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Review

National phosphorus planning for food and environmental security

Will J Brownlie[1], Peter Alexander[2], Dana Cordell[3], Mark Maslin[4], Genevieve S Metson[5], Mark A Sutton[1] and Bryan M Spears[1]

The dependence of countries on phosphorus fertilisers derived from phosphate rock to maintain crop yields and ensure food security is well established. Yet, exposure of national food systems to constrained reserves of phosphate rock and supply chain complexities still pose risks to farmers' access to this critical nutrient in many countries. Whilst phosphorus scarcity can threaten food security, suboptimal fertiliser use and poor wastewater treatment can lead to pollution of freshwaters and coasts, causing eutrophication. This impacts biodiversity, drinking water and aquatic food production. In some countries, national plans targeting the recycling of phosphorus losses back into food production are being considered, offering environmental and socio-economic benefits. Here, we review the literature on assessing risks to food security and water quality associated with national reliance on phosphate rock as the primary source of phosphorus for fertilisers. The scientific community has developed data and tools to enable countries to assess exposure in food systems from phosphorus supply and management and in the environment from pollution. However, current assessment approaches often overlook economic vulnerability, a key gap that hinders our understanding of the urgency and severity of impacts from inaction. Exposure assessments could be used to develop National Sustainable Phosphorus Plans embedding priority actions and financial instruments across existing policy frameworks. Actions include identifying local to national sources and sites for phosphorus recycling, identifying catchments and ecosystems where the benefits of reducing phosphorus pollution are greatest, and establishing an infrastructure development plan to enable greater recycling and reduced pollution. We discuss four integrated actions that will enable countries to take the first steps towards a circular phosphorus economy in the context of a challenging global situation.

Addresses
[1] UK Centre for Ecology & Hydrology, Edinburgh, UK
[2] School of GeoSciences, The University of Edinburgh, Edinburgh, UK
[3] Institute for Sustainable Futures, University of Technology Sydney, Sydney, NSW, Australia
[4] Department of Geography, University College London, London, UK
[5] Department of Geography and Environment, Western University, Ontario, Canada

Corresponding author: Brownlie, Will J (wilown@ceh.ac.uk)

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Risks of business-as-usual phosphorus use

High dependency on phosphorus imports contributes to national food system vulnerability. Food production in most countries relies on imported phosphate rock and/or mineral phosphorus fertiliser to fertilise agricultural soils. Five countries hold 83% of the planet's phosphate rock reserves: Morocco (68%), China (5%), Egypt (4%), Algeria (3%) and Tunisia (3%) [1]. However, in 2023, four countries dominated phosphate rock mining: China (41%), Morocco (16%), the USA (9%) and Russia (7%) [1]. Although estimates indicate that current global reserves could last 300 years, at current mining rates, China, the USA and Russia will deplete their reserves within 40 years, further concentrating the market [2]. Even today, restricted access to phosphorus fertiliser in parts of Africa and Asia is impeding food security objectives [3–5].

Complexities in the phosphorus supply chain result in a volatile market, impacting supply [6••]. This has been demonstrated by spikes in phosphorus prices, exceeding 800% of preceding prices in 2008 and over 400% between 2020 and 2022 [7••]. Both spikes are the result of changing market supply and demand dynamics for agricultural and phosphorus products, instability in energy prices and geopolitical control on exports. The

2020–2022 spike has been attributed to a combination of the Russia–Ukraine conflict, trade wars, escalating fuel prices and the coronavirus disease 2019 pandemic, all of which contributed to supply disruptions and increasing raw material prices [7••,8••]. In response to market disruptions, some governments implemented policies to protect domestic markets, which further exacerbated price increases. For example, tariffs on imports, increased subsidies and export restrictions have all contributed to tighter global supply and driving higher prices [7••]. The drivers of phosphorus price spikes are not well quantified, and shocks are difficult to predict and manage. This leaves countries exposed to phosphorus market instability. A key issue is that current reporting on phosphorus reserves, resources and supply chain losses is fragmented and unreliable, highlighting the need for more transparent, integrated data to support informed decisions on phosphorus use, supply and demand [9].

