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*Food security and healthy freshwater ecosystems are placed at jeopardy by poor phosphorus management. Scientists are calling for transformation across food, agriculture, waste and other sectors - mobilized through intergovernmental action, which has been missing thus far***.**

Will J. Brownlie, Mark A. Sutton, David S. Reay, Kate V. Heal, Ludwig Hermann, Christian Kabbe and Bryan M. Spears

Unsustainable phosphorus use is pushing food security further from reach[1,2], leaving a legacy of polluted freshwaters, many now beyond ecological restoration[3]. Ten years have passed since the global anthropogenic flow of phosphorus was identified to be exceeding its planetary boundary[4]. In 2013, the opportunity was highlighted for a 20% improvement in nutrient use efficiency by 2020 across the full chain of food and waste systems[5]. The working group of the Post-2020 Global Biodiversity Framework proposed to reduce pollution from excess nutrients by 50% by 2030[6]. Yet, phosphorus management remains largely ignored in the food and environmental policy agendas of most countries, and international conventions[7]. Progress remains hindered by a lack of policy and public awareness, fragmentation of actions and policies, and the absence of intergovernmental coordination.

The phosphorus emergency

In the last 70 years, mineral phosphorus fertilisers have increasingly been used to enhance crop yields, providing food for billions of people and livestock[2]. Yet, 1 in 7 farmers cannot afford sufficient fertilisers to maintain fertile soils, impacting their ability to produce food[8]. Without change, insufficient phosphorus fertiliser use in Africa will likely lead to crop yield reductions of nearly 30% by 2050[9]. In other regions such as Europe, North America and South-East Asia, excess phosphorus use through fertiliser application is threatening water quality. Globally, phosphorus losses from land to fresh waters have doubled in the last century and continue to increase[10], contributing to algal blooms, decimating biodiversity, and threatening human and environmental health[11]. An estimated 5.0-9.0 million tonnes of phosphorus is lost to fresh waters each year globally, with societal costs in billions of dollars (estimated at USD 2 billion annually for the USA, alone[12]). Freshwater aquaculture is increasingly used to meet the demands of the 3 billion people that rely on fish to provide ~20% of their intake of animal protein[13]. However, a paradox arises as phosphorus additions to increase aquaculture yield represents a growing and direct pollution threat to the integrity of this food system, and the freshwater and coastal ecosystems upon which it relies[14].

Phosphate rock contains contaminants, including cadmium, which can be transferred into fertiliser products, accumulate in soils, and end up in food[15]. Five countries hold 85% of known phosphate rock reserves; with 75% found within Morocco and Western Sahara, alone[15]. Therefore, food systems in most countries rely on importing phosphorus fertilisers, making them vulnerable to phosphorus supply risks[2]. The depletion of phosphate rock reserves is not an immediate threat. At current mining rates total reserves (which are defined as phosphate rock that can be economically produced using existing technology) would be sufficient for 259 years[16]. However, economics, geopolitics, national and regional policies, taxes, tariffs and legislation can all influence immediate access to available phosphorus reserves, domestically[17,18]. Such vulnerability was observed in 2008; the price of phosphate rock spiked by 800%, causing an increase in fertiliser prices that affected the livelihoods of many of the world's poorest farmers[2,18].

Phosphorus losses from land to fresh waters may rise further with increasing precipitation and so associated negative impacts to marine and freshwater ecosystems - including harmful algal blooms and coastal 'dead zones' – may be exacerbated as a result of climate change[19]. At the same time, phosphorus pollution has been found to alter the global carbon cycle; more productive freshwater ecosystems will emit more methane to the atmosphere and store more organic carbon in lakebed sediments. A recent study projected that increases in phosphorus losses to lakes and reservoirs will increase their methane emissions globally by up to 30% of current CO_2 emissions from fossil fuels over the next century[20].

Call for international action

By the end of 2020, over 500 scientists signed the "Call for International Action on Phosphorus" (www.opfglobal.com), a petition that calls for government support in addressing the phosphorus emergency by coordinating action across five primary sectors (Figure 1).

