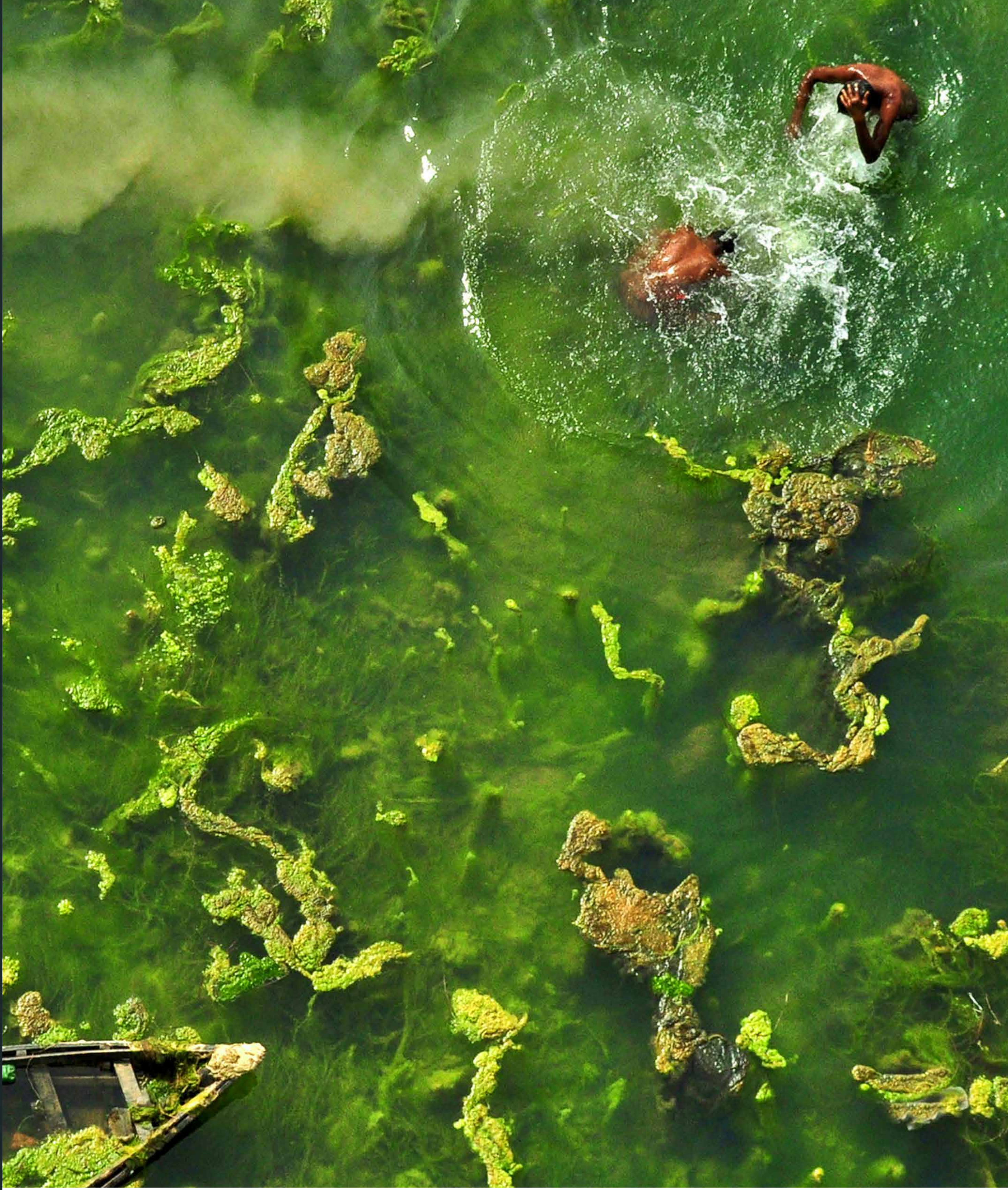


Global overview on phosphorus management - www.opfglobal.com

Summary for Policymakers

Our Phosphorus Future

Towards global phosphorus sustainability

With support from the Natural Environment Research Council, The United Nations Environment Programme, The Global Environment Facility, through the International Nitrogen Management System project and the European Sustainable Phosphorus Platform.

Recommended citation for this Summary for Policymakers: W.J. Brownlie, M.A. Sutton, K.V. Heal, D.S. Reay, B.M. Spears (eds.), (2022) Summary for Policymakers. In: Our Phosphorus Future. UK Centre for Ecology & Hydrology, Edinburgh. doi: 10.13140/RG.2.2.11029.40162

This full report and supporting media are available at **www.opfglobal.com**

Published by UK Centre for Ecology & Hydrology (UKCEH), on behalf of the Our Phosphorus Future Network. ISBN: 978-1-906698-79-9. INMS report number – 2022/01.

Preparation of the Our Phosphorus Future report has been supported with funding from the Natural Environment Research Council (NERC) International Opportunities Fund (award number NE/P008798/1), the United Nations Environment Programme (UNEP), the Global Environment Facility through the 'International Nitrogen Management System' (INMS) (GEF project ID: 5400), and the European Sustainable Phosphorus Platform (ESPP).