In contrast, suboptimal use of phosphorus fertilisers and inadequate wastewater treatment are widespread sources of phosphorus pollution to the water environment [10]. This is driving an increased risk of toxic algal blooms and coastal dead zones, posing threats to both human and animal health and leading to disruption in drinking water supplies in extreme cases [11••]. With agricultural phosphorus demand projected to double by 2050, from 2006 levels, under a business-as-usual scenario [12] and losses of phosphorus from wastewater to fresh waters estimated to increase globally by up to 70% by 2050 [13], the impacts of phosphorus pollution are expected to worsen unless transformative action is taken. Over the past 40 years, wastewater has been the primary and increasing source of phosphorus inputs from Africa into aquatic ecosystems [14]. The 2024 Nairobi Declaration proposed by the African Union (following from the Abuja Declaration, 2006) calls for a tripling of fertiliser inputs by 2034 [15]. If this target is achieved without sufficient strategies in place to mitigate phosphorus losses, the adverse impacts on lakes, rivers and coasts could be profound.

Failure to reduce phosphorus pollution is driving environmental and socio-economic impacts [16]. Climate change is increasing the severity of algal blooms [11••]. Concurrently, phosphorus enrichment of lakes contributes to greenhouse gas emissions [17]. To mitigate anthropogenic losses of phosphorus to waters globally has been estimated at $265 billion annually [10]. Currently, society bears the economic costs of eutrophication through degradation of ecosystem services essential for progress.

The susceptibility of people and the environment to harm from phosphorus scarcity and pollution has been termed ‘phosphorus vulnerability’ and encompasses exposure to price spikes, sensitivity to harm and adaptive capacity [6••]. The recent spikes in phosphorus prices heightened global concern over phosphorus vulnerability and its impact on food security, particularly in less economically developed countries [3,4]. Meanwhile, the ongoing threat to water quality remains a significant global issue [11••]. The lack of focus on phosphorus vulnerability in national and global policies is therefore alarming [18].

Although some countries are beginning to shape policies to address their phosphorus vulnerability, efforts are geographically limited and often partial in scope. For example, while Switzerland mandates phosphorus recovery from sewage sludge by 2026, and Germany requires incineration ash to be stored for nutrient recovery by 2029, with landfilling only allowed after phosphorus extraction [19], neither country requires farmers to apply the recovered phosphorus products. The UK Phosphorus Transformation Strategy [20•] proposes an integrated phosphorus management approach across the entire supply chain, but its recommendations have yet to be legislated.

Avoiding and capturing phosphorus losses before they cause environmental harm and recycling them back into agricultural production to reduce dependence on phosphate rock is a ‘win–win’ strategy to reduce national phosphorus vulnerability [21••,22•]. This approach is pivotal for advancing towards a circular economy, where economic growth is not tied to finite resource consumption [23]. In the following sections, we discuss four integrated actions (Figure 1) necessary to progress towards a circular economy for phosphorus.

Mapping national and international phosphorus flows

Identifying phosphorus losses at the local to national scale involves data collection on phosphorus inputs and outputs, monitoring nutrient flows and identifying hotspots of phosphorus accumulation or loss. Such assessments have identified phosphorus recycling from residue streams as a key component in reducing national mineral phosphorus fertiliser requirements whilst increasing soil fertility in the United Kingdom [20•], Sweden [24], the European Union (EU) [25], India [26], Pakistan [27], the USA [28], China [29] and globally [30]. Techniques such as material flow analysis and life cycle assessment can quantify phosphorus flows at multiple levels, which can be linked via spatially explicit maps, helping to identify key sources of wastage, areas of recoverable phosphorus and areas of high pollution, thus facilitating targeted recovery and recycling initiatives. This process identifies key stakeholders who need to be engaged and supported to ensure necessary actions and collaboration. However, the role of international trade on global phosphorus

Figure 1

Identify phosphorus loss sources and map nutrient flows to pinpoint wastage and recovery opportunities and key stakeholders, enabling targeted recycling efforts and to establish national phosphorus budgets.

Identify phosphorus recycling sites and requirements for infrastructure to boost recycling, through sector collaboration, landscape planning and investment in technology. Operationalize effective supply chains of organic residues/wastes for phosphorus recovery and production of recycled phosphorus materials.

Assess national phosphorus vulnerability to prioritize regional and local actions, following a comprehensive framework that examines risks related to food security, water quality, and societal impacts.

Improve coordination between actors to develop coherent, holistic policies that support a circular economy for phosphorus and to optimise co-benefits. In some cases mandatory requirements for phosphorus recycling and better enforcement of existing policies wil be requried. Clear communication of scientific evidence to stakeholders and government bodies is essential to elicit support. In the short term, subsidies and tax incentives may be required to encourage stakeholders to recycle phosphorus.

