UK Phosphorus Transformation Strategy

Towards a circular UK food system

a 2022 RePhoKUs report

About this Report

This report sets out the UK's first comprehensive national phosphorus transformation strategy, based on extensive stakeholder consultation across the UK food system, in addition to economic modelling and biophysical analyses. Unless otherwise referenced, the material in this Strategy is based on synthesised stakeholder views. The development of the report included stakeholders from England, Scotland, Wales and Northern Ireland. Key informant interviews, an online interactive survey and a virtual workshop were conducted between September 2019 and September 2021 (see Appendix A for participating sectors). This Strategy forms part of a larger, 3-year, UKRI-funded research effort, the RePhoKUs project.

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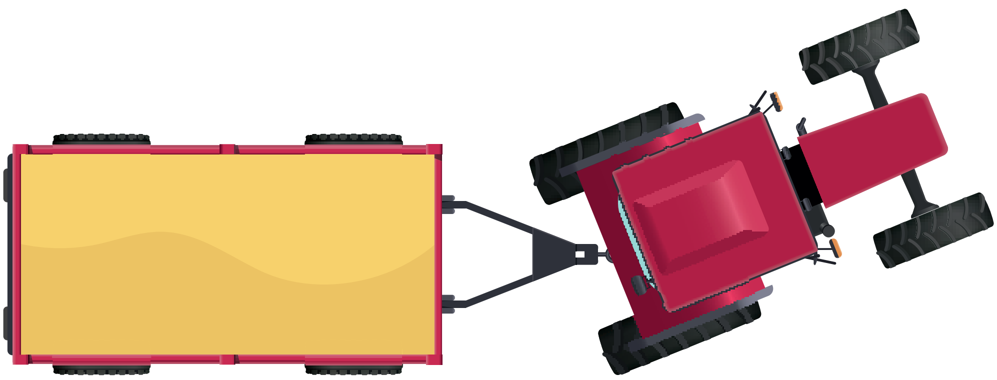
About the RePhoKUs project

The RePhoKUs project, funded under the UK's Global Food Security research programme, was established in 2018 to better understand the critical role phosphorus plays in the UK food system, and the possible changes needed to enhance its environmental sustainability and resilience to future shocks. Our interdisciplinary research team has investigated biophysical and socio-economic factors at the farm, catchment and national scales, including a detailed analysis of the complex flows of phosphorus in our food systems and all its sectors, the need to address regional phosphorus imbalances, links to water pollution, potential staple food price fluctuations, and UK-wide cross-sector action. While farmers are the main end-users of phosphorus, in a circular economy, the whole phosphorus value chain plays a critical role, including water utilities, food processers and retailers, consumers, waste managers, regulators and policy makers.

The RePhoKUs team includes researchers from: Lancaster University, University of Leeds, AFBI, CEH and the University of Technology Sydney.

The project was funded by UKRI, previously the UK's Biotechnology and Biological Science Research Council (BBSRC), the Economic and Social Research Council (ESRC), the Natural Environment Research Council (NERC), and,the Scottish Government.

Contents



Summary

The UK's food system is in transition, driven in part by major changes to agricultural policy. It is also under pressure from climate change, land use change, Brexit uncertainties, and unforeseen shocks like COVID-19. However one critical challenge that has not been sufficiently addressed is the secure supply and sustainable use of phosphorus. Phosphorus is a lynchpin of the food system and has no substitute. Yet its mismanagement has led to serious risks of compromising future food and water security in the UK and globally. The UK food system is facing five key phosphorus challenges:

1. inefficient phosphorus use
2. regional phosphorus imbalances
3. legacy phosphorus in soils
4. dependence on phosphate imports
5. risks of phosphate supply disruption and price spikes

The UK is almost entirely dependent on imported phosphorus in fertilisers and animal feed. Phosphorus imports rely on finite phosphate rock reserves from countries like Russia, China and Morocco. The market concentration in these countries has contributed to serious price spikes and supply disruptions[1]. While there is already enough phosphorus theoretically circulating in the UK, the current linear use and fragmented governance has led to serious water pollution, trade security risks and regional imbalances that are costly and inefficient. While the UK's fertiliser use has decreased over the past few decades, in part due to more efficient farming practices and nutrient recovery, phosphorus continues to be a major cause of widespread pollution of the majority of UK's rivers and lakes. This is contributing to the destruction of aquatic habitat, biodiversity, and the loss of recreational value of nature. Phosphorus is unevenly distributed across the UK with high concentrations where livestock production is intensive, food waste is concentrated and wastewater treatment plants service urban populations. Whereas arable cropping areas need to import phosphorus to support food production. Despite these challenges, the UK does not have a coherent plan for managing phosphorus across the food system, regionally and within catchments.

The good news is there are many pockets of innovation and initiatives already under way in different sectors in the UK. These can be learned from, scaled-up and integrated to help overcome some of the challenges associated with phosphorus use. However, all key actors need to play a role, and there is a significant need for integration across value chain sectors, scales, catchments, and government departments, in addition to the need for innovation, to transition towards more sustainable phosphorus use in the food system.

This report sets out the UK's first comprehensive National Phosphorus Transformation Strategy, based on extensive stakeholder consultation across the UK food system[2]. The Strategy identifies a suite of strategic pathways to transition from the current unsustainable situation, to a desirable future, framed by a transformation model (figure 1). A synthesis of the current situation of phosphorus vulnerability (Section 2) was developed from RePhoKUs primary research, including desktop analyses, laboratory trials, economic modelling, and from analysis of stakeholder views sought via in-depth interviews and an online interactive engagement platform. The future shared vision (Section 3) was developed via stakeholder responses to the interactive engagement platform, in addition to universal attributes from other European and North American phosphorus transformation models. Finally, the set of pathways was developed directly with stakeholders during a participatory stakeholder workshop.

[1] At the time of writing, phosphate fertiliser prices have spiked 400% since early 2020. Fertiliser markets have been significantly disrupted due to COVID-19 and the Russia-Ukraine war www.bbc.com/news/business-60623941. World Bank (2022) SPECIAL FOCUS: Impact of the War in Ukraine on Commodity Markets, April 2022. openknowledge.worldbank.org/bitstream/handle/10986/37223/CMO-April-2022-special-focus.pdf

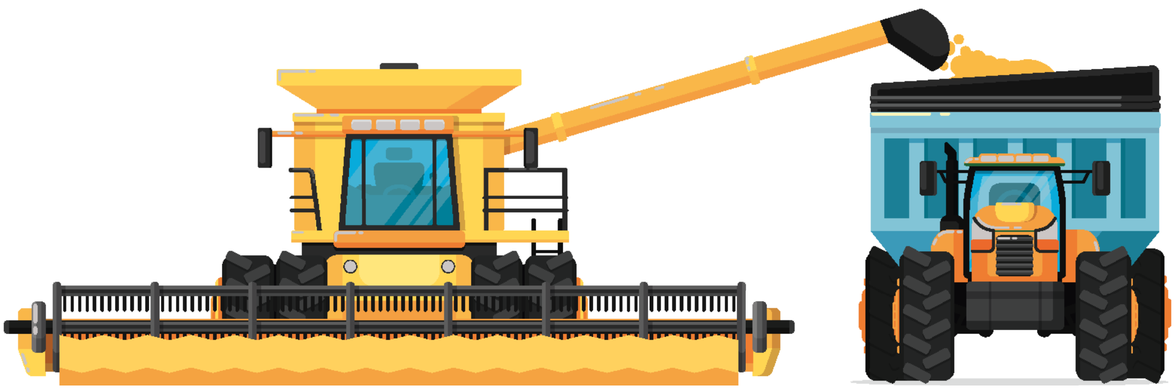
[2] See Appendix A for details of stakeholder engagement processes and participants.

The priority pathways collectively identified by stakeholders include:

- **Technology & innovation**: Develop, promote and apply innovative, scalable and cost-effective technologies for recovery of phosphorus streams, redistribution (especially animal manures), and reuse as viable renewable fertilisers.
- **Policy and governance**: Recognise phosphorus as a scarce resource and map existing policies to ensure coherence with promotion of a UK circular economy, consistent planning across regions/scales, and alignment with public visioning of the benefits of phosphorus reuse.
- **Knowledge & research**: Augment tailored nutrient management advice to the agriculture sector on effective use of recycled phosphorus sources (soil legacy, animal manures, food waste, biosolids) in UK farming systems.
- **Markets & incentives**: Provide incentives to encourage investment in technology, lower barriers to entry, and, develop markets for a viable organic phosphorus fertiliser sector that integrates other aspects of the circular economy (nitrogen, carbon) to reduce the burden of action on farmers.
- **Community, engagement and awareness**: Engage a broader range of stakeholders in setting the direction of and progress towards catchment phosphorus targets, that allow for local diversity in circular economy development pathways and demonstrate outcomes for public health and well-being (environment, society and economy).
- **Integration, connections and networks**: Establish a UK nutrient platform and a 'catchments as living labs' concept linked to information dashboards to drive data sharing among stakeholders, public engagement and cross-scale accountability for phosphorus management (imports, exports, recycling).

The next step would be for this Strategy to inform the co-development of sector-specific action plans and targets, with key stakeholders. Such action plans should: be aligned with existing sustainability initiatives; and, define each sector's current role with respect to phosphorus and potential contribution to the transition pathways in the short- and long-term. Importantly, these sector action plans should also formulate measurable indicators at regional and UK scales.

Ambitious targets at national and catchment scales also need to be defined, that support the transition pathways. Stakeholders could consider targets such as: proportion of phosphorus recovered from manures and other wastes and productively reused in agriculture; attainment of zero phosphorus surplus at farm and catchment scale; and the proportion of phosphorus obtained from domestic sources versus imports. The development of evidenced-based targets could be formulated through the establishment of a multi-stakeholder UK nutrient platform.