OUR PHOSPHORUS FUTURE

Summary for Policymakers

The Our Phosphorus Future report was edited by

Will J. Brownlie, Mark A. Sutton, Kate V. Heal, Dave S. Reay and Bryan M. Spears.

including contributions from (listed alphabetically)

Tapan K. Adhya, Julia C. Bausch, Tim G. Benton, Martin S.A. Blackwell, Marissa A. de Boer, Tom Bruulsema, Lino Camprubí, Lingyun Cheng, Dana Cordell, Kimo van Dijk, James J. Elser, Gu Feng, Helen A. Hamilton, Phil M. Haygarth, A. Louise Heathwaite, Ludwig Hermann, Penny J. Johnes, Malin Jonell, Phil Jordan, Christian Kabbe, Haigang Li, Katrina. A. Macintosh, Cargele Masso, Kazuyo Matsubae, John W. McGrath, Richard W. McDowell, Per-Erik Mellander, Geneviève S. Metson, Frank Mnthambala, Tibisay Morgandi, Tina-Simone Neset, Heidi Peterson, Ruben Sakrabani, Caroline Schill, Jianbo Shen, Marc I. Stutter, Elizabeth Tilley, Isabelle Vanderbeck, Paul J.A. Withers, Jiechen Wu, Fusuo Zhang, Chaochun Zhang.

Cover photo show two men bathing in a phosphorus polluted river in West Bengal India. Photograph taken by Apratim Pal: https://instagram.com/guycalledapratim?utm_medium=copy_link

1. Our Phosphorus Future - an overview

The 'Our Phosphorus Future' (OPF) project 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 to 2021. During this time over 100 scientists and industry experts came together to develop the report. The report identifies the priority issues, possible solutions and the capacity to address phosphorus sustainability from local to global scales. The report is supported by a range of videos and visual summaries. The full report and supporting media are freely available at www.opfglobal.com.

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 'Summary for ``Policymakers' presents key findings of the OPF report. The report is underpinned by >2000 peer-reviewed publications and reports spanning more than 300 years of scientific research and underwent an extensive review process, supported by more than 40 referees from both academia and industry bodies. The full report contains references to the scientific evidence presented in this document.

Key Messages

Unsustainable phosphorus use is at the heart of many societal challenges. Unsustainable phosphorus use affects food and water security, freshwater biodiversity and human health. Increasing demand for food to support a growing global population continues to drive increases in phosphorus inputs to the food–system, as well as losses from land-based sources to freshwater and coastal ecosystems. These losses cause ecological degradation through the proliferation of harmful algal blooms in fresh waters, contributing to alarmingly high rates of biodiversity decline, economic losses associated with clean-up, and large-scale human health risks from contaminated drinking water supplies.

The pace of species extinction, climate change and the growing number of extreme weather events, combined with population growth, geopolitical risks, and the economic impact of COVID-19, have further strengthened the need to invest in phosphorus sustainability.

Ten key actions

Ten key actions across sectors are proposed to improve sustainable phosphorus management globally. Among these actions, priorities and preferred solutions can be expected to differ nationally and between regions.

1. Increase the use of recycled phosphorus in fertiliser and other chemical industries, as an alternative or supplement to phosphate rock.
2. Optimise phosphorus inputs to agricultural soils and maximise crop uptake to minimise losses.
3. Optimise animal diets and the use of supplements to reduce phosphorus excretion.
4. Increase appropriate application of manures, other phosphorus-rich residues, and recycled fertilisers to soils, to complement appropriate mineral fertiliser use.
5. Improve global reporting and assessments of phosphorus emissions and their impacts on freshwater and coastal ecosystems.
6. Implement integrated approaches for freshwater and coastal ecosystem restoration and protection at catchment, national and transboundary scales.
7. Implement national to global strategies to increase recovery and recycling of phosphorus from solid and liquid residue streams.
8. Ensure sufficient access to affordable phosphorus fertilisers (mineral, organic and recycled) for all farmers.
9. Promote a global shift to healthy and nutritious diets with low phosphorus footprints.
10. Reduce the amounts of phosphorus lost as food waste in food processing, retail, and domestic consumption.

Towards a Sustainable Phosphorus Future

Looking to the future, significant investment aligned with increased public awareness and political support is needed to implement the solutions outlined in this report. A decade has passed since the global anthropogenic flow of phosphorus was assessed as having crossed the planetary boundary. Yet, despite clear opportunities to move towards more sustainable phosphorus use, there remains a lack of direction in relevant food and environmental policy to support such a transition. Intergovernmental coordination is urgently needed to address this issue. Multiple benefits are associated with sustainable phosphorus use, including:

- Improved sanitation, essential for health and the environment.
- Healthier diets for some individuals.

- New employment opportunities through the nutrient circular economy.
- Coherence with sustainable management of other nutrients including nitrogen, carbon and potassium.
- Return of organic carbon to soils, contributing to soil fertility and climate resilience.
- Reduction in greenhouse gas emissions including carbon dioxide and methane, and potential synergies with nitrous oxide.
- Reduced national dependency on the limited regions with phosphate rock reserves.
- Reduced mobilisation of contaminants contained in some phosphate rock reserves.
- Increased biodiversity and socioeconomic benefits associated with ecosystem recovery.

A transition towards more sustainable phosphorus use will help countries contribute to their commitments to multiple UN-SDGs, that include:

SDG 1 – No poverty and SDG 2 – Zero Hunger, through the development of business growth within the circular economy, risk reduction to sectors (and employees) reliant on healthy aquatic ecosystems and reduction in poverty-related malnutrition through the protection and provision of livelihoods.

SDG 3 – Good Health and Well-Being, by reducing the risk of harmful algal blooms, and a reduction in illnesses from hazardous water pollution (e.g., cyanotoxins produced during harmful algal blooms).

SDG 6 – Clean Water and Sanitation, through a reduced risk to drinking water supplies resulting from improvement to water resources impacted by phosphorus pollution and the protection and restoration of aquatic ecosystems, and improved sanitation where phosphorus recovery drives infrastructure investment.

