtain'd the composition from him. And upon going from Dresden to Hamburg, they both saw and learn'd from him the process of the phosphorus. But Kunkel, upon his return home, had committed some mistake in the process, and for a long time could not hit upon the phosphorus; and he sent a letter of complain to Brand, which I have seen, and in which he bewails that the secret was not communicated to him sincerely enough; but Brand repenting that he had been so easy in the communication, delay'd the setting him to rights. Kunkel, in the mean time, after various trials, corrected the error of himself; whence he pretended to be the inventor; of this Brand bitterly complain'd."

The first scientific account on P (called Noctiluca; 'night light') appears to have been published by Kirchmaier (1676), a colleague of Kunckel who published further detailed reports in his *Collegium physico-chemicum experimentale* (Kunckel, 1716). Robert Boyle, having been introduced to the product of Brand's experiments by Kraft in 1677, is credited with publishing the first account on the preparation of P in 1680 (Boyle, 1680). Boyle's contributions are reviewed in detail by Partington (1936); in which Brand's discovery is noted as

1675. The extent to which these works were influenced by Brand's methodology remains uncertain. The method was later reviewed in detail by Hellot (1737). The early history of P appears to be obscured by both academic and economic competition, with private correspondences and public presentations repeating claims and counter-claims. Beyond the initial scientific curiosity of phosphorescence, which in the case of elemental P was more long-lasting than other phosphorescent substances, potentially economic applications included uses in artificial lighting, matches and medicinal cures.

1.2.2 Scientific and economic development of phosphorus use

From the late 18th to early 20th centuries, P remained the focus of academic and economic attention, a period during which 13 scientists are credited with Nobel prizes for their work relating to P (Farber, 1965). Important discoveries relevant here include the isolation of phosphoric acid from bones by Gahn in 1769, the procedure for which is attributed to Scheele (described by Nordenskiold, 1892). The confirmation of P as an element appears to have resulted from the work of French chemist Lavoisier (1777), contributing to the development of modern day elemental nomenclature (Guyton de Morveau et al., 1787), and to Lavosier's seminal work *Traité élémentaire de chimie* (Lavoisier, 1789). This work initiated almost a century of elemental discovery and uncovered the importance of reactive hydrogen in determining the polybasicity of acids, pioneered by the study of phosphoric acid (Graham, 1833). Finally, utilising the above, von Liebig proposed acid digestion as a means for enhancing solubilisation of bones (with sulfuric or nitric acid, although not the first to do so; Farber, 1965) for improved P fertilisation of soils for plant growth (Liebig, 1843). This ultimately led to a patent being filed by John Bennet Lawes at Rothamsted for the production of 'superphosphate'. von Liebig's recommendation also accelerated the use of guano as a fertiliser around this time, opening up new markets in its extraction and supply and leading to the birth of modern agri-chemistry.

However, it was not until 1888 when James Burgess Readman developed the electric arc furnace for producing the element from phosphate rock, that mineral P fertilisers began to be produced at an industrial scale (Readman, 1889). These latter developments were central to the agricultural intensification of the 20th and 21st centuries. Phosphate rock demand increased in the USA, alone, from 0.2 Mt to 19 Mt between 1880 and 1962 (Farber, 1965), primarily for the production of fertilisers. The 'phosphorus rush' of the 20th century had begun.

1.2.3 An emerging understanding of the importance of phosphorus in freshwater ecology

The Swiss scientist François Alphonse Forel proposed the term 'Limnology' to describe the study of oceanography in lakes. Forel pioneered the field through exploration and description of the physical, chemical, and ecological condition of Swiss lakes, principally Lake Geneva (Forel, 1892). The development of the field progressed through various strands, which fostered collaborative works as reviewed by Egerton (2014). For example, Forel, and colleagues, contributed to an important collection of text on the Flora and Fauna of Fresh Water, edited by the German limnologist Zacharias (Zacharias, 1891). Around the same time, an extensive survey of 562 Scottish lochs was led by Sir John Murray and Laurence Pullar, involving the services of 50 scientists and surveyors, describing bathymetry alongside chemical, biological and geological observations (Murray and Pullar, 1910). This included one of the first global assessments in Murray's 'the characteristics of lakes in general, and their distribution over the surface of the globe' (Murray, 1910). Coincidentally, Murray, through his role in organising the collections of the Challenger expedition, and realising the economic potential of phosphate-rich guano deposits on Christmas Island, worked to influence British annexation of the island and co-founded the Christmas Island Phosphate Company. Between 1899 and 1913, some 1.4 Mt of phosphate rock were mined from Christmas Island, representing about 2% of global production at that time (Bustyn, 1975). Some of the proceeds of this venture were used to support further scientific exploration in both oceanography and limnology (Bustyn, 1975).