Agricultural sector. Reducing phosphorus losses from agricultural systems is critical to improving global phosphorus sustainability. Less than 30% of the ~35 million tonnes of phosphorus applied to soils annually makes it into the food we eat[5,21]. Legacy phosphorus, which accumulates in agricultural soils and aquatic sediments, represents both an untapped resource and a pollution burden for the future[22]. Extensive soil phosphorus testing is critical, with appropriate controls to avoid the application of phosphorus fertilisers in excess of crop needs. Innovations to utilise 'legacy' phosphorus already stored in some agricultural soils include the use of phosphate-solubilizing microbes, while phosphorus-efficient cultivars may also help[23]. Solutions do not lie only in the soil. In some regions, nutritional strategies in livestock production can reduce phosphorus losses in manures. These include optimising phosphorus consumption to match the animal's growth stage and supplementing monogastric animals with phytase enzymes to improve phosphorus uptake from feed grains[24].

Some issues can be highly region-specific. For many low and middle-income countries, the priority is still to provide affordable access to phosphorus fertilisers to avoid unsustainable depletion of soil phosphorus stocks. This may require access to credit, subsidies and better infrastructure, such as those for transport and storage of fertilisers[2]. Recycling available phosphorus-rich materials, such as manure and food waste should also be optimised. Public education programs, agricultural extension services and better infrastructure will be needed[2,24].

Though the FAO addresses phosphorus, for example through its 'International Code of Conduct for the sustainable use and management of fertilizers', there currently appears to be no mechanism to ensure codes are adopted across the world. The EU regulation on Fertilising Products (2019/1009), set limits for cadmium and other harmful contaminants in fertilisers; 'CE marked' fertilisers must contain below 60 mg cadmium kg^{-1} from 2022[25]. But implementing safe limits for cadmium and contaminants in phosphorus fertilisers and feed supplements is needed globally, especially when considering the global trade in agricultural produce.

Food consumption and production. Consumers can play a role in reducing anthropogenic phosphorus demand by avoiding excess consumption of foods with high phosphorus footprints and by reducing food waste[5,26], supported by food labels and public education. Over the last 60 years, the global average amount of mineral phosphorus fertiliser required to produce food for one person annually has risen by 38%, driven predominantly by the consumption and production of animal products[26]. Greater public awareness of the environmental impact of consuming products with high phosphorus footprints is needed[27] to support more sustainable food choice. However, this is especially complicated for imported products, with multiple ingredients from multiple countries, which may leave behind eutrophication impacts in their countries of origin[28].

There is a pressing need for governments to support more phosphorus-sustainable food systems by setting targets for organic waste recycling, reducing subsidies for meat production, and taxing the landfilling and/or incineration of food waste. In industrialized food systems, power has become increasingly concentrated into a small number of retailers and food processors[29]. For example, in the EU28 countries, some 22 million farmers produce food for more than 500 million consumers, whilst food distribution and retail markets are dominated by five large companies[30]. Policies that engage with these powerful food system actors can resonate internationally, with cascading effects on consumers and farmers worldwide [31,32].

Waste management. While there are many available methods to recover phosphorus from sewage and other organic materials[33], there is a need to invest in driving market forces to increase the use of recovered phosphorus in fertilisers. To significantly increase phosphorus recycling, economic, legislative and communication instruments are needed to help the mineral fertiliser industry to increase the use of recovered phosphorus as a raw material. In addition to developing the financial incentives, regulatory frameworks can help to enable the use of recycled phosphorus fertilisers in existing fertiliser markets, examples of which are being pioneered in Switzerland and Germany[34]. The transition to a circular phosphorus economy, in which waste products cease to be wasted products, is overdue.

Mineral resource management. For many countries, the greatest phosphorus management opportunity would be to shift reliance from mined to recycled phosphorus. For some phosphorus importing countries, however, achieving phosphorus independence by strengthening the phosphorus circular economy may not be possible, and may require significant change to national agricultural systems[35]. Ensuring rock phosphate and mineral phosphorus fertilisers are traded equitably is therefore critical, and requires international cooperation, with examples of mediation provided by the World Trade Organization

(WTO)[36]. Governments must recognise phosphorus supply risks, emphasising the need to require accurate data on reserves, resources, and supply and demand[37]. International schemes for the classification and reporting of raw material resources may help unify phosphorus data to improve accuracy. Regional bodies of the UN have a role to play, such as the Aarhus Convention on access to environmental information, which could support better public access to data on global phosphorus reserves and fertiliser production.