SDG 12 – Responsible consumption and production, through improved sustainable management and efficient use of natural phosphorus resources, and improving environmentally sound management of chemicals (e.g. fertilisers) and all wastes throughout their life cycle.

SDG 13 – Climate Action, through reduced contributions to greenhouse gas emissions from phosphorus polluted ecosystems.

SDG 14 – Life Below Water, through the sustainable management and protection of marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening their resilience.

SDG 17 – Partnerships, through improved sustainable phosphorus partnerships reliant on the development, transfer, dissemination, and diffusion of environmentally sound technologies to all countries.

An aspirational goal for phosphorus

The following goal is identified as an interim focus for 2050, which would together represent a major step on the pathway to a sustainable phosphorus future.

The OPF '50:50:50' Goal calls for a 50% reduction in global phosphorus pollution and a 50% increase in the recycling of phosphorus lost in residues and wastes, by 2050.

Key benefits of achieving the '50:50:50' goal are listed below (see Figure 1).

Figure 1. Key benefits to the environment and society of delivering a 50% reduction in global phosphorus (P) pollution and a 50% increase in the recycling of P lost in wastes, by 2050 (as outlined by the OPF 50:50:50 goal).

Towards a Sustainable Phosphorus Future

The '50:50:50' goal aligns with several aspirational goals that have also called for reductions in nutrient losses in recent years. These include:

- The UNEP Colombo Declaration which calls for the halving of nitrogen waste by 2030.
- The working group of the Post-2020 Global Biodiversity Framework which proposed to reduce pollution from excess nutrients by 50% by 2030.
- The Farm to Fork strategy underpinning the European Green Deal, which calls for actions to reduce nutrient losses by at least 50% and to reduce fertiliser use by at least 20% by 2030.

If the world is to meet climate change, biodiversity, and food security targets, and avoid building costs of predicted phosphorus impacts, positive action on phosphorus management is essential. The present report calls for the establishment of an intergovernmental coordination mechanism to catalyse integrated action on phosphorus sustainability (see Figure 2). This should be supported by an international framework to consolidate the collective knowledge, quantify the economic and societal benefits of improvements in phosphorus management and establish targets for time-bound improvements.

The report identifies a clear opportunity to raise awareness of the need for sustainable phosphorus management through the United Nations Environment Assembly (UNEA) and calls for a UNEA resolution on sustainable phosphorus management or an equivalent global commitment to act.

The following text summarises the key challenges (C X.X) and solutions (S X.X) taken from Chapters 2-8 of the OPF report.

Figure 2. Steps proposed to consolidate the knowledge, identify opportunities, and catalyse the political support needed to achieve significant improvements in phosphorus sustainability over the next decade.

2. Phosphorus reserves, resources and uses

C 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.

C 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.

C 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.

C 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. Since 2020, phosphate rock prices and fertiliser prices have increased by 400%, and prices continue to rise.

C 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.

Solutions

S 2.1 Reduce reliance on mineral phosphorus fertiliser. Improving the efficient use of phosphorus in agriculture in combination with societal change (e.g. diet change) and shifting reliance away from mined phosphorus sources by increasing phosphorus recycling is required. A goal for fertiliser products to contain a minimum of 20% recycled phosphorus could set a benchmark that demonstrates green commitment across the industry.

S 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.

S 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.

S 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.

S 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.

3. Transforming food systems: implications for phosphorus

C 3.1 **Business as usual is unsustainable: we must produce healthier food, using appropriate phosphorus inputs.** Our food system is a significant cause of nutrient pollution in terrestrial, freshwater and marine ecosystems, and of global climate change, while more than half the global population are acutely hungry, malnourished, overweight, or obese. Systemic transformation is required for food systems to become environmentally sustainable and provide nutritional security for all. Sustainable phosphorus strategies must directly support, not hinder, this transformation. On the current path, the global food system will increase the mining of finite phosphate rock to produce fertiliser, feed additives and food supplements, and is not tracking towards a circular phosphorus system (driven on recycled phosphorus inputs).

C 3.2 **Increasing global consumption of animal products is increasing phosphorus demand.** The amount of phosphorus required to produce the average per capita global diet has increased by 38% in the last 50 years, due to the rise in consumption of animal products, increase in average per capita consumption and increased food waste. Excluding phosphorus-efficient grass-based systems, a large proportion of cropland is needed to support intensive meat and dairy production through concentrated animal feeding operations.

C 3.3 **Balancing intensive agriculture with low input farming.** Agricultural intensification increases productivity yet increasing phosphorus inputs to crops can also over-enrich adjacent land and waterbodies with nutrients. Lowering phosphorus inputs reduces environmental risk and promotes biodiversity but may restrict yield in the long-term. Strategies need to provide the right balance of intensification to avoid the need to convert more land to agriculture. Optimising the multitude of costs and benefits and taking account of direct and indirect impacts can be challenging and context specific. The challenge we face is in developing low phosphorus input farming systems which can sustain food production.

C 3.4 **Many farmers lack access to phosphorus, threatening their livelihoods.** Currently, 1 in 7 farmers cannot access or afford phosphorus fertilisers to increase productivity, reducing their ability to maintain food security and livelihoods. Those farmers most affected are rural smallholder farming families, particularly in less economically developed countries, but also in some more economically developed countries. There are marked global inequalities in access to phosphorus as a resource, leading to substantial inequalities in the distribution of risks to food security.