These building blocks of limnology were to further the understanding of ecological theory in fresh waters. The German limnologist August Friedrich Thienemann recognised that species of benthic chironomid larvae varied with oxygen concentrations in lake bottom waters, and, in turn, with phytoplankton development in surface waters; concluding that the communities were linked (Thienemann, 1921). The Swedish limnologist Einar Naumann described the natural succession of lake plankton communities using the terms 'oligotrophic' and 'eutrophic', representing the continuum of communities from nutrient-poor to rich waters, respectively (Naumann, 1921). Together, Thienemann and Naumann worked to further develop these concepts and fostered collaborative efforts in the field, establishing the Internationale Vereinigung für Limnologie, now the International Society of Limnology, which celebrated its centenary in 2022. This period saw the establishment of major research stations, including, for example, the UK Freshwater Biological Association at Windermere (1929) and the Plöner See Research Station (1891), now the Max Planck Institute for Evolutionary Biology (Germany), and others. An understanding of biogeochemistry in lakes and of interactions across food-webs was subsequently developed by Hutchinson, demonstrating, for example, rapid uptake of radio-isotope labelled P by phytoplankton and confirming that the supply of this nutrient is critical in determining ecological processes at the ecosystem scale (Hutchinson and Bowen, 1947; Hutchinson, 1957). Just as in agriculture, P was key to the growth of plants in freshwater ecosystems.

Shortly following World War II, attention was drawn to the effects of urban development on increasing P discharges to fresh waters from wastewater (Hasler, 1947). This resulted in a surge in scientific meetings and reports on cultural eutrophication, including notable case studies of water quality deterioration and increasing algal blooms in lakes of northern America (e.g., Lake Washington; Edmondson, 1961) and Europe (e.g., Lake Norrviken; Rodhe, 1948; Ahlgren, 1967). These events attracted international attention. For example, the historical development and global extent of cultural eutrophication and its causes were discussed in a special meeting of the Limnological Society of America on "Fertilization of Aquatic Areas," Boston, 1946, and have been reviewed in several contemporary texts (e.g., Wetzel, 2001; O'Sullivan and Reynolds, 2005).

The discoveries that followed set the paradigm for the present-day scientific response to cultural eutrophication (Chapter 5). For example, Vollenweider, (1968) examined nutrient loading to lakes from agriculture and other terrestrial sources. In doing so, he proposed modelling approaches with which to define P load reduction targets in line with water quality and ecological responses. Schindler (1974) and colleagues at the Canadian Experimental Lakes Area conducted whole-lake experiments to disentangle the processes operating during eutrophication, confirming P reduction to be a primary aim of eutrophication management. Between 1964 and 1974 the International Biological Programme of the International Council of Scientific Unions (ICSU), through its subcommittee on the Productivity of Freshwater Communities, coordinated a long term global monitoring programme to establish the 'productivity of biological resources, human adaptability to environmental change, and environmental change itself' (Burgis and Dunn, 2012).

Some of these programmes continue to date, providing essential insights into lake ecosystem responses to nutrients and other pressures. Lakes act as sentinel ecosystems with which to detect the ecological effects of long-term environmental change, including cultural eutrophication and ecological recovery following the reduction of nutrient emissions (e.g. Jeppesen et al., 2005; McCrackin et al., 2017). In some countries, large scale and coordinated monitoring programmes have been initiated in recent decades to provide large scale assessments of the impacts of nutrient emissions in both freshwater and coastal ecosystems (Chapter 5). The evidence produced from such programmes continues to underpin the development of lake basin and national scale environmental policies and directives (e.g., the Federal Water Pollution Control Act, USA, 1942; latterly the Clean Water Act, 1972). These have focussed primarily on the treatment or diversion of wastewater discharges and agricultural emissions (Chapter 5). As the United Nations Environment Programme works to support countries in developing monitoring and assessment programmes, designed to protect freshwater and coastal ecosystems, it is clear that much remains to be achieved in the coming decade on nutrient emissions and impacts to inform policy responses (Focus Box 1.1; UNEP, 2021a). Indeed, the Alliance for Freshwater Life (Darwall et al., 2018), in its recent call for a more coordinated response to the decline of freshwater biodiversity, argues that existing policies relevant to safeguarding freshwater ecosystems are failing due to a lack of conviction and enforcement in implementation. The implementation of the UN Sustainable Development Goals and the Decade on Ecosystem Restoration are primed to address this call from the scientific community, providing an opportunity to forge a new direction for sustainable nutrient use with a focus on ecosystem recovery and protection.