Action in aquatic resources management. Phosphorus losses throughout the landscape, from source to sea, need to be mitigated, ensuring that the benefits resonate to the large scale, especially where transboundary waters and large marine ecosystems are involved. The building blocks for such an integrated approach are in place. UNEP's Framework for Freshwater Ecosystem Management, for example, provides guidance to countries to sustainably manage freshwater ecosystems, including setting phosphorus targets for healthy freshwater ecosystems[38]. Multiple existing international bodies, including the UN Conventions on Transboundary Waters, Law of the Sea and Biological Diversity, can strengthen regional action on phosphorus pollution (Figure 1).

Nonetheless, for some waterbodies where historical phosphorus pollution has been severe a reduction in contemporary phosphorus inputs, alone, maybe insufficient to deliver ecological and socio-economic recovery. Novel measures are being developed to address this problem. For example, geoengineering measures, although contentious, have been proposed to address the symptoms of nutrient pollution in the Baltic Sea[39]. This includes aeration of anaerobic waters by installing 100 pumping stations to transport oxygen-rich surface waters to a depth of 125m for several decades, with an estimated cost of €200 million[39]. Restoration can also be costly and socio-economic analysis is needed to demonstrate the return on investments, for example, the revenue from eco-tourism associated with clean waterbodies[40]. Even where restoration makes financial sense, our capacity to deliver rapid improvements may be limited. Disaster response plans should be developed for cases where phosphorus pollution triggers toxic algal blooms, such as to help communities prepare for emergency supplies of clean water when local supplies become undrinkable[41].

Policy and public awareness

At present, sustainable phosphorus management strategies are missing in many regions. There is little intergovernmental action on the challenges of transboundary phosphorus pollution or transport of contaminants from phosphate rock within mineral phosphorus fertilisers. Similarly, there are few policies relating to sustainable phosphorus management at national scales, and none at the global scale[2,7]. The current fragmentation of actions and policies across intergovernmental frameworks risks that collective knowledge for phosphorus sustainability remains dormant in silos with little communication between them. To ensure that socio-economic and environmental gains are delivered globally these bodies must work systematically (Figure 1).

The “Call for International Action on Phosphorus” seeks the establishment or extension of an intergovernmental coordination mechanism, such as that already being developed for nitrogen[42]. This should support governments, existing conventions, and intergovernmental frameworks, as well as stakeholders, to catalyse integrated action on phosphorus sustainability. An international framework must be applied to consolidate the collective knowledge on national to global phosphorus cycles, establish internationally agreed targets for time-bound improvements in phosphorus management, and quantify the economic and societal benefits of improving phosphorus sustainability. A future UNEA resolution on phosphorus represents a key opportunity to mobilize intergovernmental action to deliver these goals, it also represents a strong will to support change.

Figure 1. The global phosphorus system. Global phosphorus flows[21] and fragmentation of existing international frameworks are shown. There is currently no intergovernmental coordination mechanism on phosphorus, which is needed to link phosphorus science-policy support between existing intergovernmental frameworks and other initiatives. Key bodies with relevant interests include the UN Environment Programme (UNEP) and Food and Agriculture Organization (FAO), UN-Water, the UN Regional Economic Commissions, the UN Framework Classification for Resources (UNFC), the World Trade Organization (WTO), the UN Convention on Biological Diversity (CBD), the UN the Global Programme of Action for the Protection of the Marine Environment from Land-based Activities (UN-GPA) and the UN Climate Change Convention (UN Climate Change). Arrow widths are proportional to the magnitude of phosphorus flows in 2013; units shown are in megatonnes of phosphorus per year.