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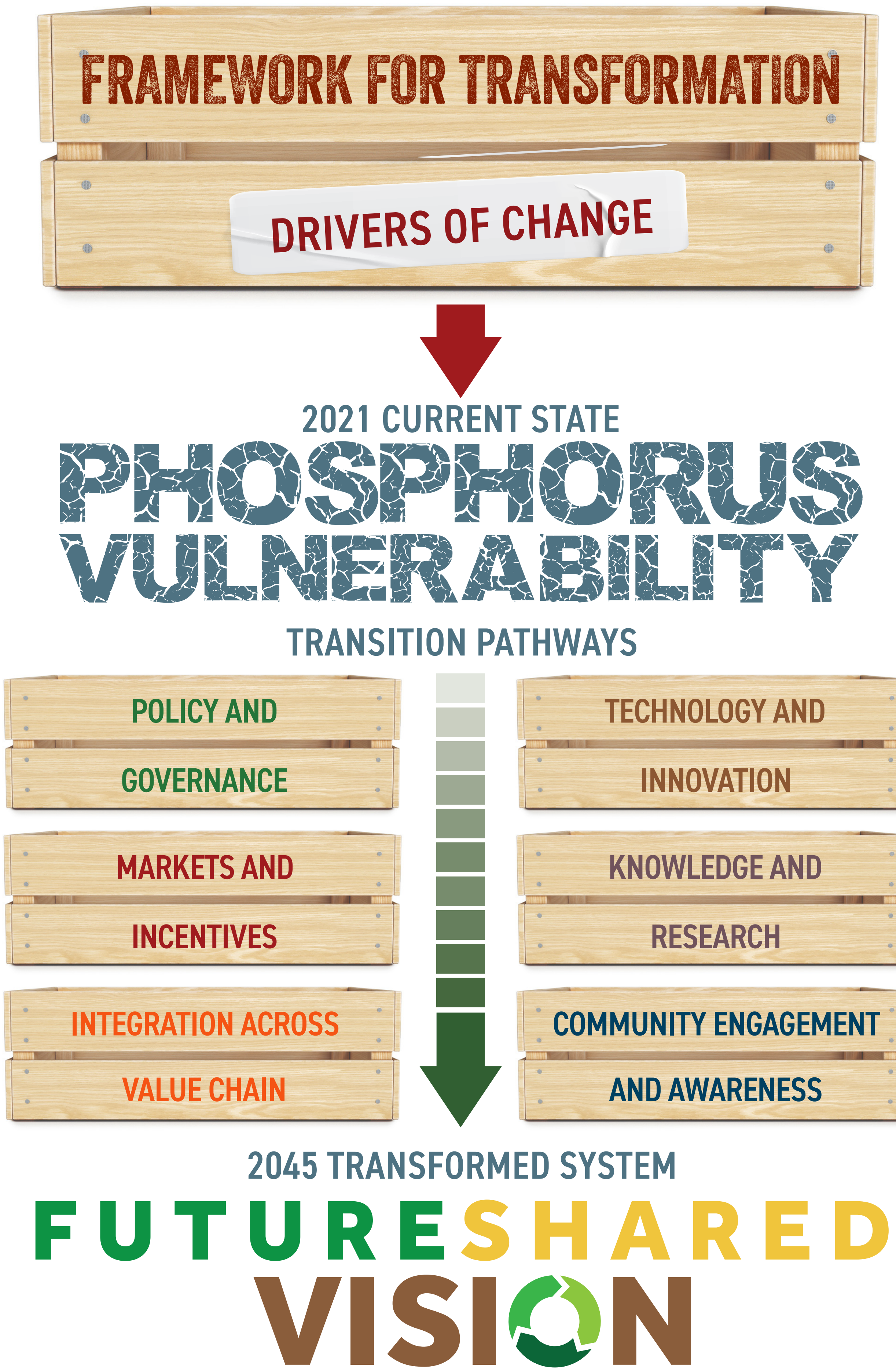


Figure 1: A framework for transformation: Pathways to transition phosphorus in the UK's food system from risky and inefficient to sustainable, circular and resilient.

1 The need for a national phosphorus strategy?

1.1 Why phosphorus

We cannot grow food without phosphorus. The UK theoretically has enough phosphorus already circulating in the food system, yet is currently dependent on imported non-renewable phosphate in fertiliser and animal feed to produce food. In addition, major phosphate price spikes in the past have impacted these imports making it costlier for farmers to use and food more expensive. Future disruptions to phosphate supply and price spikes are likely – indeed, phosphate fertiliser prices increased four-fold between 2020 and 2022 due to the COVID-19 outbreak and rising energy prices, leading the major phosphate producing countries Russia and China to impose restrictions on their phosphate exports to safeguard their domestic food security[3]. At the same time, inefficient farm-to-fork flows of phosphorus also result in major losses and pollution. Up to three-quarters of our rivers and lakes fail to meet water regulations - phosphorus is a main cause of failure.

Despite this, the UK does not have a coherent plan for managing phosphorus across the food system, regionally and within catchments[4].

1.2 The phosphorus value chain

Phosphorus plays many different roles in society and is therefore perceived differently by various stakeholders. Phosphorus is a globally traded commodity to fertiliser supply chain actors, a key farm input to farmers and agronomists, a macronutrient to human nutritionists[5], a key water indicator to wastewater companies, and a nuisance environmental pollutant to many catchment managers[6].

Phosphorus largely flows linearly in a value chain that is embedded within the broader UK food system (figure 2). From foreign phosphate mining activities, it is processed in the fertiliser and feed sectors then distributed to the agriculture and livestock sectors for use on farms. Farm produce containing phosphorus is then harvested, processed and distributed to wholesalers and retailers for purchase by food consumers. Finally, phosphorus-containing by-products and waste that occur at each stage of the value chain and household wastes (such as manure, human excreta and food waste) are handled by farmers and waste managers (such as wastewater utilities). While productivity gains have been made across some sectors, including agriculture, on the whole inefficient recovery and recycling means most of this phosphorus ends up accumulating unused in our agricultural soils, or is lost to landfills or water bodies.

Yet there is a disconnection between the physical flow of phosphorus and the institutions governing it. While wastewater discharges to water bodies are regulated by government, and guidance on phosphorus fertiliser use is available for farmers, phosphorus is rarely an issue of focus for other sectors of the food system. For example, phosphorus is not directly managed by food retailers such as supermarkets, despite their activities and actions playing a crucial role in the flow of phosphorus in the UK (figure 5). The procurement decisions supermarkets make about their suppliers can, however, impact how sustainably phosphorus is managed on farms[7], or their food waste initiatives can reduce the avoidable loss of phosphorus contained in spoiled foods.

[3] World Bank, 2021. Soaring fertilizer prices add to inflationary pressures and food security concerns. https://blogs.worldbank.org/opendata/soaring-fertilizer-prices-add-inflationary-pressures-and-food-security-concerns

[4] Yuille, A., Rothwell, S., Blake, L., Forber, K.J., Marshall, R., Rhodes, R., Waterton, C., Withers, P.J.A. 2022. UK government policy and the transition to a circular nutrient economy. Sustainability 14, 3310. doi.org/10.3390/su14063310.

[5] While phosphorus is essential to human health and a building block of DNA, RNA and our bones, deficiencies are uncommon and hence it does not receive much attention by nutritionists and health professionals, compared to say calcium. lpi.oregonstate.edu/mic/minerals/phosphorus

[6] RePhoKUs evidence statement to the House of Commons Environmental Audit Committee on river water quality based on the Wye catchment

[7] It would be important that such downward pressure on farmers was reciprocated, for example by paying farmers a fair price relative to the cost of production.

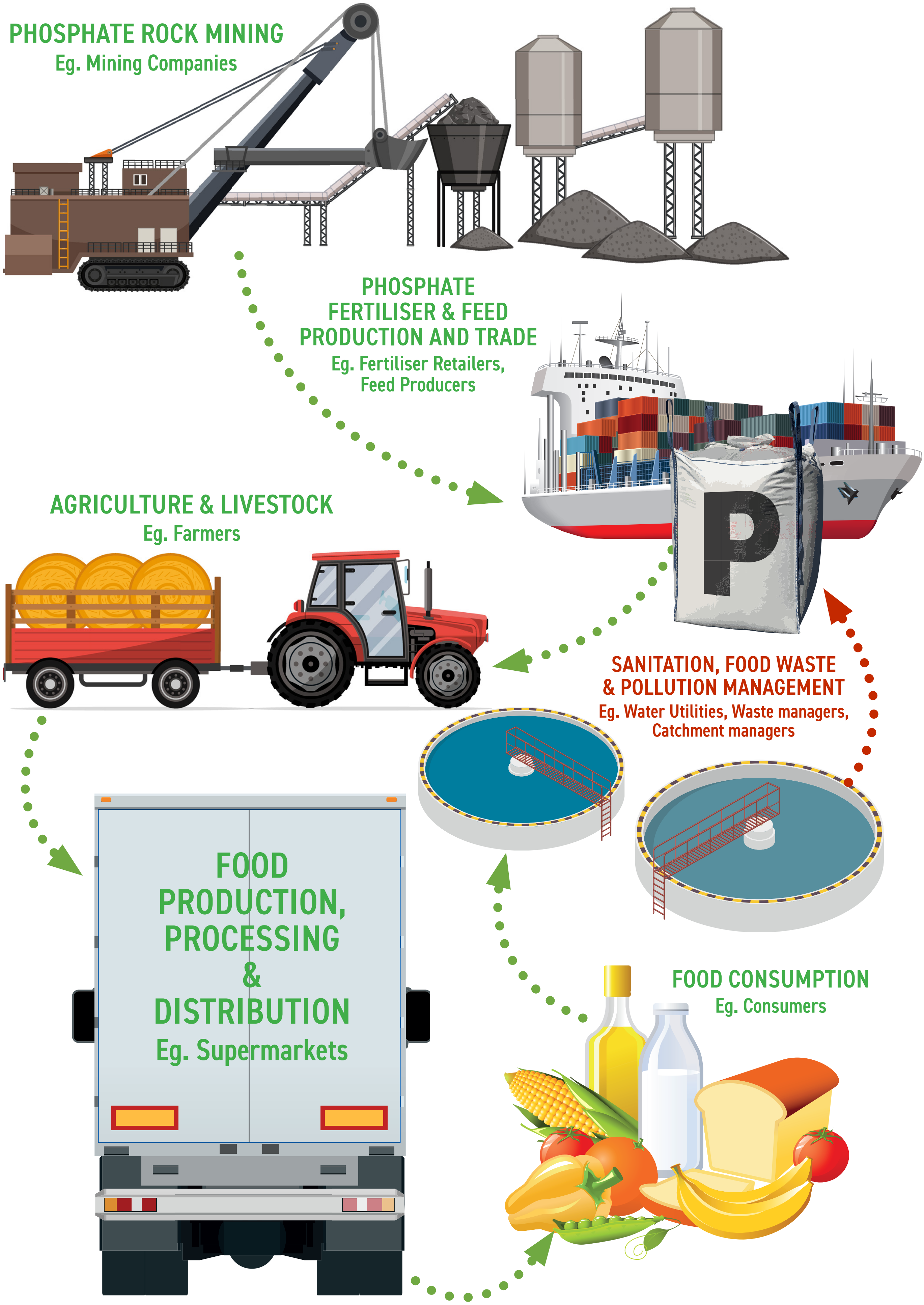


Figure 2: The phosphorus value chain embedded within the UK food system, indicating sector activities and actors.

1.3 The UK food system

The UK Food System is comprised of value chain activities (like producing, processing, retailing, consuming, and disposing), undertaken by a wide range of actors operating across multiple scales[8]. The food system activities and actors are supported by a diverse range of facilities, like transport and market infrastructure, financial services, trade, logistics and IT systems, and are governed by regulations, policies, laws, certifications, and norms across multiple sectors. In addition to food security and nutrition, these activities affect economic and social well-being, and environmental sustainability (figure 3).

The UK food supply chain represents 6.8% of gross value added (around £107 billion) and 4 million jobs with around 500,000 people in farming and fishing, and over 400,000 people in food manufacturing. Indeed, food and soft drinks is the UK's largest manufacturing sector. Despite having a highly successful agricultural industry, the UK is not self-sufficient in food production, importing 48% of the total food consumed, with this proportion rising. This means the UK relies on both imports and a thriving agriculture sector to feed itself and drive economic growth[9].

Many domestic and international factors can affect food production and prices for consumers in the UK[10]. According to the UK Parliament, shocks and stresses that threaten the food system include environmental change, public health crises and political disputes, with some of these threats increasing[11]. Phosphorus is one of those threats, because without reliable access to an affordable and secure future supply we cannot produce food, and its current mismanagement is leading to widespread pollution of the UK's rivers and lakes[12]. Transforming the way phosphorus is used in the UK food system is therefore essential to food and water security, and to maintain a clean healthy environment for generations to come, but it requires all sectors to come on board.

[8] Hasnain, S., Ingram, J. and Zurek, M. 2020. *Mapping the UK Food System – a report for the UKRI Transforming UK Food Systems Programme*. Environmental Change Institute, University of Oxford, Oxford. ISBN 978-1-874370-81-9

[9] Global Food Security 2020. UK Threat. The UK cross-government program on food security research www.foodsecurity.ac.uk/challenge/uk-threat

[10] The Parliamentary Office of Science and Technology, 2020. A resilient UK food system, POSTNOTE 626 June 2020. www.foodsystemresilienceuk.org/wp-content/uploads/POST-PN-0626.pdf

[11] Zurek, M., Hebinck, A., Leip, A., Vervoort, J., Kuiper, M., Garrone, M. et al. 2018. *Assessing sustainable food and nutrition security of the EU food system – an integrated approach*. Sustainability, 10 (11): 4271.