In recent years, resolutions of the United Nations Environment Assembly have brought sustainable nutrient management (UNEP/EA5/L12/REV.1), water quality assessment and improvement (UNEP/EA.3/Res.10), and sustainable lake management (UNEP/EA5/L8/REV.1) into focus.
For example, UNEP/EA.3/Res.10 on "Addressing water pollution to protect and restore water-related ecosystems" requested UNEP to develop a global water quality assessment in collaboration with UN-Water and relevant stakeholders by UNEA-5.
In response, and in addition to the World Water Quality Assessment process, UNEP coordinated the formation of the World Water Quality Alliance (WWQA), an open community of practice, representing a voluntary and flexible multi-stakeholder network with a shared goal; to improve freshwater quality to achieve prosperity and sustainability. The WWQA includes a strong focus on assessing global nutrient impacts on freshwater ecosystems and has mobilised a working group dedicated to accelerating ecosystem restoration globally, the WWQA Ecosystems Work-stream. This group and others are working together to ensure that nutrient management and water quality improvement are at the heart of sustainable development plans.

Figure 1.4 Painting Title: The Alchymist, in Search of the Philosopher's Stone, discovers Phosphorus, and prays for the successful conclusion of his operation, as was the custom of the ancient chymical astrologers (1771, by Joseph Wright), displayed in Derby Museum and Art Gallery, Derby, UK. Source: https://commons.wikimedia.org/wiki/File:Hennig_Brand.jpg#/media/File:JosephWright-Alchemist.jpg

Focus Box 1.1 - What is phosphorus and how was it discovered?

Authors: Jim Elser and Phil Haygarth, *passages excerpted from "Phosphorus Past and Future" By Jim Elser and Phil Haygarth (2021).*

What is phosphorus and how did we first learn about it?

"Did you know that there's ~0.62 kg (1.35 pounds) of phosphorus in your (average) body, right now, and that during your (average) lifetime you'll consume ~34 kg (75 pounds)? With too much phosphorus (or in the wrong form), you die. Without it, you die. With too much, humanity suffers. Without it, humanity falters. Phosphorus is vitally important and yet its role is often hidden and unappreciated."

But, what is phosphorus, actually?

"Remember that an atom is made up of protons (positively charged) and neutrons (no charge, hence their neutrality) in the nucleus and, buzzing around them, negatively charged electrons. … In the case of our hero phosphorus, there are 15 protons (and 15 neutrons), balanced by 15 electrons (Figure 1.3); phosphorus thus has an "atomic number" of 15. Figure 1 shows Bohr-like orbits, occupied by different numbers of electrons: two in the first, eight in the second, and five in the third, adding up to 15."

Our first knowledge of phosphorus came from urine….

"Lots of urine. The urine collected from dozens of beer-drinking German soldiers and from horses (presumably they abstained from beer). More than 5000 litres of it was brought, in big pails and all manner of containers, to the Hamburg workshop of a German named Hennig Brand (or Nicholas Brandt, depending on where you look). Today we call him an alchemist. In his day, the mid-17th century, he was a merchant and a high-tech entrepreneur, seeking health and wealth via the pursuit of the Philosopher's Stone. Back in those days, the Philosopher's Stone was a mythical material, knowledge of which was passed (inefficiently, it seems) from generation to generation and which was capable of transmuting lead into gold and even of extending human life (hence, it was thought, the impressive life spans reported for various Biblical figures). In the famous painting (Figure 1.4), we see Herr Brand, genuflecting before the glowing flask, his young helpers behind him looking a bit quizzical. The first chemical element had been purified. The date is 1669."