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Four integrated actions for advancing a circular phosphorus economy. Though defined individually, these actions overlap significantly and are implemented iteratively, with each action reinforcing or driving others. For instance, mapping phosphorus flows and identifying recycling sites can inform national vulnerability assessments and policy development, while policies requiring such assessments can drive infrastructure and supply chain improvements for better recycling.

demand and local phosphorus footprints remains unclear [22•,31], with increasing international trade in food and feed potentially limiting nutrient recycling in food systems [22•] and influencing dietary preferences in other countries. Mapping national and international phosphorus flows, including the establishment of 'national phosphorus budgets', is a key starting point for all countries because it identifies the major opportunities for investment and returns in nutrient recovery.

Globally, < 50% of the phosphorus in organic wastes/residues is recycled back into the food system [32••]. At ~16 Mt P per year, manure is the largest global source of phosphorus-rich organic material. Whilst ~70% of EU manures are recycled [25], in some other regions, manures are less effectively managed. In China, mitigating livestock-related pollutant discharges is a key issue for environmental sustainability, especially for waterbodies [33]. Similar issues exist in East and South-East Asia and South America [34]. Where manure is recycled, careful management is essential to ensure crops utilise phosphorus effectively and losses are minimised. Phosphorus losses from domestic and food processing residues (including aquaculture) and human excreta total ~11 Mt P per year globally, with < 20% being recycled [35]. Whilst in Europe and North America, ~50% of sewage sludge is processed for agricultural use, globally,

> 80% of wastewater is discharged untreated [36]. Abattoirs present an opportunity for nutrient recovery from high-phosphorus animal bones. In the EU, ~4 Mt of animal bone biomass is produced annually, mostly incinerated without phosphorus recovery [32••]. With 33 megacities worldwide and increasing urbanisation, phosphorus will be increasingly concentrated in urban areas. This poses pollution risks but also underutilised recycling opportunities within agri-urban food systems [37••]. Phosphorus losses also occur in industrial wastes, which are often overlooked for recovery, for example, from steelmaking [38].

However, recycling phosphorus-rich organic materials can be challenging. Phosphorus concentrations in organic materials vary, are hard to measure quickly and are lower than in mineral fertilisers, challenging farm-scale nutrient management [39]. The bioavailability of phosphorus in organic materials, influenced by soil type, pH and crop breed, affects their performance as fertilisers. The bulky nature of some organic materials can also complicate consistent application. Some organic materials may contain contaminants like pathogens, hormones, antibiotics, toxic elements and microplastics, necessitating treatment to reduce them to safe levels [40,41]. Processing phosphorus-rich organic materials, such as composting and vermicomposting, can improve their fertiliser qualities and reduce some contaminants [32••]. Minimising intake of toxic elements and unnecessary antibiotic use in livestock and humans reduces upstream contamination in manure and biosolids [42]. Developing systems to evaluate phosphorus content and bioavailability enhances farmers' ability to use them efficiently [43].

In some cases, substantial processing is needed to recover and detoxify organic wastes/residues to allow safe use and sufficient nutrient use efficiency [44]. Phosphorus recovery refers to the capture of phosphorus from organic by-products, such as isolating high-quality phosphorus through chemical extraction, while phosphorus recycling involves the use of this recovered phosphorus or organic materials from waste/residue streams to produce products suitable for any number of end uses, including agriculture. High-concentrated recovered phosphorus products include struvite ($NH_4MgPO_4{\bullet}6H_2O$), or materials like calcium phosphates can substitute for phosphate rock-derived phosphorus. This is useful when transporting bulky residues long distances to croplands is not feasible or contaminants persist despite treatment. Over 30 technologies exist for phosphorus recovery [45], with commercial processes mainly applied to sewage sludge and digestate (from anaerobic digestions) as well as to abattoir wastes, poultry litter, manure, food processing and industrial wastes [44].

Identifying phosphorus recycling sites, infrastructure and supply chains

Identifying phosphorus recycling sites guides infrastructure development, which in turn shapes future recycling opportunities, reinforcing a circular phosphorus economy. Identifying phosphorus recycling sites requires an assessment of soil phosphorus reserves, crop needs and soil acidity to optimise application rates for optimal yields [46,47]. Depending on the scale of infrastructure envisaged, planning may be at landscape or regional level. Such assessments should minimise losses by considering topography, erosion risk and proximity to water bodies to prevent runoff and eutrophication [11••]. Temporal and spatial separation between sites of phosphorus accumulation (livestock farms and cities) and phosphorus demand (croplands) means that phosphorus-rich organic materials must often be stored for long periods and/or transported long distances before use [48]. Where infrastructure is being planned for agricultural use of recovered phosphorus resources, it is essential to understand farmers' capacities to utilise recycled phosphorus and ensure the necessary infrastructure for transportation and storage.