Solutions

S 3.1 Managing phosphorus sustainably can support a shift to healthier diets. Global food systems must produce, actively support, and provide access to nutritious food and diets for all. This shift, from 'market-led' to 'sustainable' food security, can reduce phosphorus demand and adverse impacts on ecosystems and society. Concurrently, strategies to deliver better phosphorus sustainability, including circular phosphorus value chains, can benefit agricultural economies, whilst effective monitoring systems, data sharing, and knowledge exchange can ensure strategies adapt to a transforming food system.

S 3.2 Shift global consumption of animal products towards plant-based diets. Reduced consumption of animal products especially from intensive production systems in some regions may reduce global agricultural phosphorus demand and contribute to healthier environments. Increased awareness amongst policymakers and the public of the environmental impacts of phosphorus use in food production, and the human health risks of excessive consumption of animal products, will be an essential driver of change. Knowledge exchange between academics, stakeholders and the public can help identify solutions to support a transition to more phosphorus sustainable consumer behaviour, as could policy and regulatory changes (including internalising the environmental costs into food pricing).

S 3.3 Integrated landscape strategies to improve phosphorus use efficiency and reduce losses. There is an opportunity to develop novel land-use planning approaches to support more sustainable phosphorus use across multiple and interacting contexts. These include agricultural production, ecosystem and human health, local economies and regional capacity for institutional planning and coordination. Sustainable farming systems in which animal and crop production are more integrated and animal residues and manures are treated as valuable phosphorus resources, will support efforts to increase phosphorus use efficiency within landscapes while reducing negative impacts on aquatic and terrestrial ecosystems.

S 3.4 Better support for smallholder farmers. Affordable access to sustainable phosphorus sources is imperative to ensure food provision for all and to protect the livelihoods of smallholder and marginal farmers. Multiple options exist to help improve phosphorus access in these communities. These include access to credit, extension services, investment in sustainable infrastructure (such as local phosphorus recycling systems from food waste and sanitation where available), and knowledge exchange to support better phosphorus use efficiency and recycling. Developing the capacity to recycle phosphorus from local and regional food systems where available can help to shift reliance away from mineral phosphorus fertilisers.

4. Opportunities for better phosphorus use in agriculture

Challenges

C 4.1 Low phosphorus use efficiency (~20%) and high phosphorus losses are common in agriculture Phosphorus losses from agricultural land to waterbodies is a growing problem globally and is exacerbated by climate change and rainfall extremes. In some cases, slow/controlled-release fertilisers can improve phosphorus use efficiency but these are not yet widely used. In regions where access to phosphorus fertilisers is not a limiting factor, there is a trend to apply high rates of phosphorus to compensate for soil phosphorus fixation, which can increase potential losses. Improving the utilisation of residual phosphorus in soils is critical for achieving efficient agricultural phosphorus use in these regions.

C 4.2 The complexity of soil-crop phosphorus cycles can confound management efforts. The phosphorus cycles that underpin organic, intensive monoculture and mixed farming systems vary widely and are sometimes poorly understood. This can make crop uptake of phosphorus difficult to predict, resulting in inaccurate estimates of fertiliser requirements that may confound attempts to improve phosphorus use efficiency.

C 4.3: Livestock in intensive farming operations are often fed phosphorus in excess leading to high excretion rates. Demand for animal products is increasing. In some regions, poor management (i.e. collection, storage, and application) of manures leads to avoidable phosphorus losses to waterbodies. Livestock and poultry are commonly fed more phosphorus than they can utilise, leading to excretion of phosphorus-rich manures; they typically retain less than 30% of the phosphorus ingested.

C 4.4 Recycled phosphorus is not sufficiently used in agriculture. A circular approach to phosphorus management in agriculture is critical to address the significant amounts of phosphorus currently lost to the environment or landfills. Recycling is currently limited by transport costs of recycled resources and decoupling of phosphorus cycles across agricultural sectors due to intensification of livestock production. Policies and negative public perceptions about the safety of use can limit phosphorus recycling of certain wastes and residues. Phosphorus recovery technologies can produce contaminant-free phosphorus materials for safe reuse in recycled fertilisers.

C 4.5 There are insufficient policies and targets to deliver integrated action on phosphorus. Policies and/or regulations relating to sustainable phosphorus management at national or regional scales are sparse, and none exist at the global scale. Where regulations exist, policy incoherence and weak enforcement due to the lack of coordination among relevant ministries is commonly observed. Aspirational goals/targets (e.g. for phosphorus recycling, phosphorus losses, phosphorus use efficiency) and indicators to monitor improvement are also lacking for most regions.

Solutions

S 4.1 Provide farmers with the support needed to increase phosphorus use efficiency. Farmers should not apply more phosphorus than needed to maximise crop yields. Fertiliser use can be optimised and should consider all nutrients. Soil phosphorus testing and appropriate control limits on phosphorus inputs may be needed. In some regions, such as parts of Africa, more phosphorus should be applied to improve/maintain crop productivity. Slow-release fertilisers, structural farming measures to reduce erosion and runoff and, innovations to improve uptake of residual phosphorus stores may reduce phosphorus losses whilst maintaining yield. Training farmers and advisors in nutrient management and providing access to decision support systems/tools for nutrient budgeting are required.

S 4.2 Implement crop management measures that improve plant uptake of phosphorus in soils. Multiple strategies can be used to optimise phosphorus use efficiency of crops, through site-specific modifications to crop management, integrated soil fertility management (including water and weed management), rhizosphere management and the use of phosphorus efficient cultivars and bio-fertilisers. Strategies can now be developed to improve plant uptake of applied and residual phosphorus in the soil.