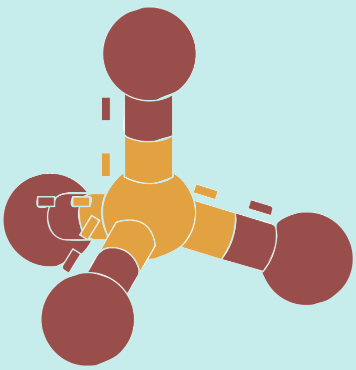

Figure 1.3 The structure of a phosphorus (P) atom (left). A 3D illusration (right) of a P atom bonded with four oxygen atoms to form phosphate (small dashed lines represent bonded pairs); this represents the most common chemical form of P in nature. Modified from Elser and Haygarth (2021).

1.3 Defining the global phosphorus sustainability challenge

1.3.1 Present concerns and future outlook

By the mid- to late-20th century, the sustainability of the global anthropogenic P cycle for the long-term provision of food and fresh water was brought sharply into focus. Stumm (1973) in his early assessment of the anthropogenic P cycle, concluded:

"By mining phosphorus in progressively increasing quantities, man disturbs the ecological balance and creates undesirable conditions in inland waters, estuaries and coastal marine waters… Our present agricultural practice of excessively fertilizing land needs to be re-examined; our present agricultural technology must not without modification be exported to tropical areas."

The suggestion here is that, if unchecked, unsustainable P use would create environmental conditions that are unacceptable for humanity. Rockström et al. (2009a; b) termed this concept, 'the Planetary Boundaries', and as Stumm correctly surmised, humanity was fast approaching the P boundary in the mid- to late-20th century.

Despite Stumm's warning, the global anthropogenic P cycle continued on its trajectory of increasing flows through the early 1970s (Chapters 2 and 3). The net result is that global P input to fresh waters had doubled by the end of the 20th century (Beusen et al., 2016). Carpenter and Bennett (2011) concluded that the planetary boundary for P had already been exceeded for freshwater eutrophication, but not yet for the extraction of phosphate rock. However, Carpenter and Bennett (2011) also raise the issue of balancing heterogeneity in P demand for food and emissions to fresh waters as a major future challenge.

The global outlook for anthropogenic P emissions to fresh waters is especially worrying. Phosphorus demand in the agricultural sector is predicted to double, again, by 2050 (from 2006 levels), further increasing risk of emissions to fresh waters (Mogollón et al., 2021). Phosphorus losses from food production for domestic consumption will impact directly on catchments that have been 'set-aside' for agriculture. Losses of P from wastewater to fresh waters could increase globally by up to 70%, by 2050 (van Puijenbroek et al., 2019). Yet, as is widely acknowledged (see Chapters 2-9), sustainable P management remains largely ignored in the food and environmental policy agendas of many countries, despite the social and economic burden it carries.

1.3.2 Geographic variation in phosphorus consumption

Arguably, progress on more sustainable P use has been hampered in recent decades by a fixation on whether or not depletion of the world's mineral P reserves (and resources) represents a risk to food security – the so-called Peak Phosphorus debate (Cordell et al., 2009; Van Vuuren et al., 2010; Syers et al., 2011; Scholz and Wellmer, 2013). Recent estimates indicate that phosphate rock reserve supply does not represent a near term risk for global food security, with a projected lifetime of P reserves of around 320 years (Jasinski, 2021).

However, national exposures to such risk are variable, especially where countries are reliant on either fertiliser exports as their economic foundation or fertiliser imports to maintain food security (Chapter 2). The fertiliser market is tight and subject to geopolitical and market tensions. The challenges of price spikes and export controls, such as experienced in 2008 (Chapter 3) and in 2021 are expected to continue.

Assuming business as usual for sustainable P management, Sutton et al., present two simple scenarios to frame the consequences of either P replete or limited supply chains, both of which entail significant societal challenges that must be addressed (see page 4 in Sutton et al., 2013).

- **Phosphorus limited scenario.** Insufficient P supplies lead to higher fertiliser prices, food prices and higher food system vulnerability, all of which will be exacerbated by increased human population and growing per capita demand for animal products. There is little economic capacity to address pollution in freshwater and coastal ecosystems.
- **Phosphorus replete scenario.** The continued supply of relatively cheap P fertilisers provides weak motivation to avoid losses to the environment, with the result that freshwater and coastal pollution problems are exacerbated through meeting increased demand for food to meet the growing population.