[12] UK Parliament, 2014. Phosphate Resources, POSTnote 22 August 2014, post.parliament.uk/research-briefings/post-pn-477

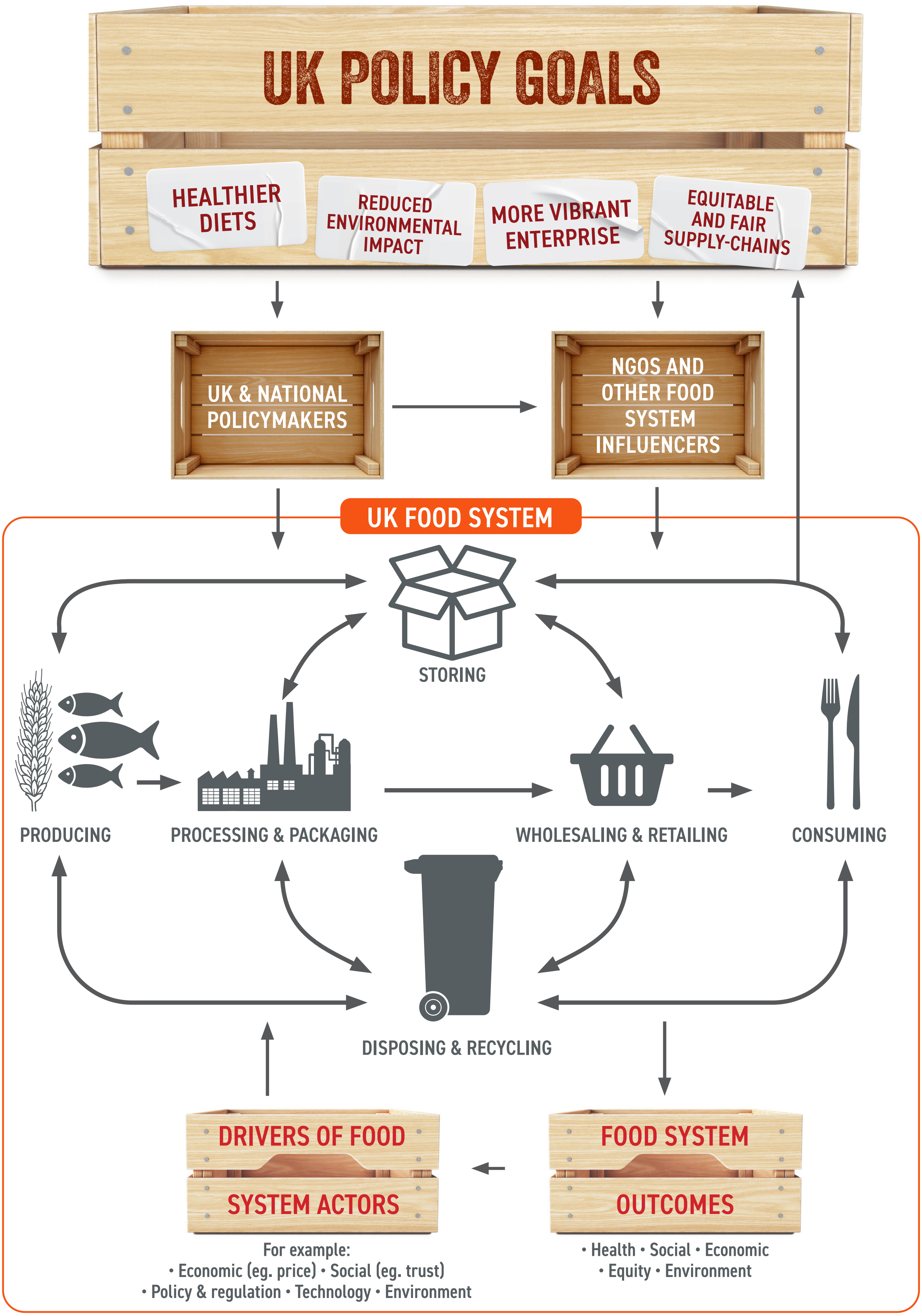


Figure 3: The UK Food system: activities, drivers, outcomes and policy influences (Hasnain et al 2020[8])

2 The current situation: Phosphorus vulnerability in the UK food system

2.1 Drivers of change: shocks and stresses

Five key interlinked phosphorus stresses and shocks are placing the UK food system in a vulnerable and unsustainable situation[13] (Table 1). These are in part a result of inadequate governance.

1. Inefficient use	Losses and waste throughout the value chain, from fertiliser production to agriculture to food waste, leading to water pollution
2. Regional imbalances	Excess phosphorus from livestock manures in the West of England and NI, while there is high phosphorus soil demand in cropping systems in other parts of the UK.
3. Legacy soil phosphorus	We know there's a tremendous amount of phosphorus in the 'soil bank' but how much, and how do we measure and/or access it?
4. Dependence on imports	UK imports all of its fertiliser and half of its feed – how reliable are these supply-chains?
5. Supply disruption & price spikes	Short and long-term disruptions have different consequences for farmers and the food value chain

Table 1: Five key interlinked phosphorus challenges for the UK

Aside from the challenges posed by phosphorus, the UK food system is facing a number of other issues. For example, post-Brexit uncertainties related to future import availability and price, and the availability and form of future agri-environment schemes to support the Agricultural Transition Plan[14]. The viability of food production is also under pressure from declining terms of trade, and an uncertain investment environment made worse by global politics. More recently COVID-19 has impacted supply chains including labour restrictions, sudden changes in demand for certain products like meat cuts, or shortages of chemicals required for processing food system waste. These issues have contributed to a general decline in human capital in food production as farmers that exit the industry take skills and knowledge that may not be replaced by new entrants.

Impacts of climate change in the UK range from local extreme events anticipated to affect domestic produce, specifically crop yield, to events that affect food importing countries, leading to fluctuations in product availability and price. Environmental issues, such as biodiversity loss, natural resource decline, loss of pollinators, and anti-microbial resistance are also of concern. These pressures are together posing challenges for the UK food system.

[13] These five stressors were identified through RePhoKUs research detailed below, including a phosphorus flow analysis, soil legacy phosphorus lab trials, economic modelling, in addition to extensive stakeholder engagement (see Appendix A).

[14] Namely through the so-called Environmental Land Management (ELMs) schemes in England and similar approaches in the devolved administrations (such as the Sustainable Farming Scheme in Wales).

2.1.1 Inefficient and linear phosphorus use

Fertiliser use in the UK has decreased over the past few decades[15], in part due to awareness of environmental impacts and industry-led initiatives[16]. Despite this progress, phosphorus use in the UK's food system remains one of the most inefficient value chains. Less than half of the 174,000 tonnes of phosphorus imported into the UK each year is productively used, that is, converted into 74,000 tonnes of phosphorus in food consumed domestically and exported in food and commodities (figure 4). Inefficiency results in significant avoidable costs to farmers, some of which may flow on to impact food prices. Phosphorus has been relatively cheap[17] and the costs of environmental pollution from inefficiency are generally not borne by phosphorus users. Phosphorus leakages from point sources like wastewater discharges and non-point sources like agriculture are the most common reason for English water bodies not achieving good ecological status under the Water Framework Directive (WFD). Water pollution can limit recreational uses of down-stream surface waters, affect human health, and place greater pressure on already stressed biodiversity and ecosystem functioning with the potential for local species extinction and ecosystem collapse[18].

While the UK national food system requires phosphorus to meet the demand for food production, theoretically, much of this could be met by what is already in the system, rather than relying on imports. Although manures, and to a lesser extent biosolids, are typically returned to land in the UK, this is often done inefficiently and applied to agricultural land above agronomic requirement, leading to soil phosphorus accumulation. Understanding the imports, movements, losses and exports of phosphorus is therefore a key first step towards more efficient and sustainable phosphorus management in the UK food system. The RePhoKUs project's phosphorus flow analysis identified three hotspot areas of phosphorus inefficiency and loss in the UK food system:

- phosphorus accumulation in agricultural soils (90 kt P yr) (this surplus contributes to legacy phosphorus)
- phosphorus loss to water bodies (26 kt P yr)
- phosphorus sent to landfill and construction (22 kt P yr)

The flows of phosphorus to water bodies may appear relatively small in the UK phosphorus flow analysis[19] (figure 5), however many rivers and lakes are sensitive to even small additions of the nutrient. The amount of phosphorus that leaks into rivers and lakes varies depending on soil phosphorus buffering capacity, erosion risk, how carefully fertilisers and manures are applied and the movement of water through the landscape[20]. In addition to rivers and lakes, phosphorus is also deposited in landfills, where much of the UK's food and other wastes are deposited, or ends up in construction aggregates.

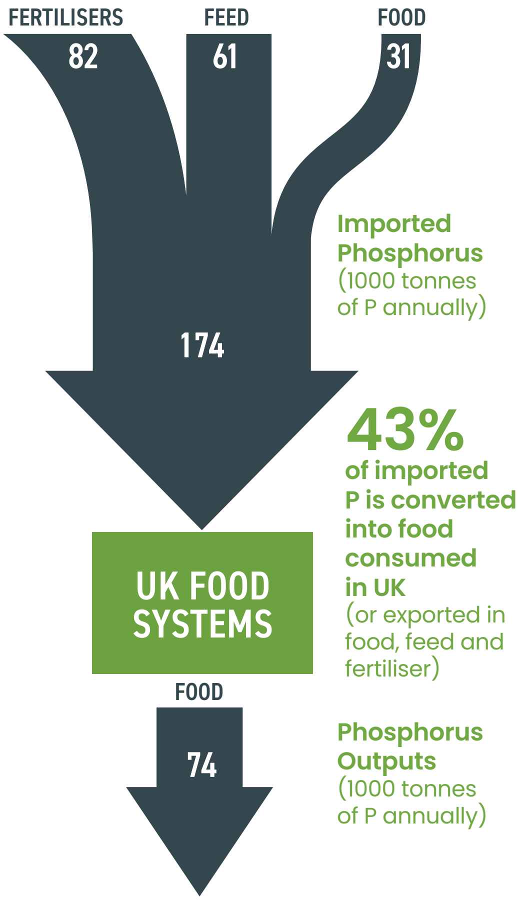


Figure 4: An inefficient phosphorus value chain (RePhoKUs 2021)

[15] AIC 2020, *Fertiliser use in Great Britain*, www.agindustries.org.uk/resource/fertiliser-use-in-great-britain.html

[16] Agricultural industry initiatives like Tried & Tested offer advice and tools to better nutrient management, alongside schemes like Catchment Sensitive Farming which provides farmers with advice and grants.

[17] However as at November 2021 prices had already doubled since the previous year. ahdb.org.uk/GB-fertiliser-prices

[18] Environment Agency, 2021. Phosphorus and freshwater eutrophication: challenges for the water environment. www.gov.uk/government/publications/phosphorus-challenges-for-the-water-environment

[19] Rothwell et al. 2022. *A new direction for tackling phosphorus inefficiency in the UK food system*, Journal of Environmental Management, Volume 314, 15 July 2022, doi.org/10.1016/j.jenvman.2022.115021. The results of RePhoKUs's UK food system P substance flow analysis (SFA) at national and regional scales highlights P use, efficiency and losses of different sectors of the food system and present examples of how P management could be improved.

[20] Withers, P.J.A. and Jarvie, H.P. 2008. *Delivery and cycling of phosphorus in UK rivers: implications for catchment management*. Science of the Total Environment 400, 379-395.