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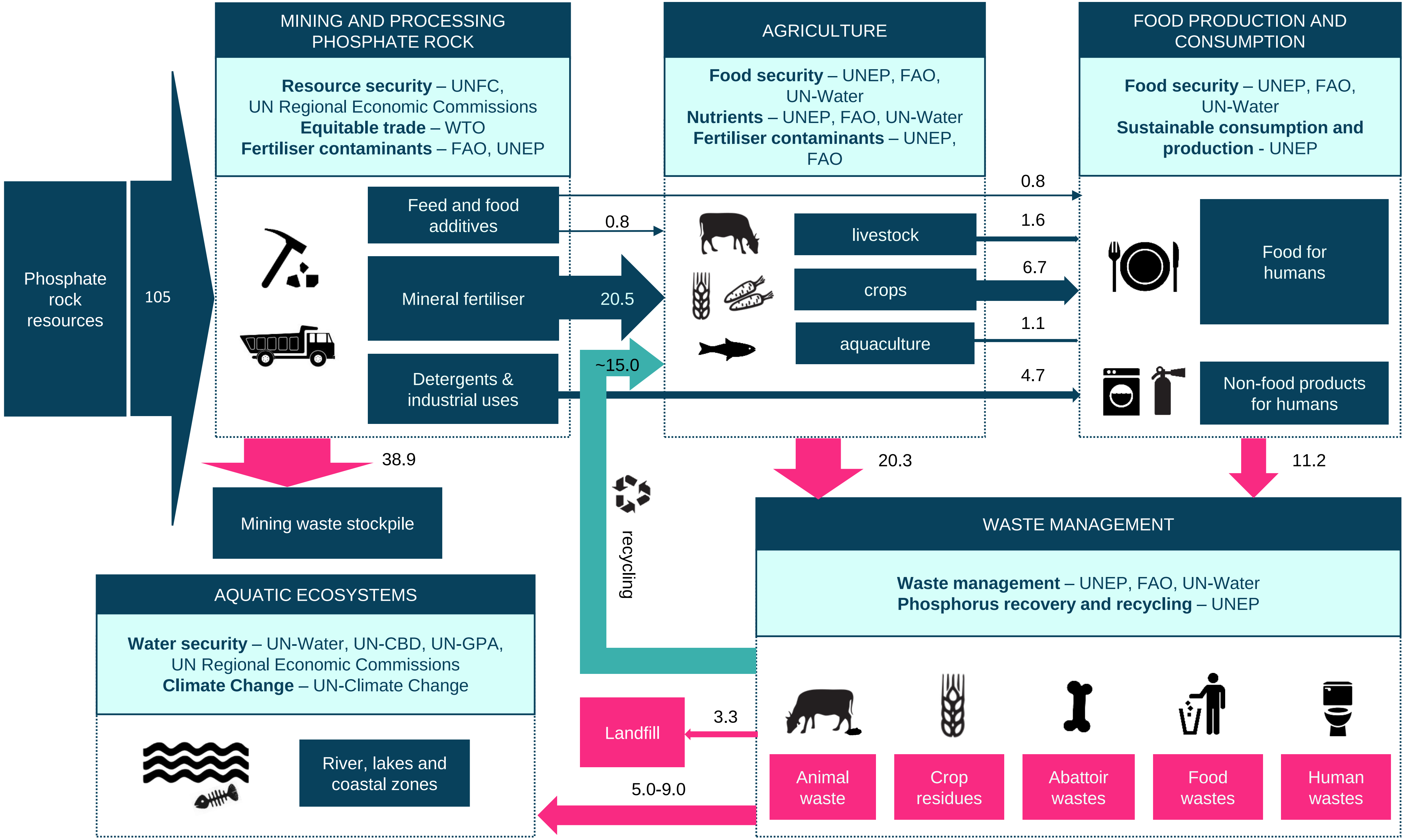
Author Contributions

WJB co-conceived the idea of the manuscript and led the writing of the paper, and collated and conducted data analysis; MAS, DSR, KVH, LH, CK contributed to writing the paper; BMS co-conceived the idea of the manuscript and was the principal investigator of the project that supported this work and contributed to writing the paper.

Competing Interests

The authors declare no competing interests.



Phosphate rock resources

MINING AND PROCESSING PHOSPHATE ROCK

Resource security – UNFC,
UN Regional Economic Commissions
Equitable trade – WTO
Fertiliser contaminants – FAO, UNEP

Feed and food additives

Mineral fertiliser

Detergents & industrial uses

Mining waste stockpile

AGRICULTURE

Food security – UNEP, FAO,
UN-Water
Nutrients – UNEP, FAO, UN-Water
Fertiliser contaminants – UNEP,
FAO

livestock

crops

aquaculture

FOOD PRODUCTION AND CONSUMPTION

Food security – UNEP, FAO,
UN-Water
Sustainable consumption and production - UNEP

Food for humans

Non-food products for humans

WASTE MANAGEMENT

Waste management – UNEP, FAO, UN-Water
Phosphorus recovery and recycling – UNEP

Animal waste

Crop residues

Abattoir wastes

Food wastes

Human wastes

Landfill

AQUATIC ECOSYSTEMS

Water security – UN-Water, UN-CBD, UN-GPA,
UN Regional Economic Commissions
Climate Change – UN-Climate Change

River, lakes and coastal zones

➡	Intended flows
➡	Unintended flows
➡	Recycling flows

All flows in megatonnes of phosphorus per year.