S 4.3 Optimise animal diets to lower phosphorus excretion and improve manure management. Optimising the diets of animals in intensive farming operations to match growth requirements, and supplementing monogastric animals with phytase enzymes can reduce phosphorus excretion. Governments should provide guidance on dietary phosphorus allowance for livestock based on current scientific knowledge.

S 4.4 Increase phosphorus recycling from manures and residue streams. Globally, recycling of treated animal manures and residues and the use of recycled fertilisers should be increased, with corresponding reductions in mineral fertiliser use. Integrating arable and livestock systems can help to reduce costs associated with transporting phosphorus rich animal manures and residues to crops. In some cases, education, extension services and investment in infrastructure and technology are needed to support stakeholders and make phosphorus recycling more efficient.

S 4.5 Develop integrated policies and phosphorus use efficiency targets across scales. An integrated approach is essential to increase sustainable phosphorus use in the agricultural sector and will require actions across scales, sectors, disciplines, and regions. Targets to increase phosphorus use efficiency in agriculture and indicators to monitor improvement from farm to global scales are needed. Phosphorus budgets at the farm level are needed to develop catchment management plans that scale phosphorus use efficiency assessments to national, regional, and global scales. We must maximise synergies with other nutrients and ensure that policies are adaptive.

5 Phosphorus and water quality

Challenges

C 5.1 Phosphorus pollution is increasing globally. Over the course of the 20th-century, phosphorus losses from land to fresh waters almost doubled because of human activity. Whilst sources of phosphorus pollution vary between regions, they are dominated by agricultural (e.g. livestock manures and fertilisers) and wastewater discharges. In many regions, phosphorus losses continue to increase.

C 5.2 The global impacts of phosphorus pollution are not well quantified. Elevated phosphorus concentrations in freshwater and coastal marine ecosystems are contributing to the unprecedented loss of freshwater biodiversity and the growing global phenomenon of freshwater and marine 'dead zones' (see Figure 3). However, the true scale of the problem is difficult to estimate as baseline data are lacking across all regions and scales. Long-term monitoring programmes are necessary to track and study recovery following nutrient reduction strategies and to inform adaptive management initiatives.

C 5.3: Phosphorus losses and their impacts are expensive. The direct and indirect impacts of eutrophication are costly, in terms of losses of ecosystem services, clean up expenses, and losses to local economies. Phosphorus losses also represent a significant waste of resources. Global or regional assessments on the costs of eutrophication or the effectiveness of measures to reduce phosphorus losses are lacking. This severely compromises the ability to communicate the need for action with stakeholders and policymakers.

C 5.4 There is a lack of phosphorus policy and legislation covering water security. Phosphorus sustainability is not consistently enacted in regional policies and global action is needed to bring phosphorus enrichment of waters to the attention of policymakers. No global holistic policy on nutrient management in aquatic ecosystems exists. A key challenge is therefore enabling better integration of a sustainable phosphorus strategy across existing and emerging policy frameworks.

S 5.1 **Reduce phosphorus losses and improve phosphorus use efficiency.** Improved agricultural and wastewater management should be implemented to reduce losses of phosphorus from land to water. There is also a clear opportunity to improve phosphorus use efficiency in aquaculture. In order to reduce phosphorus pollution on a global scale, we must identify opportunities to decrease the amount of 'mined' phosphorus entering the anthropogenic phosphorus cycle, enhance uptake of sustainable fertiliser management approaches, and take action to close the phosphorus loop. This can be done by cutting phosphorus losses and increasing recycling and phosphorus storage within the landscape

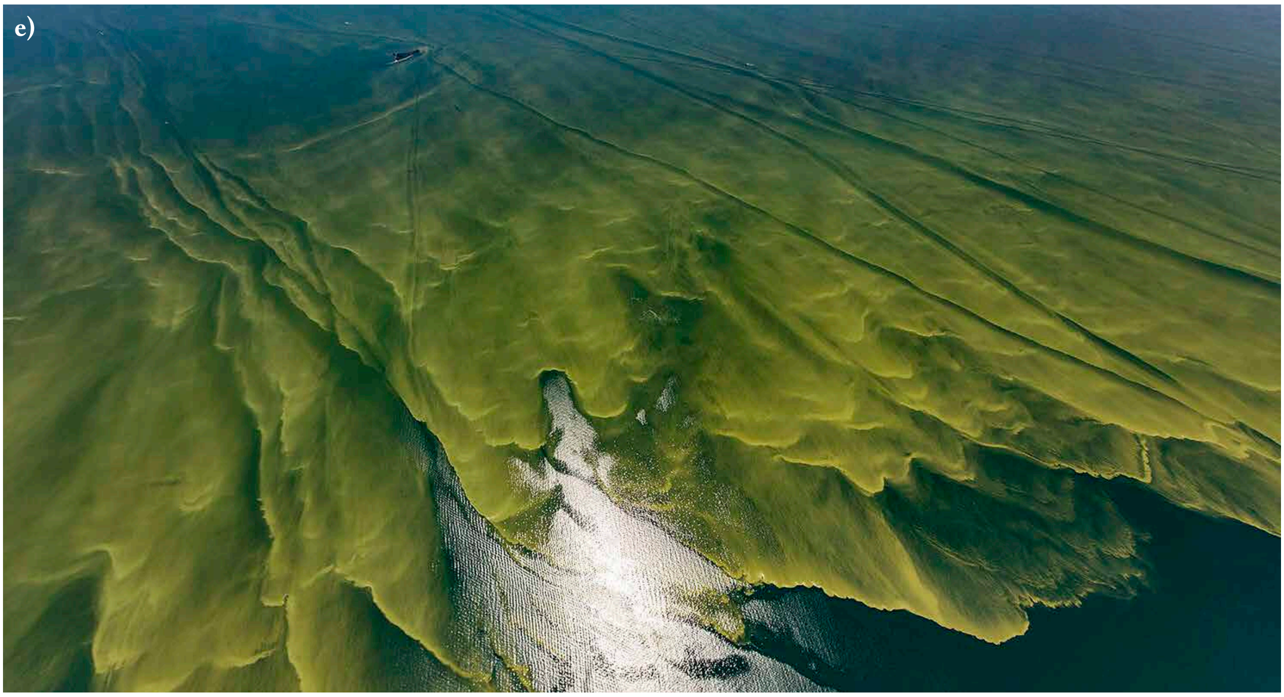
S 5.2 **Implement new and utilise existing data collection systems to inform adaptive management.** Monitoring programmes provide a critical link between information, evidence-based decision making, and policy development, and should be used to inform adaptive management frameworks. This is especially important given ecosystem restoration is often a long-term process, and considering the impacts on waterbodies of multiple stressors, including those associated with climate change, population growth, and urbanisation. Restoration efforts must be coupled with preventative interventions to safeguard those ecosystems that are sensitive to future increases in phosphorus input.