Landscape planning to integrate arable and livestock farming can enhance nutrient recycling potential [49], minimising the need for long-distance transport of recovered nutrients. Such localisation strategies can also support habitat diversity and increase the adaptability of farming systems to cope with socio-economic and climate change–induced shocks [50]. To maintain sustainable animal production systems, livestock densities should match local crop nutrient needs [47]. When these needs are exceeded, options for manure recycling further away should be explored [51]. In some regions, concentrated animal feeding operations (CAFOs) and intensively managed housed livestock often depend on contractual manure export agreements [52]. In areas where livestock seriously impairs water quality, reducing livestock numbers may be necessary, requiring support for diversifying outputs [53]. Arable-livestock partnerships can support manure recycling [54]. For example, some organic farmers rely on collaborative partnerships for feed and manure exchange, enhancing adaptability amid tightening regulations [55].

In areas with dense human, animal and cropland populations, significant phosphorus flows converge, making them hotspots for recycling opportunities [56•]. However, local challenges, identified through consultation with key stakeholders, must be addressed. These may include ensuring the compatibility of recycled phosphorus fertilisers with existing agricultural machinery to understanding local soil types and their influence on the phosphorus bioavailability of recycled products [32••]. Recovered phosphorus in a sufficiently concentrated form can be transported over longer distances (> 1000 km) if local conditions are unsuitable for immediate use. This approach could help redistribute nutrients to food-insecure regions, enhancing food security and mitigating environmental degradation, financed by trading accumulated rights to foster innovations in processing, logistics and equitable resource management [57•]. Here, collaboration is needed across multiple sectors, from national to international scales involving producers of phosphorus residues, users of recycled products and industries that handle storage, transport, processing and conversion of phosphorus-rich residues [44]. Beyond the requirement of necessary infrastructure, there is a need to operationalise effective supply chains of organic residues/wastes for phosphorus recovery and of the enhanced phosphorus materials produced. In particular, a stable demand for cost-effective recovered phosphorus products is needed in order to mobilise investment in upscaling phosphorus and other nutrient recovery processes. This can strengthen the case to invest in recovery from large-scale nutrient sources (e.g. sewage treatment plants, CAFOs) and mobilise a wider transition to phosphorus circularity.

The investment in infrastructure and technologies to make phosphorus recycling easy and efficient [21••,22•] must be balanced against the economic gains. Recycling phosphorus-rich organic wastes can provide economic value through greater crop yields and reduced mineral phosphorus fertiliser costs, which can be used to support changes directed through policy and regulation [32••,44]. Selecting methods that produce co-benefits, such as biogas production and co-recovery of nitrogen and potassium, maximises this value. Longer-term benefits for farmers include resilience to fertiliser cost fluctuations and improved soil health [8••,21••].

Assessing national phosphorus vulnerability

Assessing national phosphorus vulnerability is an essential component in identifying priority actions regionally and locally and involves a comprehensive framework to examine sensitivity and adaptive capacity to various risks associated with phosphorus dependence, encompassing food security, water quality and societal impacts [6••,8••]. The UK Phosphorus Transformation Strategy [20•] exemplifies this approach, developed through collaboration with diverse stakeholders across the food value chain. Together, they created a shared vision for sustainable phosphorus management set within national contexts. The final step was co-developing pathways to transition from the current state to the envisioned future through a collaborative workshop.

Food security risks are tied to reliance on phosphorus imports, with the potential for source diversification to help mitigate some of these risks. This depends on national phosphorus stocks in agricultural soils, fertiliser stockpiles and phosphate rock reserves [8,21••]. Farmers' ability to afford and efficiently use phosphorus fertilisers as well as adopt low-phosphorus farming methods are also critical factors [47]. Water quality risks depend on the ability of water bodies to absorb phosphorus loads, considering potential changes in land use, population growth and climate impacts, including severe weather and internal phosphorus loading in lakes [11••]. Societal risks involve impacts on citizens' health and income from algal blooms and phosphorus price spikes [7••,11••]. Those relying on affected water bodies for drinking water, aquatic foods, or livelihoods in aquaculture or eco-tourism are especially vulnerable [58]. Globally, smallholder farmers in Africa are at the greatest risk from elevated fertiliser prices, which could lead to yield losses due to unaffordable phosphorus fertilisers [5].