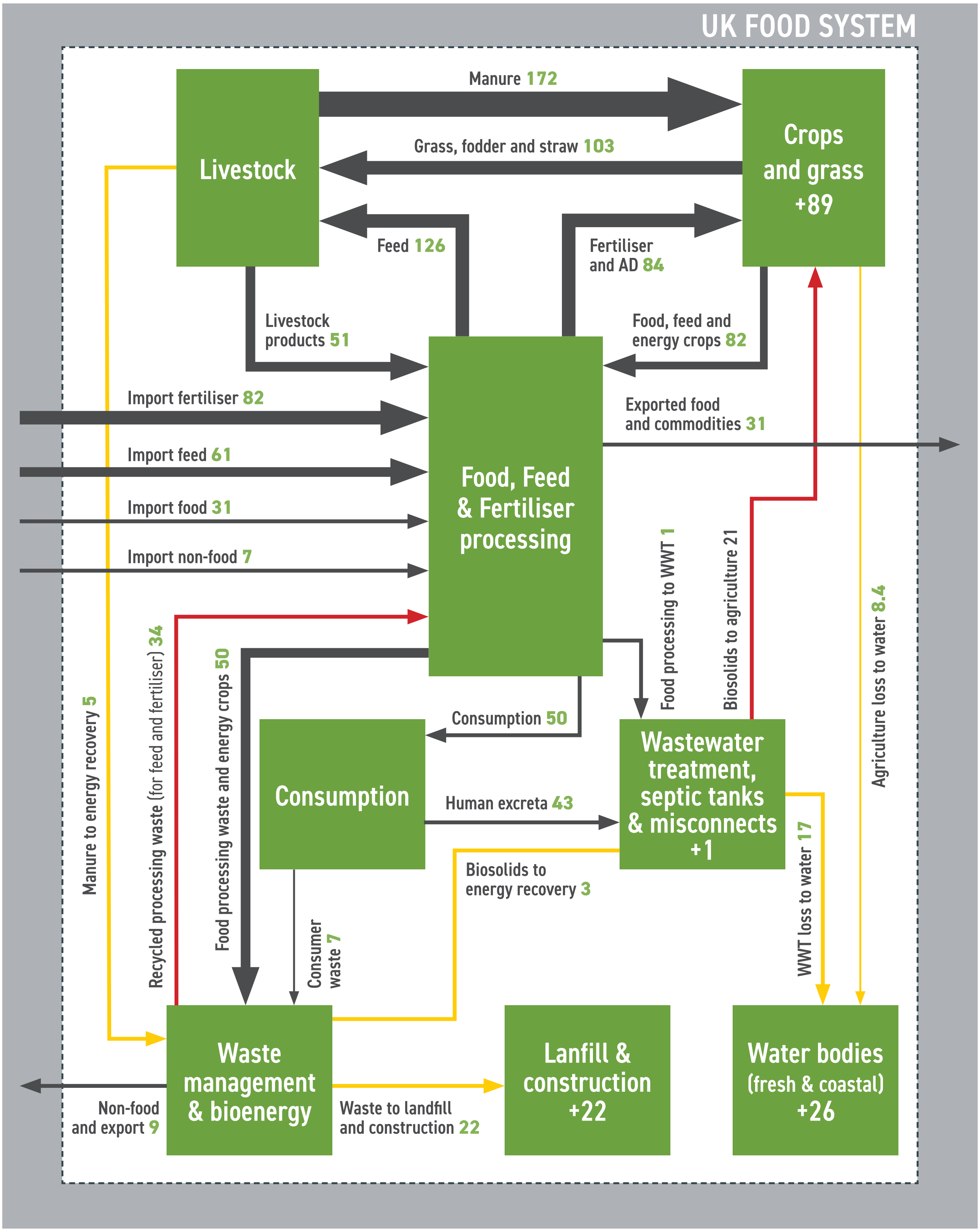
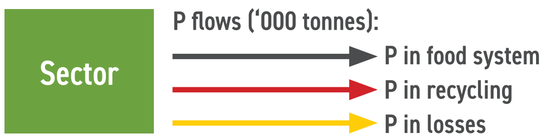


Figure 5: Phosphorus flows through the UK food system, indicating major trade of phosphorus in commodities/materials between sectors for the year 2018 in '000 tonnes of P[21]. The figure also indicates phosphorus losses, accumulation and recycling (RePhoKUs 2021).



[21] Note this is a simplified diagram only representing major and/or aggregated flows, hence not all flows are fully balanced. For the full analysis, including individual sector analysis, see: Rothwell et al. 2022. A new direction for tackling phosphorus inefficiency in the UK food system, Journal of Environmental Management, Volume 314, 15 July 2022, doi.org/10.1016/j.jenvman.2022.115021.

2.1.2 The UK has a regional phosphorus imbalance

Regionally, phosphorus efficiency of food production in the UK varies depending on the dominant form of agriculture. For example, England's North West is dominated by livestock agriculture (85% of agricultural land is pasture) and the Eastern region is dominated by crops (83% of agricultural land is arable). Soil phosphorus efficiency, that is, phosphorus applied as fertiliser and manure that actually ends up in the pasture or crop, is only 47% in the North West but is 110% in the Eastern region, meaning the crops there are taking up more phosphorus than is applied.

This creates an annual soil phosphorus surplus for the North West of around 14 kg/ha compared to a deficit of -3.2 kg/ha for the Eastern region (figure 6).

Surplus application of phosphorus not only increases the risk of environmental damage through losses to water but wastes a valuable resource. Excess phosphorus applied in England's North West alone is equivalent to nearly £30 million worth of triple super phosphate fertiliser[22].

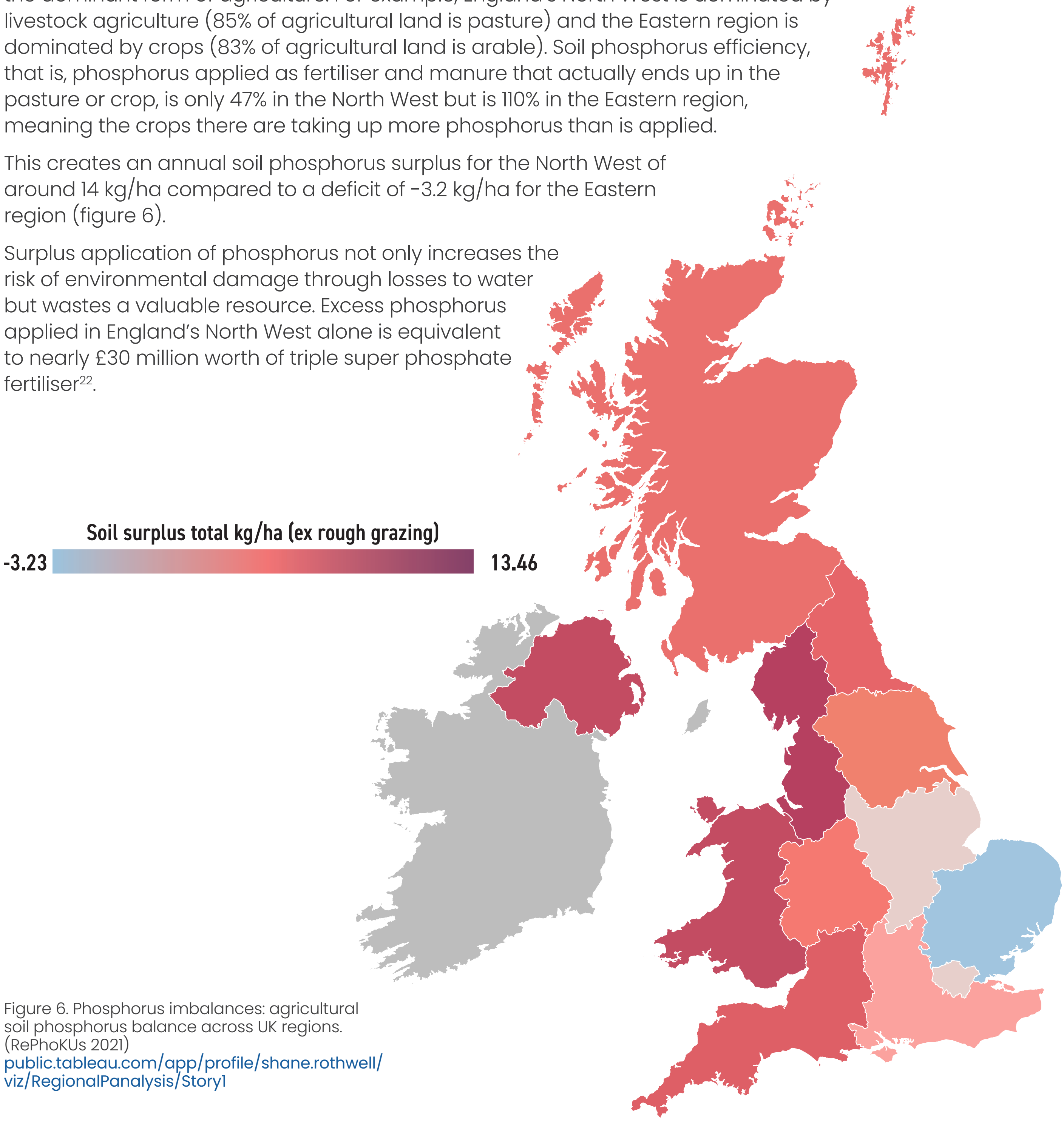


Figure 6. Phosphorus imbalances: agricultural soil phosphorus balance across UK regions. (RePhoKUs 2021) public.tableau.com/app/profile/shane.rothwell/viz/RegionalPanalysis/Story1

Within individual regions, estimates of the availability of secondary phosphorus sources (manures, biosolids and recycled food waste) that theoretically could replace demand for imported fertilisers suggest that the North West has nearly twice as much secondary phosphorus available than is required by its pastures and crops (184%). In contrast, the Eastern region could meet only 45% of its agricultural phosphorus demand from secondary sources[23]. A similar regional imbalance occurs in Scotland.

[22] Calculated using current TSP fertiliser prices (Oct 2021, £521/t) https://ahdb.org.UK/GB-fertiliser-prices and assuming 1 tonne of TSP contains 200 kg elemental P. The NW surplus of 11.4 KT P actually gives a TSP P equivalent value of £29.5M.

[23] Explore RePhoKUs interactive maps of the UK regional phosphorus balance by scrolling using the arrows to the side of the green boxes: https://public.tableau.com/app/profile/shane.rothwell/viz/RegionalPanalysis/Story1.

More intensive and specialised forms of agricultural production have focused on maximising regional comparative advantage to ensure commercial viability. This has led to a move away from more traditional forms of mixed farming systems that integrate crop and livestock production and are better positioned to balance nutrient supply and demand.

The logistics of storing and moving large volumes of bulky manure from one region to another are impractical. So, finding innovative and cost-effective ways to extract or relocate phosphorus in manure from livestock intensive areas like Northern Ireland and North West England to arable cropping areas, will be key to addressing regional imbalances. The potential for shifting livestock away from currently livestock-dense regions and reintroducing livestock into arable farming systems offers an alternative to inter-regional transport of phosphorus in some situations. However, because there is more phosphorus in livestock manures than the UK imports in fertilisers, the UK could also consider exporting recovered phosphorus, or producing fewer livestock[24].

Similarly, urban development patterns concentrate the levels of phosphorus collected in biosolids, with limited scope for local reuse, which can result in disposal to landfill.