S 5.3 **Implement integrated catchment management and develop algal bloom response plans.** A road map for capacity development is required to support the wider development of long-term integrated catchment management programmes focused on phosphorus. Rapid response plans are needed to manage the risk of damage to both ecosystem and human health associated with harmful algal blooms.

S 5.4 **Develop integrated policy approaches and globally coordinated phosphorus initiatives.** The development of regional targets, mandates and incentives are essential, and will often require transboundary cooperation. Where regional policies exist on phosphorus or other nutrients, experiences with these should be synthesised to inform their improvement as well as support policy development in other regions where no relevant policies exist.


a)
b)
c)
d)

e)



f)

Figure 3. Deleterious effects of eutrophication.
a) An algal bloom in Dianchi Lake, China in 2007. Despite millions spent to clean up the lake, the water remains undrinkable and unfit for agricultural or industrial uses. Photo Credit: Greenpeace China.
b) Satellite image of an algal bloom in the Baltic Sea (approximately 290 km wide by 390 km long). Photo credit: European Space Agency.
c) Soldiers clear algae along the coastline of Qingdao, Shandong province, in 2008. More than 10,000 people and 1,200 vessels were mobilised to tackle the huge algae bloom that threatened the Olympic sailing event in Qingdao. Photo Credit: Asianewsphoto - Ju Chuanjiang.
d) An aquaculture farmer cleans away dead fish at a lake in Wuhan, China, 2007. More than 110,000 pounds of fish died due to phosphorus pollution and hot weather in the lake. Photograph courtesy of China Daily/Reuters.
e) Huge harmful algal blooms float towards the coastline of Lake Erie, US, in 2017. Photo Credit: Aerial Associates Photography, Inc. by Zachary Haslick.
f) A fisherman sets out nets to catch fish in a river heavily polluted by phosphorus in West Bengal, India. Photograph taken by Apratim Pal - https://www.instagram.com/guycalledapratim/?utm_medium=copy_link.

6 Opportunities to recycle phosphorus-rich organic materials

Challenges

C 6.1 Organic wastes and residues are often treated as pollutants and not nutrient resources. Organic materials are often managed as pollution rather than as a valuable nutrient resource. Consequently, improvements in the management of phosphorus-rich organic materials are necessary including collection and storage, processing, and application practices. Farmers and stakeholders may reject recycling some organic materials as fertilisers because of negative perceptions over the safety of their use in food production; these concerns must be overcome.

C 6.2 Manure and waste production is often 'decoupled' from croplands where it can be recycled. In many regions, the distances between the production of phosphorus-rich organic materials and arable land are increasing, driven by the expansion of specialised and intensive farming, urbanisation, and globalised trade. This can make transporting such materials to areas where they can be recycled prohibitively expensive. Decoupling of livestock and arable farming systems is particularly problematic for farmers producing organic foods and feeds. This is because 'conventional' mineral phosphorus fertilisers, and in some cases manures from confined animal feeding operations, cannot be used to fertilise organic crops.

C 6.3 The reliability of phosphorus-rich organic materials is often lower than mineral fertilisers. The concentrations of phosphorus in organic materials are variable, not easy to determine quickly and lower than mineral phosphorus fertilisers, representing a challenge for farm-scale nutrient management. The bioavailability of phosphorus in organic materials varies and influences their performance as fertilisers, and can be affected by soil type, pH, and crop breed. The bulky nature of many organic materials can make them difficult to spread consistently, affecting their reliability as a fertiliser.

C 6.4 Some phosphorus-rich organic materials can contain contaminants. Pathogens, hormones, antibiotics, potentially toxic elements, and microplastics can be present in some phosphorus-rich organic materials. It is important to ensure contaminants are removed, destroyed or concentrations reduced to safe levels in any phosphorus-rich organic materials to be used as fertilisers. In some cases, contaminants can accumulate in soils and may pose a risk to human and animal health and environmental quality.

C 6.5 Policy, infrastructure, and financial support are lacking for phosphorus recycling. There is a lack of coordinated policy and regulation to support an increase in the recycling of phosphorus-rich organic materials. In some regions, there is little economic incentive for farmers to switch from mineral phosphorus fertiliser to phosphorus-rich organic materials. Some farmers can face legal and certification barriers stopping them from recycling certain phosphorus-rich organic materials.