The geographic concentration of phosphate rock reserves risks impacting food security for countries and regions dependent on imported phosphate rock and/or fertilisers (e.g. Sub-Saharan Africa, India, the EU, Australia and Brazil) (Jasinski, 2021). Unsurprisingly, wealth is an important determinant of whether a nation's farmers have access to P fertilisers (Obersteiner et al., 2013). When describing P fertiliser consumption patterns, most countries can be classified in, or are transitioning between, one of three broad categories, each with different P sustainability issues:

- **Countries that consume too little phosphorus.** Typically less economically developed countries, e.g. some nations in Sub-Saharan Africa and parts of Asia. In these countries insufficient access to P fertiliser can constrain agricultural production, impacting food security. Often these countries have a growing population, increasing urbanisation and poor sanitation. This can create ‘hotspots’ of P loss from human wastes in and around cities, contributing to eutrophication.
- **Countries that are significantly increasing phosphorus consumption.** Typically large countries with emerging economies, e.g. Brazil, India, and China. In these countries increasing mineral P fertiliser use is contributing to rapid increases in agricultural output. However, low P use efficiency, and in some cases, insufficient sanitation, often cause substantial P losses resulting in increasing and/or significant eutrophication issues.

- **Countries levelling off or reducing phosphorus consumption.** Typically more economically developed countries, e.g. most nations in the EU, and the USA. In these countries, long-term high consumption of P fertiliser has fuelled agricultural sectors. However, typically high and/or improving P use efficiency combined with improved access to legacy P stores in soils is allowing a levelling off or reduction in P fertiliser use. Good sanitation mitigates some P losses from human wastes in comparison to less economically developed countries. However, historic poor P management has left widespread chronic eutrophication issues, representing a financial, environmental and human health burden.

1.4 Towards a sustainable phosphorus future

As the global anthropogenic nitrogen and carbon cycles are being transformed towards more sustainable futures, the 'business as usual' outlook for P remains locked-in to the outdated assumption that 'to sustain food production and economic growth, we must bear the cost of environmental degradation, today'. Yet, as laid out in detail in subsequent chapters, even though the evidence exists to support a more sustainable future for P, it remains out of focus in the global policy arena.

Under the business as usual scenario, as the global population continues to rise, so demand for food will increase (Chapter 3). As economic development progresses, so the consumption of high P foods will increase (Chapter 8). Both of these drivers will tend to increase P losses from the food system (Chapter 5). As well as representing an economic loss to farmers (Chapters 4 and 9). Phosphorus losses from the food system will further degrade the ecosystems into which it flows, contributing to biodiversity loss and reducing ecosystem capacity to deliver services essential for sustaining life on earth (Chapter 5). Unless action is taken global P demand will remain buried within national economic development plans and undetected across the global sustainability policy arena (Chapters 2 to 9).

A more sustainable P future is essential for global food and water security. It promises economic benefits through improved natural capital (Dasgupta, 2021). The investment needed to deliver on emissions reductions, for example, using nature-based solutions, can deliver co-benefits for other pollutants. As identified by the UNEP International Resource Panel coordinated measures to reduce land based pollution will benefit coastal and transboundary ecosystems (IRP, 2021). The opportunity for improved circularity in the global P cycle is clear; currently less than about 50% of P residues are recycled back to the global food system (Figure 1.5). This represents an untapped resource in countries whose food security is exposed to the risks of high reliance on imported P fertilisers.