2.1.3 Legacy phosphorus locked in soils

Many farm soils contain large amounts of phosphorus, 'the phosphorus bank', that have built up over decades from repeated fertiliser and manure applications to crops and pastures and pose a significant risk to aquatic ecosystems[25]. The amount of this phosphorus legacy in the 'bank' is many times greater than the amount we measure in soil tests as available to plants and which is used to determine fertiliser applications. The phosphorus bank represents billions of pounds of phosphorus locked-up in UK topsoil. Knowing how to access and manage that phosphorus in agriculture is central to improving efficiency. New research by the RePhoKUs team has shed light on the potential magnitude of this phosphorus bank in their study catchments , and hence how it might be unlocked to save on farm inputs, costs and reduce water pollution risk from nutrient runoff.

Legacy phosphorus is potentially available to plants in significant amounts under controlled conditions, however the means to access this stored phosphorus is not readily available. How UK farmers can practically tap this phosphorus in agricultural production to save on farm inputs, costs and reduce water pollution risks from catchment[26] runoff needs further investigation. Promising research suggests that inoculating plant root zones with microbes (such as mycorrhizae fungi) and breeding plant varieties that can better tap into soil phosphorus reserves may help unlock legacy phosphorus[27].

[24] The socio-economic implications for farmers of reducing livestock numbers would need to be addressed.

[25] Since the 1930's when P use became more widespread, over 1 tonne of legacy P has accumulated in every hectare of arable and productive grassland in the UK (Withers, P.J.A., Edwards, A.C. and Foy, R.H. 2001. *Phosphorus cycling in UK agriculture and implications for phosphorus loss from soil*. Soil Use and Management 17, 139-149).

[26] In some soils collected from farmer's fields across the Upper Bann, Welland and Wye catchments, plants removed the equivalent of up to 15 years of grass growth (at 7t/ha/yr) or 8 years of winter wheat crops (at 10t/ha/yr grain) before signs of phosphorus deficiency appeared. These lab trials indicate how plants can access the phosphorus bank in soils.

[27] Vengavasi, K., Pandey, R., Soumya, P. R., Hawkesford, M. J., & Siddique, K. H. 2021. *Below-ground physiological processes enhancing phosphorus acquisition in plants*. Plant Physiology Reports, 1-14; Powell, C. L., & Bagyaraj, D. J. (2018). *VA mycorrhizae: why all the interest?* (pp. 1-3). CRC press.

2.1.4 Dependence on phosphorus imports

The UK does not have mineral phosphorus resources. Much of the phosphorus in food consumed in the UK is thought to originate in Russian and other foreign mines[28]. But how much is available, and how secure and sustainable these supply chains are into the future is uncertain. Indeed, in late 2021 Russia imposed export quotas on its phosphate rock[29]. Further, the UK imports around half of all its phosphorus in feed for livestock.

This dependence on imports makes the UK food system vulnerable to supply disruptions, as has been seen in recent months because of Brexit and COVID-19, and previously, in 2008, with a 800% phosphate price spike[30]. The 2022 war in Ukraine has brought this UK vulnerability even more into focus. According to UK food system stakeholders, the potential negative consequences of a phosphate disruption are spread across almost all sectors (table 2). Potential positive impacts can be harnessed through planned transitions, to avoid negative impacts. One way to reduce food system vulnerability is by applying the principles of 'circular economy' to phosphorus in the UK.

Sector	Positive impact	Negative impact
Fertiliser & nutrient products	N/A	✘ Reduced supply capacity to produce fertilisers and meet market demand ✘ Reduced market size and production efficiency
Agriculture	✔ Increased farmer interest in nutrient management advice ✔ Reduced reliance on imported phosphorus ✔ Reduced phosphorus use ✔ Rethinking farming methods ✔ Global commodity prices could mitigate higher phosphate prices, e.g. Grain prices in 2008	✘ Possible reduced availability of fertilisers and price impact ✘ Possible impact on yields and reduced productivity due to reduced fertiliser use ✘ Financial survival for some farming businesses – could threaten viability of agricultural production in an already challenging time ✘ Specialisation makes it hard to adapt and use alternative phosphorus sources, where sludge reuse may not be permitted for example
Livestock	✔ Increased dependence on manures (subject to overcoming restrictions)	✘ Reduced feed production ✘ Possible impact on animal health and fertility due to reduced feed used ✘ Reduced milk production
Environment	✔ Reduced nutrient losses to the environment, hence improved ecosystems	N/A
Water & wastewater	✔ Reduced wastewater processing costs ✔ Improved water quality	✘ Potential increase of lead leaching from wastewater pipes (if utilities can't access orthophosphate)

Table 2: Potential consequences of a disruption to phosphorus supplies

[28] There are only a few phosphate rock producing countries in the world, including Morocco, China, US, Syria and Egypt. Most countries – and almost all of Europe – are currently dependent on imported phosphate (HCSS (2012) *'Risks and opportunities in the global phosphate rock market'*, Hague Centre for Strategic Studies No.17|12|12. hcss.nl/report/risks-and-opportunities-in-the-global-phosphate-rock-market-robust-strategies-in-times-of-uncertainty

[29] blogs.worldbank.org/opendata/soaring-fertilizer-prices-add-inflationary-pressures-and-food-security-concerns?cid=SHR_BlogSiteTweetable_EN_EXT

[30] Scientists warn of lack of vital phosphorus as biofuels raise demand. The Times (London), 23rd June, 2008: www.timesonline.co.uk/tol/business/industry_sectors/natural_resources/article4193017.ece

2.1.5 Supply disruption and price spikes

Shocks in the global market for phosphate rock are expected to impact agriculture in the UK. There are complex linkages between the prices of key inputs, such as fertiliser, and those of outputs such as grains, which in turn are a key input to livestock production. This means that the higher price of phosphorus typically flows through the agriculture sector and results in higher food prices[31]. If food prices are kept artificially low even when phosphate input prices increase, then the volume of food produced will decline.

RePhoKUs modelling shows that sharp increases in the price of mined phosphate can raise global cereal, milk and meat prices between 5% and 30%, which in turn raise UK prices (figure 7). Wheat, barley, beef and sheep production levels decline in the UK between 1% and 5%. Milk production volume declines only if the price is not allowed to adjust, by 1.6%[32].

These economic scenarios could impact UK phosphorus value chain actors in a number of ways. For example, high phosphorus prices could eventually cause a decline in food production and nitrogen use efficiency if farmers limit their use of mineral phosphate fertilisers. They could also affect the global competitiveness of UK food production, the viability of the UK crop production sector, and stimulate the search for alternative phosphorus sources with benefits for the environment. Some sectors, like extensive livestock systems, may be less affected because fertiliser is a relatively small component of total costs. Further, during the 2008 fertiliser price spike, it was observed that for some farms, crop productivity did not decline where legacy phosphorus was accessible to crops[33].

[31] In reality, the influence of input prices, such as fertiliser, on the price of food is complex. Farmers are largely price-takers, because they produce commodities that are subject to global market prices. A shortage of phosphorus means that the supply is restricted. The supply restriction leads to an increase in fertiliser price because the cost of producing fertiliser increases. In the short-run farmers, as price-takers, can only respond by using less fertiliser, which can reduce yields, potentially restricting the supply of crops, and leading to an increase in crop prices. Given the international nature of the food supply chain, even if there is not a notable impact on UK yields in the face of higher fertiliser prices, if there is enough of an impact on the global supply of crops, higher global commodity prices will increase the price of crops imported to the UK. This means the higher global prices will also increase UK crop prices, and filter along the supply chain to other food commodities that depend on crops as a key input such as dairy and meat.

[32] The RePhoKUs project modelled the potential impact of phosphorus spikes on food commodity prices. In the interactive platform services.afbini.gov.uk/PhosphorusPriceShock, select the degree of phosphate rock price shock (100%-500%) and whether the market price freely adjusts, or is constrained, and generate a bespoke chart of the food price and production impacts.

[33] DEFRA, 2021. *Agriculture in the UK database*. https://www.gov.uk/government/statistical-data-sets/agriculture-in-the-united-kingdom

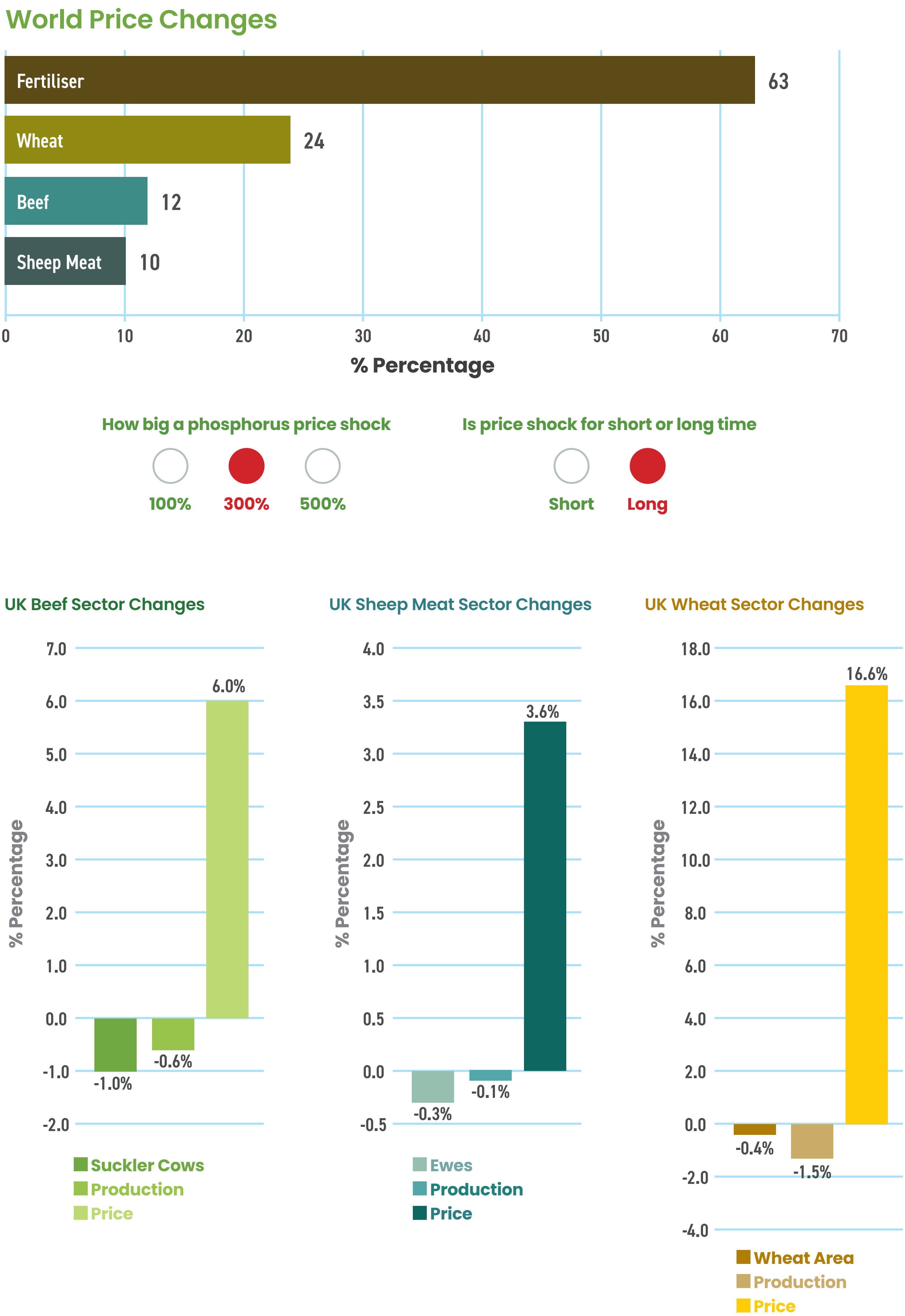


Figure 7: Economic modelling indicating, for example, a 300% global phosphorus price spike in the long term could lead to UK agricultural commodity price spikes of 6%, 3.6% and 16.6% for beef sheep meat and wheat respectively. RePhoKUs (2021) eservices.afbini.gov.uk/PhosphorusPriceShock

2.2 Fragmented governance of phosphorus

The challenges are not just with the production of livestock and crops – it's about people managing, producing, consuming, and processing food that contains phosphorus in a complex value-chain. There are many different policies and actors responsible for managing different parts of the phosphorus value chain at a range of scales. In the absence of any coherent phosphorus governance, these are often operating in an uncoordinated, disjointed and informal manner.