Solutions

S 6.1 Treat waste streams as valuable nutrient resources. A paradigm shift in how we view waste streams is needed; from pollutant to valued nutrient resource. Key actions in delivering this shift include raising awareness of the costs of phosphorus losses and benefits of phosphorus recycling, providing education and extension services to encourage stakeholders to recycle phosphorus, and mobilising investment in infrastructure and technology to make phosphorus recycling safe, easy, and efficient.

S 6.2 Optimise the spatial integration of arable and livestock agricultural systems. Landscape planning can integrate arable and livestock farming to maximise nutrient recycling. Whilst efforts should be made to ensure animal densities in livestock farming do not exceed nutrient needs, some farming systems must rely on disposal/utilisation contracts. Arable-livestock farming partnerships can support the exchange of crops, grains, and manures, and coordinate land-use to support more regionally closed feed-manure loops.

S 6.3 Utilise available technology, tools and provide education. The reliability of phosphorus-rich organic materials as fertilisers can be improved by processing to improve fertiliser quality, and developing better systems to help farmers assess the phosphorus content and phosphorus bioavailability of the materials. Furthermore, farmers can be better supported to optimise the application of recycled phosphorus products and other nutrients in order to maximise phosphorus uptake by plants. However, critical to this is a sufficient understanding of farm- and local-scale nutrient budgets.

S 6.4 Process organic materials appropriately and provide safety certification schemes. Most phosphorus-rich organic materials need some processing to reduce contaminants and pathogens to safe levels for use in food production. Reducing livestock dietary intake of potentially toxic elements and imposing strict limits on the non-therapeutic use of antibiotics in livestock, will reduce levels of these contaminants in manure and biosolids.

S 6.5 Develop policies, regulations, and financial instruments that support phosphorus recycling. Improved coordination between relevant government bodies and relevant stakeholders is required to develop coherent, holistic policies and create markets for recovered phosphorus fertiliser. Investment in infrastructure and technologies supported by cross-sectorial innovation, co-creation and sharing of knowledge can help to make phosphorus recycling simple and efficient. The economic benefits for society of recycling phosphorus need to be better quantified and used to encourage stakeholders to recycle phosphorus more efficiently. The value of recovering phosphorus can be maximised by selecting methods to process organic materials that produce additional co-benefits.

7 Opportunities for recovering phosphorus from residue streams

C 7.1 **Many waste streams and residues represent a significant untapped phosphorus resource.** The phosphorus in many organic waste streams and residues, including food wastes, biosolids and abattoir residues, is commonly lost to the environment. Many phosphorus-rich wastes are managed as pollution rather than valuable phosphorus resources. The ashes of incinerated residues are often landfilled or used in building materials without recovering the phosphorus they contain. There are significant opportunities to increase phosphorus recovery in all regions.

C 7.2 **Recovered phosphorus materials must have a competitive commercial value.** Phosphorus recovery processes that do not generate industry compatible raw materials or finished products with a clearly defined market potential may fail to contribute to phosphorus recycling. Where recovered phosphorus fertiliser match mineral phosphorus fertiliser in terms of performance, systems to support large scale production, transport and handling are currently insufficient.

C 7.3 **There is a lack of policy and market support for phosphorus recovery.** There is a global lack of tangible policy support for phosphorus recovery, which has hindered the building of commercial markets for renewable phosphorus products, including financial instruments such as subsidies, tax incentives, or support for farmers to adopt sustainable measures. Certifying recovered phosphorus products as fertilisers can provide a significant challenge for phosphorus recovery enterprises.

Solutions

S 7.1 **Establish a global commitment to recycling nutrients in wastes and residues.** Nations should commit to ambitious targets to recover and recycle nutrients from livestock manure, wastewaters, abattoir residues and industrial waste streams, whilst discontinuing landfilling phosphorus-rich ashes and their displacement into building materials. A significant increase in phosphorus use efficiency, in conjunction with good management practices to reduce and mitigate phosphorus losses is also critical.

S 7.2 **Optimise the commercial viability of recovered phosphorus products.** Phosphorus recovery technologies must produce commercially viable materials with defined market potential or that are industry compatible as a raw material for fertilisers or other products. Opportunities to produce co-value products and services (i.e. produce energy, other nutrients), and the environmental sustainability of recovery processes, should be optimised. Some recovered phosphorus products/fertilisers have a potential market opportunity to provide efficient, pollutant-free fertilisers. A key challenge for phosphorus recyclers is producing relevant volumes and homogeneous quality to meet demand. The market price of recovered phosphorus products/fertiliser alone should not define the economic feasibility of phosphorus recovery. According to the "polluters pay" principle, stakeholders could share the cost of recovery, at least in more economically developed countries.

S **7.3** **Develop policies that support phosphorus recovery and recycling.** Critical policy needs to include a regulatory framework to boost the use of recovered phosphorus materials as an alternative to phosphate rock as the primary source of phosphorus in mineral fertilisers. In some regions, the necessary infrastructure to collect wastes and residues is still required. The next step could be global binding agreements and a paradigm change: taxing the consumption of natural resources and related externalities and reducing the tax burden of renewable resources and labour.

8 Consumption: the missing link towards phosphorus security

C 8.1 Animal products have high phosphorus footprints. The production of meat, dairy and eggs requires disproportionately high amounts of mineral phosphorus fertilisers. Under 2011 global farming practices, it took 16 times more mineral phosphorus fertiliser to produce 1 g of beef protein than 1 g of legume/pulse protein.