An economic assessment is essential for comparing the costs of action versus inaction, covering potential losses in ecosystem services such as food security, property values, tourism and food production [59•]. Evaluating the cost–benefit relationships of strategies like selling recycled fertilisers and producing bioenergy can identify income streams that offset initial costs and enhance the viability of implementation [44].

Developing policy frameworks and financial mechanisms

Improved co-ordination between relevant government bodies and actors is required to develop coherent, holistic policies and create markets for recovered phosphorus fertiliser [40]. Most regions could develop mandatory requirements for phosphorus recycling and, where present, better enforce relevant existing policies [60]. Policies and standards for agricultural practices should reflect accurate knowledge of the risks associated with using biosolid fertilisers, avoiding unnecessary barriers when there is negligible threat to health. For example, some farmers avoid fertilisers derived from human excreta because of strict certification standards such as the Global Food Safety Initiative's GlobalG.A.P. (Good Agricultural Practices), which are crucial to meet export requirements for many farmers in low-income countries [61]. Although not globally mandated, these standards can influence phosphorus recycling practices and impact financially constrained smallholder farmers [61]. This points to the need for engagement with such frameworks to ensure that they provide opportunities to enable rather than block the transition to a circular phosphorus economy.

Clear communication of scientific evidence to stakeholders and government bodies is essential to elicit a supportive response to sustainable phosphorus strategies, which often need to be retrofitted into existing policies and legislation. For example, in Chile, the Lake Villarica Decontamination Plan, supported by the Global Environment Facility/United Nations Environment Programme uPcycle project (www.upcyclelakes.org/), is developing tools to address phosphorus pollution. Here, public consultation continues to be crucial in securing the support needed to integrate actions into existing policy and legislation.

In the short term, subsidies and tax incentives may likely be required to encourage stakeholders to recycle phosphorus from waste streams [60], especially to stimulate increased innovation towards ultimate profitability of phosphorus recovery. In some regions, this could be extended to financial credit to cover capital costs for recycling equipment. Especially in low-income countries, significant investment is required in infrastructure and technologies to make phosphorus recycling efficient and cost-effective (e.g. communal manure storage facilities, better systems and access roads to transport phosphorus-rich organic materials to croplands). Additionally, opportunities to retrofit existing infrastructure, such as wastewater treatment facilities, to handle multiple residue sources (e.g. aquaculture wastewater) and support nutrient recovery should be identified. Whilst the type and level of support needed will vary between sector and region, actors should be supported to implement the changes needed without significant hardship and ideally with economic/production gains. Further efforts are needed to develop business cases for why different financiers should invest. For example, stakeholders targeting international development banks may wish to emphasise the value of avoided environmental harm, while those targeting business investors may emphasise the need to invest in approaches that can ultimately pay for themselves. To achieve this, practical strategies may need to link all the co-benefits of actions, including the value of nutrient recovery (phosphorus, nitrogen, potassium, micronutrients) as well as of water and energy recovery.

While we have outlined a framework for assessing phosphorus vulnerability, tangible financial mechanisms for enabling this are essential. Drawing on tools and approaches from the Green Finance sector, such as sustainable agriculture investments and disclosure practices [62], could drive investments toward building a sustainable phosphorus economy. Additionally, conducting an economic assessment of phosphorus-related risks, as seen in nature-related risk frameworks [59•], is crucial for identifying opportunities that align with green economic growth.

Way forward: towards a circular phosphorus economy

Conducting national phosphorus vulnerability assessments will help identify priority actions and tailor policies for actors. However, a major challenge remains in mobilising capital investment, resources and policy support for transitioning to a circular phosphorus economy. Here, a comprehensive financial assessment is imperative that can address the economic dimensions of phosphorus security. This assessment should elucidate the benefits and return on investment, supporting governments in integrating the transition into broader initiatives like the EU Green Deal and the EU's Nature Restoration Law. The economic benefits must be clearly laid out and embedded within green economic growth plans, such as the EU Green Deal and the EU's Nature Restoration Law.

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CRediT authorship contribution statement

W.J.B. conceived the idea of the paper and led the writing of the publication. P.A., D.C. M.M. G.S.M. M.A.S. and B.M.S. contributed to writing the paper.

Data Availability

No data were used for the research described in the article.

Declaration of Competing Interest

The authors declare no competing interests.

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