For example, at the catchment scale, an informal network of farmers, water utilities, local authorities and environmental organisations directly manage phosphorus as a pollutant and impact water quality. These stakeholders, are often organised through formal institutions (like sensitive farming partnerships), liaise and share knowledge about phosphorus. While farmers are at the 'frontline' of phosphorus management at the catchment scale and many are indeed aware of the phosphorus challenges in water systems, they are often more concerned about optimising inputs to crops to maintain productivity and comply with regulations[34]. Other indirect stakeholders, such as private sector water companies, tend to have limited incentive but high potential to manage upstream and downstream phosphorus loss from farms.

Even within sectors, governance of phosphorus can be fragmented. For example, tension in the water sector between managing phosphorus solely as a pollutant versus a potential fertiliser source. The biochemical processes for phosphorus removal to meet discharge limits can result in phosphorus products that aren't bioavailable and appropriate for reuse as fertiliser (e.g. using iron to precipitate phosphorus).

Smaller, catchment level NGOs can be well placed to reach farmers and other stakeholders, but are limited in resources and often face uncertain funding arrangements[35]. Finally, 'supporting' stakeholders, such as government organisations (local authorities, Natural England, and the Environment Agency) provide regulatory support, enforcement, and programme funding for catchment level stakeholders, but still work in largely uncoordinated ways[34].

There is little clear strategic guidance and resources for sustainable phosphorus management, to combat increasing catchment-scale vulnerability to phosphorus risks. The system lacks a clear operating framework and access to resources, compounded by current uncertainty over Brexit (and now COVID-19). Stakeholders are generally undertaking phosphorus-risk reduction practices, but with low coherence or levels of subscription. Ultimately, many of the elements of catchment level phosphorus resilience are in place, but in a contingent and not well supported form[34].

While at the national scale, government regulators, fertiliser companies, food processors and consumers are significant players. Despite the challenges that inefficient phosphorus management causes, the governance of phosphorus in the food system is fragmented, and often lacks effective policies and guidance. It is currently unclear who is responsible for governing phosphorus and how various actors can play a role in a coordinated and joined-up way.

[34] Lyon, C., Jacobs, B., Martin-Ortega, J., Rothwell, S., Davies, L., Stoate, C., Forber, K., Doody, D., Withers, P. 2022. Exploring adaptive capacity to phosphorus challenges through two United Kingdom river catchments. Environmental Science and Policy 136: 255-236. https://authors.elsevier.com/sd/article/S1462-9011(22)00182-4

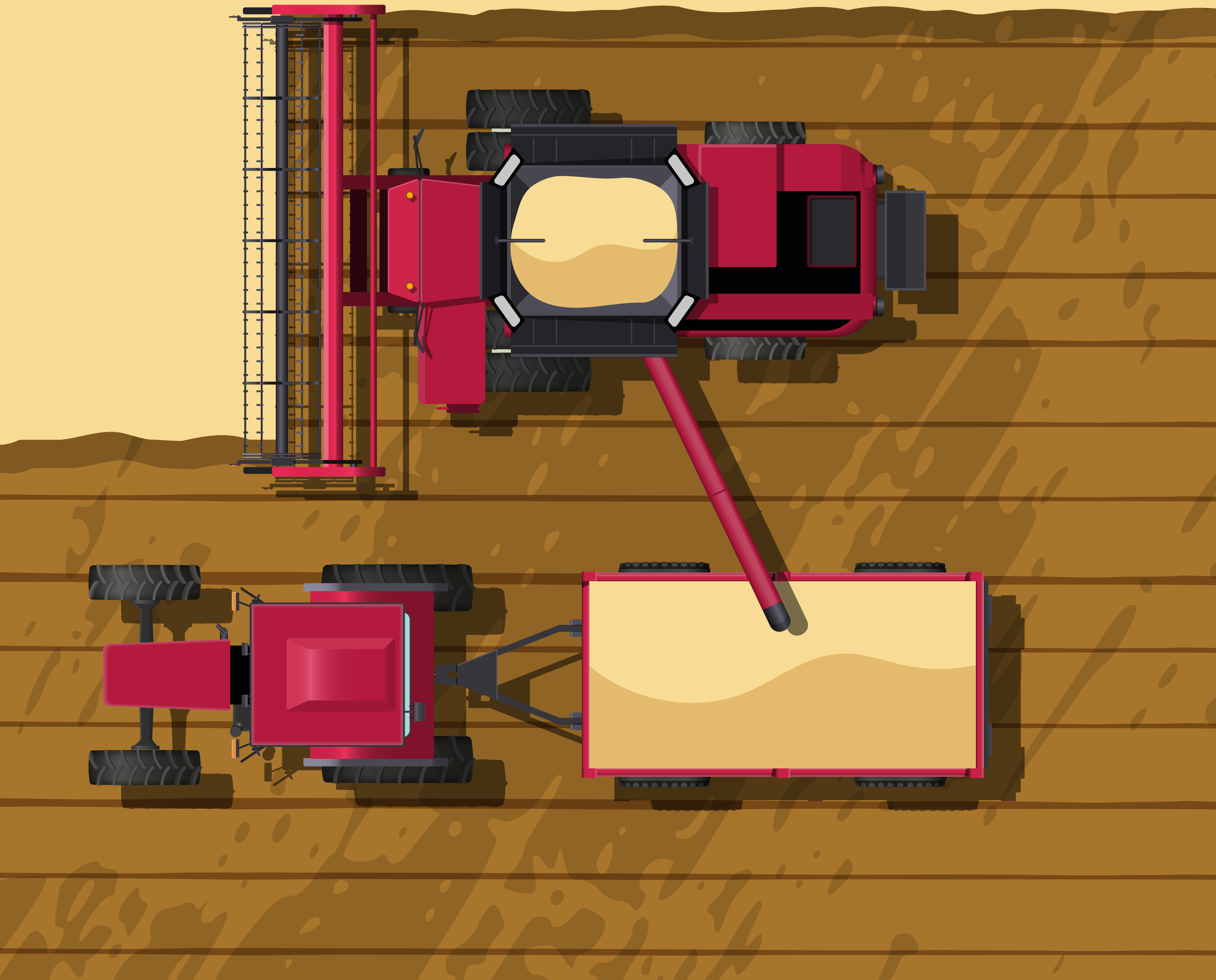
[35] While NGOs can often provide good environmental and sustainability advice, they may not always be in a position to balance this with the business advice farmers are seeking.

2.3 Opportunities for stakeholders

A strengthened circular phosphorus flow can reduce both phosphorus inputs (hence imports), waste and pollution. However, there are significant barriers which must first be overcome. Table 3 highlights stakeholder views on opportunities and barriers to implementing a circular phosphorus economy in the UK. For example, technology to enable phosphorus recovery and reuse is often available but is not currently cost-effective at scale and its utilisation is constrained by fragmented regulatory frameworks.

Potential opportunities and risks are not spread evenly across sectors and stakeholders, and dialogue is required to achieve a more equitable sharing of costs and benefits. The views provided by several sectors are synthesized in table 3 and highlight opportunities for cross-sector cooperation to overcome barriers and blockages to transition the UK food system to a circular phosphorus economy.

For example, an effective policy or regulatory framework for phosphorus recycling can simultaneously stimulate the UK renewable fertiliser market and reduce dependence on imports, incentivise competitive and efficient phosphorus recovery from wastewater, manures and food waste, and increase environmental outcomes for UK waters in the medium-term.



Sector	Opportunities	Barriers
Fertiliser & nutrient products	✔ Increase the use of recycled P in fertiliser products ✔ Increase sustainability of fertiliser businesses, and reduce climate impact	✘ Prohibitive costs of recycled P (e.g. from wastewater) ✘ Lack of available suitable raw materials to incorporate into fertilisers ✘ Logistical impracticality of moving bulky raw materials like manure from one region to another
Agriculture	✔ Facilitate better integration across sectors ✔ Expand existing circular P economy, including increase availability of alternative P products sourced from bulky manures and sludges ✔ Potentially reduce farm input costs ✔ Reduce P losses from farm, entering waterways ✔ Improve soil quality and health ✔ Potentially improve crop and animal yields ✔ Improve corporate image and public perception of agriculture (and Corporate Social Responsibility) ✔ Facilitate new research to support evidence-based policy	✘ Lack of practical means to access legacy P stored in soils. ✘ Lack of practical means to apply recycled P (e.g. in Spring) ✘ Fragmented institutional landscape, inconsistent advice to farmers; outdated thinking ✘ Lack of legislation, rules, regulations, policy frameworks to encourage, finance and support; ✘ Costs & commercial feasibility: ■ Imported P is still cheaper than recovered P ■ Transport costs due to geospatial separation between raw P sources (like manure) and demand in cropping systems ■ Low concentration of P in recycled sources ■ Cost of soil testing nutrients ✘ Lack of awareness and farmer willingness to change ✘ Short term lease on land in NI prevents long-term commitment to manage soil nutrients
Livestock	✔ Financial benefit to capturing surplus P in manure, if P has a value and it could be exported economically ✔ Facilitate growing feed on-farm and reducing imported feed	✘ Costs to process and transport livestock manure ✘ Regulatory constraints to recycle P in feed ✘ Market acceptance to recycle P in feed ✘ High dependence on imported feed
Environment	✔ Reduce environmental P losses to waterways, if all sectors work closely together ✔ Facilitate more soil, crop and manure samples for analysis as part of drives towards zero P surplus	✘ Logistical and administrative cost associated with risk of land contamination due to recycled P application ✘ Attitude/behaviour of some agricultural customers' needs to change
Water & wastewater	✔ Increased economic viability of P recovery and reuse if higher price and/or restrictions in place (e.g. for raw P sources like biosolids) ✔ Recognition of importance of biosolids as a source of P ✔ Increased focus on P recovery innovation and technologies	✘ Economic limitations (e.g. economy of scale needed) ✘ Low % recovery ✘ Low concentration of P in wastes ✘ Dispersed flow of P in wastewater makes recovery costly

Table 3: Opportunities and barriers to implementing a circular phosphorus economy in the UK