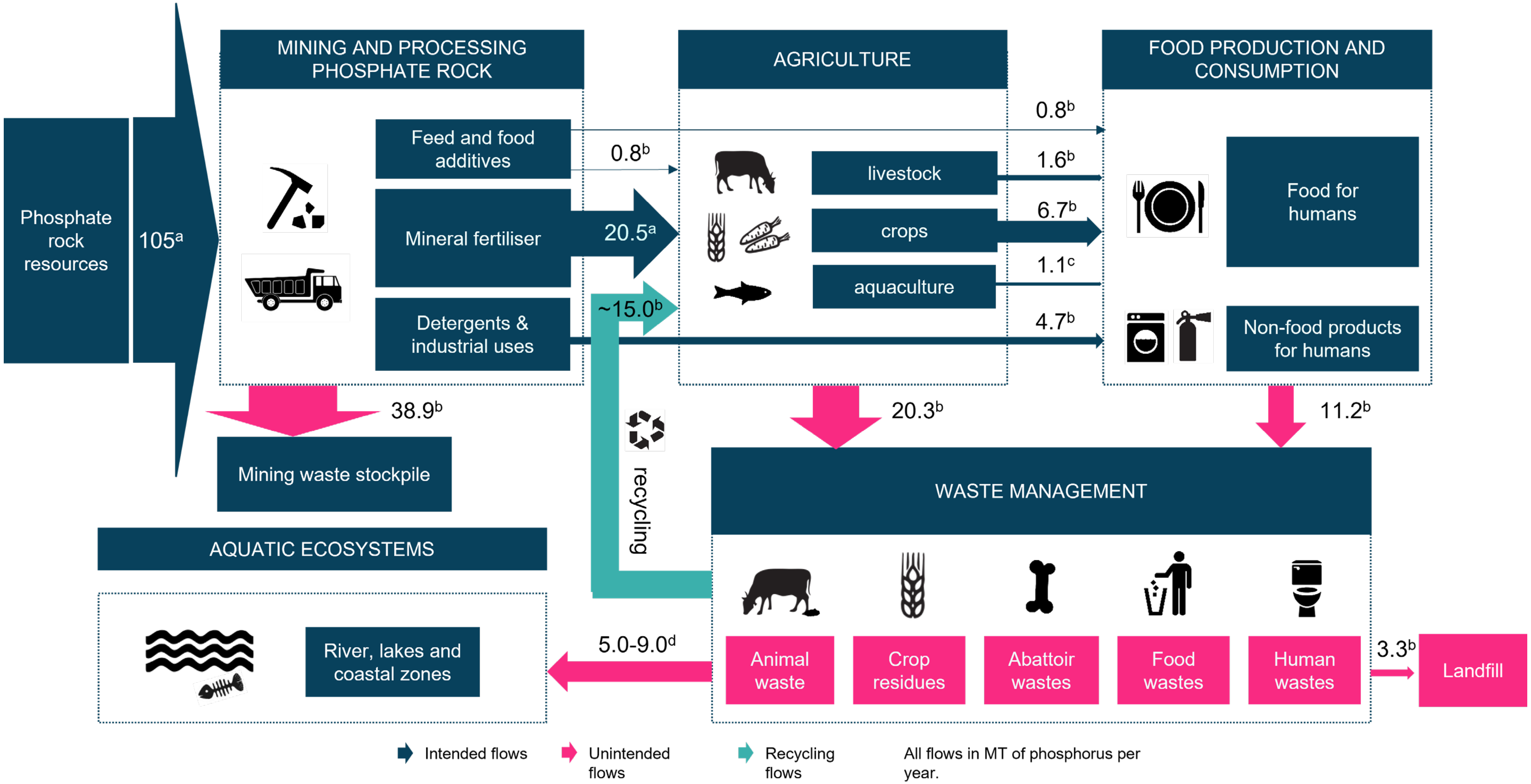

Figure 1.5 Phosphorus (Mt of P year^{-1}) flows between the key parts of the global P cycle modified from Brownlie et al. (2021). The width of arrows represents the magnitude of flows based on the current literature ([a]Jasinski, 2021; [b]Chen and Graedel, 2016; [c]Huang et al., 2020 [d]Beusen et al., 2016).

It is being increasingly acknowledged the world cannot afford to continue on its current path for phosphorus (Focus Box 1.1). In 2019 over 500 scientists signed 'The Helsinki Declaration' calling for transformation across food, agriculture, waste and other sectors to deliver much needed improvements to global phosphorus sustainability (see www.opfglobal.com to read the declaration).

This report considers the evidence required to underpin a more sustainable P future. It reflects on the need for improvements across the entire P value chain, from mine to fork, and from field to freshwater and coastal ecosystems. It considers the roles and opportunities for stakeholders in delivering such gains and the need to deliver a long-term process to track progress. Finally, an analysis of the existing policy arena is provided alongside a proposal for improved international coordination for P sustainability, identifying country-level opportunities to align P with actions on other nutrients. In doing so, a clear message emerges – that the green shoots of change are upon us. Innovation and the application of trans-disciplinary thinking are already leading to pockets of more sustainable P use, as is evident in the many pioneering case studies presented across all of the OPF Pillars.

The challenge now lies in connecting opportunities into a coherent package of measures designed to address the ultimate societal goal: to deliver global food security for a growing population, whilst reversing and preventing the destruction of the natural environment. If society is to meet this goal, then sustainable P use must be at the heart of the solution.

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