C 8.2 Consumption of animal products is increasing. A 38% rise in the phosphorus footprint of the average diet in the last 50 years is mostly associated with the increased consumption of animal products. A remarkable increase has occurred in China and Brazil; however, their footprints are still below the USA and other industrialised countries (e.g. average per capita protein intake in the EU is about 70% higher than recommended). Economic development correlates with increased consumption of animal products. Some populations still require a more diverse and calorie-rich diet.

C 8.3 Food loss and waste is high across the globe. Globally, 23% of nutrients in fertilisers are used to produce products that are then lost in agricultural and food wastes. The loss at each stage, from farm to fork, differs among regions. Generally, waste is higher on a per-capita basis in industrialised countries, whilst in lower-income countries, losses are driven by insufficient infrastructure.

C 8.4 Changing consumer food habits is difficult. Whilst a shift towards more phosphorus-sustainable diets and waste management practices is required, a complex network of conditions must be met for an individual to change behaviour, which varies by region, country, town, and even family. Raising awareness of negative environmental and/or health impacts (including phosphorus sustainability issues) of certain food choices alone is not enough to change behaviours. People's resources and capacity to change need to be considered as well.

C 8.5 Unsustainable pricing models may slow a transition to sustainable practices. There is a disconnect between what a consumer pays for food and the true 'costs' of food production. The costs involved in mitigating environmental degradation and biodiversity loss from phosphorus losses, and in developing more phosphorus sustainable agriculture systems, are not covered in the price of food products.

Solutions

S 8.1 Reduce consumption of animal products to recommended levels. Wider adoption of healthy diets with low to moderate amounts of meat and dairy (especially low in red meat) could radically reduce demand for mineral phosphorus fertilisers and thus phosphate rock mining. While some demographics could benefit from increased access to animal products, large gains can be made from reducing meat consumption in countries that already consume more than is recommended. The global adoption of a vegetarian diet would cut both fertiliser needs and eutrophication effects by 50%. Although this may be unrealistic, it indicates the major influence of diet change on the global phosphorus cycle.

S 8.2 Promote the wide adoption of healthy and regionally appropriate diets. The wide adoption of healthy diets rich in plant-based foods and sustainable aquaculture produce is compatible with sustainable phosphorus management. Sustained communication, along with global and regional structural changes to food systems can help consumers adopt diets that are good for them and the environment.

S 8.3 Reduce food loss throughout food production, retail, and consumption sectors. Most food loss in low-income countries occurs before products reach consumers; meanwhile wealthier nations waste more food in retail and at home. Efficient strategies to reduce waste will target the most wasteful, with support underpinned by evidence that quantifies the benefits of change.

S 8.4 Make being 'sustainable' easy and rewarding for consumers. It should be easy and affordable for everyone to make healthy diet choices, decrease food waste, and support the safe use of recycled phosphorus from organic wastes (e.g. food waste and excreta) in food production. Incentive structures (including 'health nudges' and 'choice editing') embedded in food systems should be transformed to make phosphorus-sustainable food choices the 'default' option.

S 8.5 Develop policies that encourage and support consumers to lead sustainable phosphorus lifestyles. Developing economic and regulatory policies that encourage and support high recycling rates, low animal product consumption and low waste production will be necessary for sustainable change. This may involve setting high goals for organic waste recycling, direct taxes on animal products, or decreasing subsidies that affect the price of meat.

.

Our Phosphorus Future

The challenges and solutions to improving phosphorus sustainability

Prepared by the Our Phosphorus Future network with support from the NERC International Opportunities Fund, the United Nations Environment Programme and the Global Environment Facility through the 'International Nitrogen Management System', and the European Sustainable Phosphorus Platform.

The report draws attention to the multiple benefits and threats of human phosphorus use. It highlights the critical role phosphorus plays in food security and bioenergy needs, as an essential component of fertiliser. Whilst geological depletion of phosphate rock reserves is not an immediate threat, geopolitical, institutional, economic, and managerial factors may impact phosphorus access. It demonstrates phosphorus emissions to water bodies are a key driver of the biodiversity loss emergency in aquatic ecosystems. Impacts include toxic algal blooms, mass fish kills, greenhouse gas emissions, and the loss of economic, societal, and cultural value associated with high-quality ecosystems.

Ten key actions are identified that would help maximise the benefits of phosphorus use for humanity, whilst minimising environmental threats. The actions listed should be delivered cooperatively, as part of an integrated plan across sectors and scales. Whilst national framing of nutrient sustainability strategies is vital, several phosphorus sustainability issues cannot easily be addressed without international cooperation. Examples of current national and regional phosphorus policies are illustrated, revealing green shoots of success in the transition to phosphorus sustainability. However, coordinated action on phosphorus to support governments, existing conventions, and intergovernmental frameworks, as well as stakeholders, to catalyse improvements in phosphorus sustainability is urgently required.

The report highlights there is a need for an inter-conventional coordination mechanism to address fragmented phosphorus policy. A blueprint for such an initiative is outlined, considering institutional options. The potential for economic benefits of improving phosphorus sustainability is illustrated by estimating the consequences of meeting a global aspirational goal to make a 50% reduction in global phosphorus pollution and a 50% increase in the recycling of phosphorus lost in residues/wastes, by 2050. The ideas expressed in this report should be seen as a starting point to mobilise actions by UN Member States, and actors across society, all of whom stand to gain from sustainable phosphorus management for multiple environmental, health, climate, and economic benefits.

UK Centre for Ecology & Hydrology

THE UNIVERSITY *of* EDINBURGH