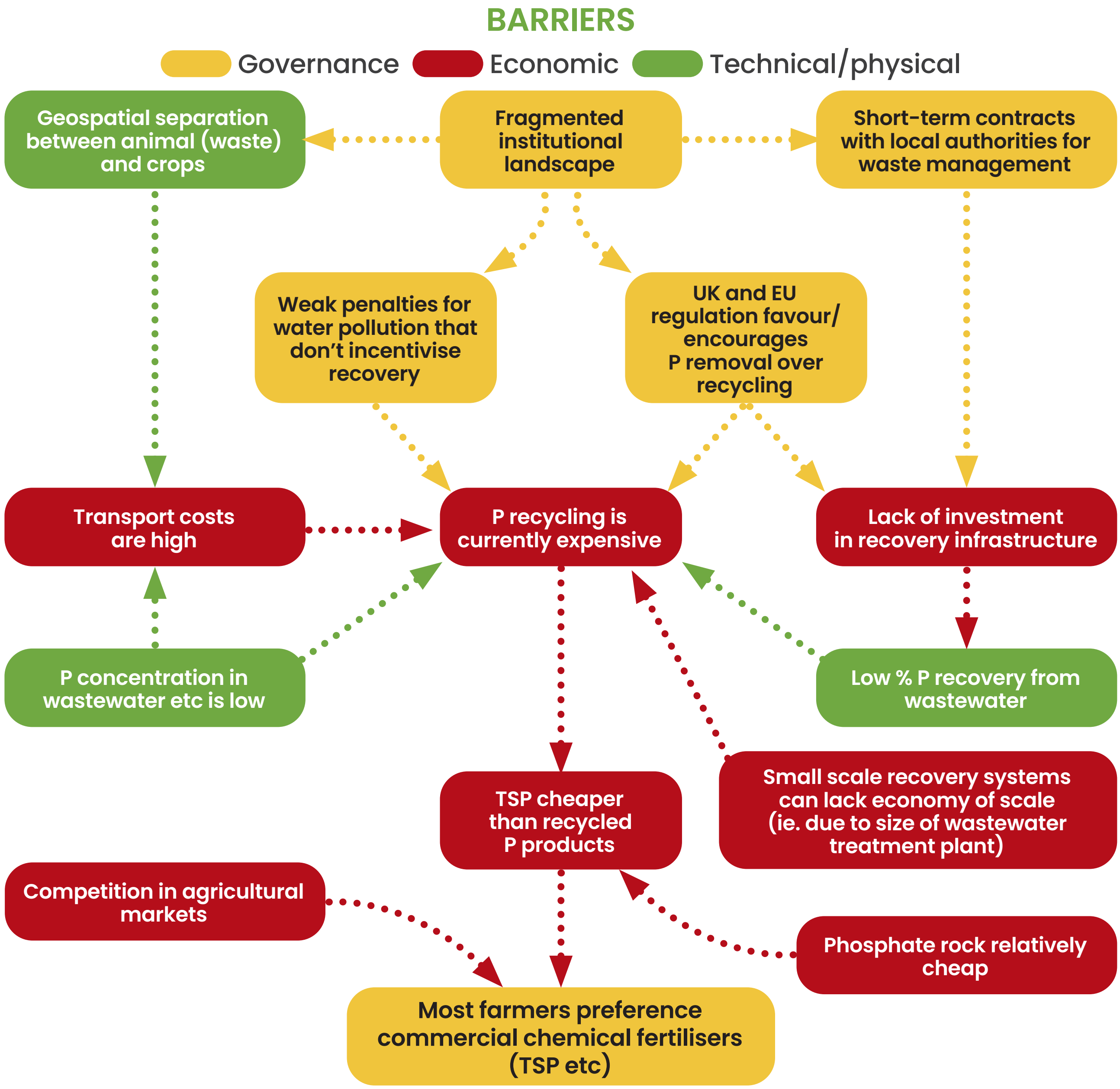


Figure 8: A synthesis of stakeholder views on barriers to phosphorus recycling in the UK[36]

Similarly, improved management of legacy phosphorus in UK soils can create opportunities for different stakeholders. For example, environment stakeholders saw benefits in improved ecosystem functioning of grasslands and surface waters with reductions in pollution remediation costs. Agriculture stakeholders saw the potential to redesign farming systems using improved knowledge of soil phosphorus dynamics and associated technological innovations such as new organic phosphorus fertilisers, soil bio stimulants, and enhanced crop cultivars. While water stakeholders were concerned that exploitation of legacy phosphorus could reduce biosolids demand, they saw opportunities in the development of new sustainable water treatment processes and that could lead to widespread commercialisation of recycled phosphorus products.

Finally, while phosphate and fertiliser price spikes are undesirable and could cause some farmers to go out of business, farmers rarely see this type of disruption as a potential threat to production. However, price spikes can also present opportunities for some stakeholders by triggering change. For example, short-term adjustments or coping mechanisms like greater demand for biosolids in crop production and changes in crop rotations, or more transformational change like reducing reliance on imported phosphorus fertilisers and improved soil nutrient management. To inform a coherent set of pathways and next steps for stakeholders, a shared vision of the future must first be articulated.

[36] Many of these barriers refer to issues facing wastewater and waste companies.

3 The future: a shared vision

Transformation entails fundamental change in the rules that govern phosphorus and the management practices involved in its use. By defining the attributes of a more resilient future system we can design and plan for system transformation. Below are 10 attributes that define features of a desirable future phosphorus system for the UK, two decades into the future. They were collected and synthesized from a broad range of UK food system stakeholders, building on phosphorus stakeholder views in other parts of the world[37].

ATTRIBUTES OF IDEAL FUTURE PHOSPHORUS SYSTEM
1. VIABLE & CIRCULAR ECONOMY
A viable phosphorus economy is established, phosphorus is appropriately valued and waste is now viewed as a resource. Closed loops and market mechanisms maximise recycling of phosphorus from all sources. Waste and wastewater utilities are now profitable resource factories supplying affordable nutrient products that meet user needs.
2. ENHANCED WATER QUALITY
Water quality and ecosystem health in lakes, rivers and oceans have been restored. Water quality obligations are ambitious and are being met –and exceeded– which reduces eutrophication and pollution, improving biodiversity and amenity.
3. INTEGRATED PHOSPHORUS VALUE CHAIN
Farmers, industry, scientists, and others effectively communicate, coordinate, collaborate in or partner on a suite of innovative sustainability solutions across the whole value chain. Land use is optimised for multiple benefits through integrated nutrient management in agricultural systems, landscapes & catchments.
4. SELF-SUFFICIENT
Phosphorus self-sufficiency is addressed via reduced dependency on fertiliser imports (and associated trade risks), diversification and increased investment in local phosphorus recovery.
5. APPROPRIATE AND FLEXIBLE TECHNOLOGIES
Scale-appropriate technologies and flexible solutions for phosphorus recovery and co-recovery from waste streams have been widely adopted and are applicable to all farms. All potential waste streams are considered (including food waste, wastewater, manure, animal waste).

[37] See: Macintosh, K. Chin, J., Jacobs, B., Cordell, D., McDowell, R., Butler, Haygarth, P., Williams Quinn, O'Flaherty, McGrath, J. 2019, *Transforming phosphorus use on the island of Ireland: A model for a sustainable system*, Science of the Total Environment 656 (2019) 852–861; and: Jacobs, B., Cordell, D., Chin, J and Rowe, H. 2017, *Towards phosphorus sustainability in North America: A model for transformational change*. Environmental Science and Policy 77 (2017) 151–159.

6. EQUITABLE AND EFFECTIVE GOVERNANCE

Phosphorus is recognised as a strategic resource. Appropriate use of policy instruments (such as regulation, monitoring, certification, incentives and nutrient trading) drive sustainable phosphorus practices and technologies. Decision-makers and policy-makers collaborate across sectors. Phosphorus sustainability has been adopted through targets and incentives for recovery through reuse and recycling. Environmental and social costs of phosphorus use are internalised and shared among actors in watersheds, the phosphorus value chain and society at large.

7. EFFICIENT VALUE CHAIN

Phosphorus inputs are closely aligned with outputs throughout the phosphorus value chain to balance cost-effectiveness and minimise losses from agriculture, industry and other parts of the food system.

8. SUSTAINABLY SOURCED PHOSPHORUS

Phosphorus is produced from a range of diverse sources, that are commercially available, accessible, reliable, substitutable, affordable, renewable where possible (including legacy P), low environmental-impact, ethically sourced, plant-available and safe to process and use in agriculture. Phosphorus resources are globally secure, equitably distributed and accessible.

9. NUTRIENT-AWARE FARMERS & CONSUMERS

Action on nutrient sustainability is widely embraced throughout society. Phosphorus-literate farmers and consumers make informed choices aided by meaningful communication, decision tools and sustainability metrics. Environmental intelligence drives consumer choices promoting production best practice. Empowered and tech-savvy farmers are supported to actively adopt new innovations and implement knowledge specifically tailored to on-farm requirements.

10. HEALTHY, NUTRITIONALLY-SECURE DIETS

Consumers enjoy healthy, sustainable diets with low phosphorus footprints (i.e. minimal phosphorus fertiliser produced per unit of food consumed).

4 Pathways to a sustainable future system

This section sets out six key pathways for the UK to achieve the sustainable transformed future outlined in Section 4. These interlinked pathways include:

1. Technology & Innovation, **2. Knowledge & Research**, **3. Policy & Governance**, **4. Markets & Incentives**, **5. Community, Engagement & Awareness** and **6. Integration**. These pathways were co-developed by stakeholders in the national stakeholder workshop (see Appendix A). While extensive changes are required, some progress has been made along several of these pathways and many existing initiatives are underway that can be scaled-up and -out. Importantly, all sectors can and need to play a role in supporting this transition.

Figure 9 indicates the current state of phosphorus vulnerability in the UK (left side), and some of the key drivers of change (top-left), putting pressure on this business-as-usual situation. The far-right box articulates the 10 attributes of a transformed phosphorus system, that is, the future desired by UK food system stakeholders. The 6 arrows in the centre represent the critical pathways for the UK to move from the current vulnerable state towards the desired future state.

4.1 Technology and Innovation

Pathway 1: Develop, promote and apply innovative, scalable and cost-effective technologies for recovery of phosphorus streams, redistribution (especially animal manures), and reuse as viable renewable fertilisers.

Opportunities for technology and innovation were identified across the phosphorus value chain - from improved recovery at the waste-stream end, to efficient redistribution, and creation of viable markets. The recovery and recycling of phosphorus streams, especially from manures, is needed, along with increased demonstration of these technological solutions. Scottish Water's 'Innovation Centres', for example, provide real-time testing and demonstration of phosphorus removal technologies at scale, enabling successful technologies to be immediately rolled out at scale, eliminating the need for small-scale pilots.

Some farmers already use 'renewable fertilisers' . The fertiliser industry estimate that 5% of the phosphorus in fertilisers is currently sourced from recovered materials like incineration ashes and struvite). However, new products need to be brought to market to substantially increase this percentage. For example, processing the nutrient rich digestate from Anaerobic Digestion (AD) systems as a raw material input to fertiliser production could be a valuable co-benefit of renewable energy generation from livestock waste. However, like manures, digestate can be bulky to transport, and economies of scale in technology mean it is too expensive for many individual farmers to process either raw manure or digestate. These barriers, and indeed the trade-offs between recovering carbon, nitrogen and phosphorus from such systems, need to be addressed moving forward. The current regulations around the management of digestate mean regulators are key actors to involve in an expansion of AD capacity that includes fertiliser production. Indeed, discussions to develop quality protocols for digestate are already underway.

Importantly, from the fertiliser industry and farmers' perspectives, recovered materials to be processed into recycled phosphorus fertilisers need to be fit-for-purpose to better match market requirements. Organic phosphorus fertilisers must be safe to use, comply with UK fertiliser regulations and support good practice nutrient management. To meet the needs of agri-business, their production must reliably match industry demand and be suppled in the right specification and form for specific agronomic practices (e.g. bioavailable soluble forms for some uses and insoluble for others).

[38] Fertilisers produced from renewable recycled organic raw materials, such as manures, food waste, sewage digestate etc.

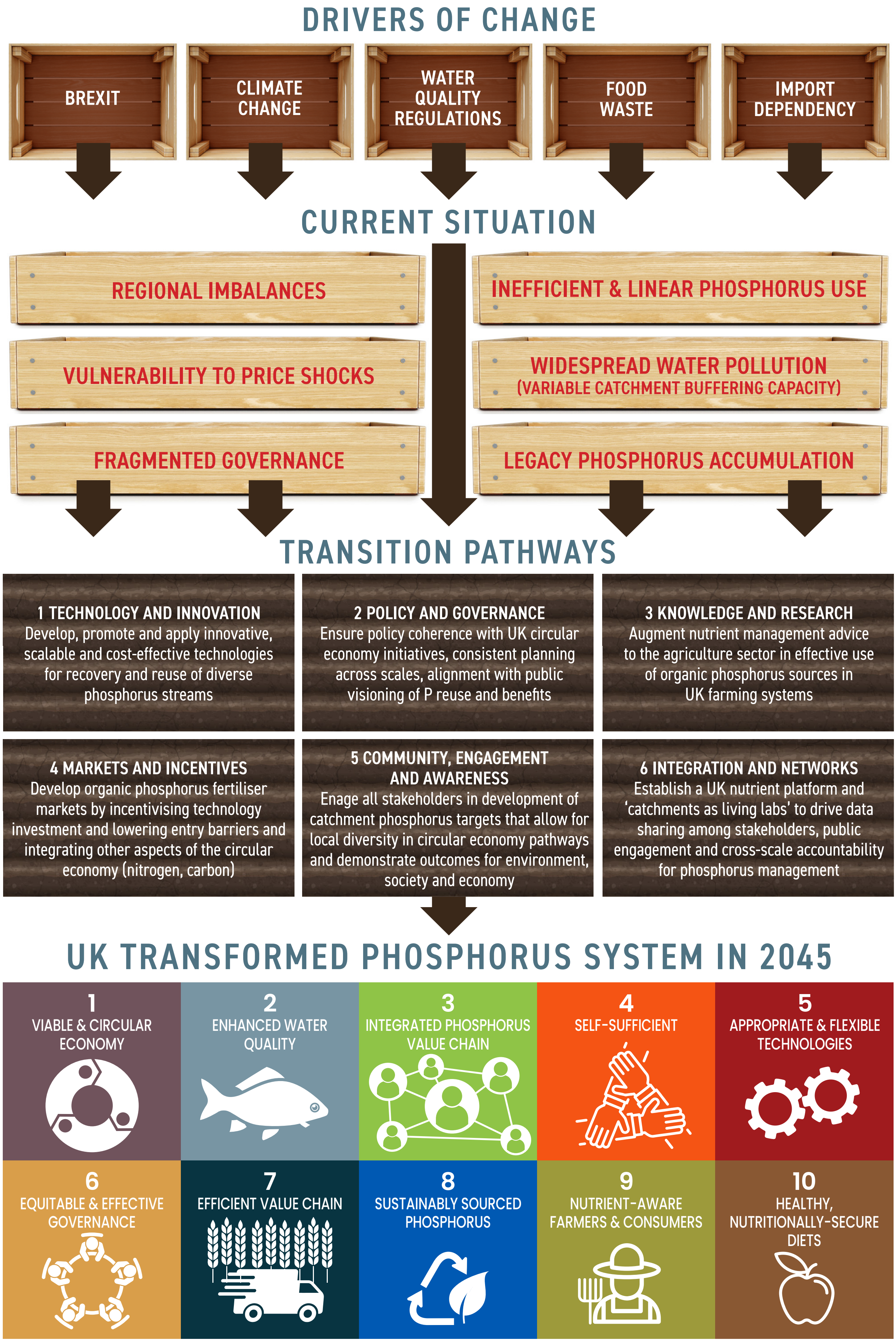


Figure 9: UK phosphorus transformation framework: 6 key pathways to achieve a sustainable future.

More effective redistribution of recycled phosphorus is also an important component of this pathway. This could be achieved through the movement of a processed, phosphorus-dense product, to overcome some of the current economic barriers to biomass transport. As phosphorus balances vary regionally across the UK[39] it is also important to identify areas of surplus production and of soil phosphorus deficit to support efficient redistribution. This could be aided through the development of additional user-friendly soil legacy phosphorus tests that considers factors affecting the dynamics of long-term nutrient availability. Researchers and soil testing labs were identified as key actors for this potential development.

4.2 Policy and Governance

Pathway 2: Recognise phosphorus as a scarce resource and map existing policies to ensure coherence with promotion of a UK circular economy, consistent planning across regions/scales, and alignment with public visioning of the benefits of phosphorus reuse.

To overcome some of the challenges associated with managing phosphorus, increased support and assurance is needed from the government to help reduce overall phosphorus demand by the food system and encourage circularity[40]. While all stakeholders in the phosphorus value chain have a role to play, government can play a coordinating role (e.g. setting the direction and expectations, establishing coherent policies, legislation, regulatory frameworks, monitoring and enforcement). This can involve all levels – from central government, to national departments of agriculture and the environment, through to FACTS[41] advisors.

For example, as a first step, UK policy needs to recognize mineral phosphorus a scarce resource[42]. This would shift the policy focus towards the use of more organic phosphorus as raw inputs to reduce food system vulnerability to supply chain issues like international trade disruptions and climate change. Financial incentives as a supporting mechanism for legislation are also needed, as well as planning support for new processing technology or infrastructure at a range of scales from individual farms to centralized, organics processing hubs. This form of government support could help achieve economies of scale that often limit investment in processing facilities.

Further, policy and regulatory frameworks, currently highly fragmented, need to be made coherent, holistic and nuanced to local conditions. For example, conflicting legislation that currently restricts the application of manures and organic materials in autumn due to environmental risks, could be re-examined to consider safe application in the right place, right time and of appropriate materials to capitalize on benefits while being cognizant of place-based risks.

Other value chain stakeholders like farmers, the fertiliser industry, food sector, agricultural industry, waste service providers and community groups have a role to play in collectively 'setting the vision' for a sustainable future, that encompasses aspects of day-to-day management, the need for investment in knowledge, and self-regulation of phosphorus reuse where appropriate. Such engagement with stakeholders could provide government an opportunity to better understand issues of concern and determine appropriate legislative responses[43]. Framing the vision positively, by focusing more on the benefits of reducing phosphorus pollution, like increased biodiversity, tourism, and food supply resilience, rather than the damage caused by pollution would encourage community buy-in. For example, the Scottish Government takes a 'flipped' approach to water governance, going beyond compliance by seeking to maximise the economic, social and environmental value of water resources. This approach asks, 'how can rivers become a great place that people want to use, and that support their mental and physical wellbeing?'. Similarly, there is an opportunity to better support farmers in an integrated way to deliver productivity improvements in addition to environmental benefits.

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[39] See RePhoKUs regional phosphorus imbalance maps: public.tableau.com/app/profile/shane.rothwell/viz/RegionalPanalysis/Story1

[40] See also Yuille, A., Rothwell, S., Blake, L., Forber, K.J., Marshall, R., Rhodes, R., Waterton, C., Withers, P.J.A. 2022. *UK government policy and the transition to a circular nutrient economy*. Sustainability 14, 3310. https://doi.org/10.3390/su14063310.

[41] www.factsinfo.org.uk/facts/home.eb

[42] The EU has recognised phosphorus and phosphate rock as critical raw materials since 2014, ec.europa.eu/growth/sectors/raw-materials/areas-specific-interest/critical-raw-materials_en.

[43] see Section 3 – A Shared Vision.

4.3 Knowledge and Research

Pathway 3: Augment tailored nutrient management advice to the agriculture sector on effective use of recycled phosphorus sources (animal manures, food waste, biosolids) and soil legacy phosphorus in UK farming systems.

The knowledge network around organic phosphorus products is currently fractured and incomplete. More effort is needed to produce information on the phosphorus content of alternative organic sources, how they perform in a range of agricultural scenarios and, to translate this into accessible knowledge for farmers, such as decision support guidance, and improved understanding of environmental risks of using recycled phosphorus materials. Nutrient management advice needs to be better communicated, include information on the right time and place for manure application, and how to more precisely match fertiliser nutrient content to crop nutrient requirement at different times in the year.

A centralised system to collate information on phosphorus distribution, movement and soil levels could assist in tracking change and mapping supply and demand for nutrients. The fertiliser industry's 2050 Roadmap sets out a plan for improving farm nutrient balance, and provides an opportunity to ensure all feed, FACTS, and nutrient advisors are trained to support this initiative.

The key actors in research and knowledge exchange on nutrient management should include agronomists, feed advisers and other service providers that advise farmers. A positive example of knowledge transfer which could be replicated in other UK locations comes from Northern Ireland, where farmers are being engaged on multi-challenge scenarios and co-design improvements with experts. Farmers should also be encouraged to make greater use of existing tools that aid manure management, especially in relation to soil phosphorus status. It is important to note though that, while advice and information provision is important, farmers need to actively engage in and be able to reflect on the practice for it to lead to behavioural changes (experiential learning)[44].

Research is needed on the use of manure on arable land and the dynamics and interactions between soil health, soil legacy phosphorus and soil type/chemistry to more efficiently utilize phosphorus in the soil. This could be coupled to stronger communication of the positive benefits of harnessing legacy phosphorus for water quality, which would encourage increased community engagement. The techniques used to measure quality of water bodies may also need to be re-examined, to move beyond individual reductionist indicators to more holistic indices that reflect the functionality of the aquatic environment.

More research is needed to better understand phosphorus dynamics in other parts of the food system beyond food production, including effects of consumer preferences and dietary change. For example, more modelling to better understand how to cost-effectively support diets with lower phosphorus-footprints[45].

[44] Okumah et al. 2021. *The role of experiential learning in the adoption of best land management practices*. Land Use Policy. Volume 105, June 2021, 105397. doi.org/10.1016/j.landusepol.2021.105397

[45] Forber, K.J., Rothwell, S.A., Metson, G.S., Jarvie, H.P and Withers, P.J.A. 2020. *Plant based diets add to the wastewater phosphorus burden*. Environment Research Letters 15, 094018.

4.4 Markets and Incentives

Pathway 4: Provide incentives to encourage investment in technology, lower barriers to entry and develop markets for a viable organic phosphorus fertiliser sector that integrates other aspects of the circular economy (nitrogen, carbon) to reduce the burden of action on farmers.

High dependence on phosphate imports could be reduced through a number of means, including taxing the use of mined phosphates that are not already part of the food system. Closely linked with the governance pathway, this policy mechanism could disincentivize the use of mined finite material in manufactured products. The revenue raised could be invested in circular nutrient economy initiatives, rather than imposing further financial burdens of greater use of recycled phosphorus on farmers.

The expansion of existing nutrient trading schemes in combination with new stakeholder-led nutrient trading platforms provides a market-based industry-led approach for reducing phosphorus pollution. The integration of carbon, nitrogen and phosphorus into an expanded platform could increase stakeholder interest, improve market viability, and accelerate the establishment of phosphorus circularity. For example, the Sustainable Landscapes[46] program currently focuses on improving nitrogen use efficiency (as the biggest carbon footprint of an arable crop), however this could theoretically also incorporate phosphorus efficiency, putting a value on phosphorus.

In common with the technology and innovation pathway, one barrier to the creation of a circular economy for phosphorus is the inaccessibility of manure treatment processes, which are currently 'beyond reach' for farmers. Increased flows of capital and planning support could overcome this and increase the uptake of farm processing technologies, storage and the removal of phosphorus from catchments. Processed animal manures currently have a market value that is incommensurate with the nutrient composition of the material; this market failure needs to be addressed. Without an appropriate market value, the regional redistribution of processed manure products remains unviable, placing the financial and social burden of phosphorus circularity on farmers alone, when wider stakeholder involvement is needed. Government assistance to develop a legitimate export market for recycled phosphorus fertilisers would increase their value and encourage investment in infrastructure by other stakeholders like water and waste companies. While some water companies are already recovering some phosphorus, the economic viability can be very site-specific (such as for struvite recovery).

Policy instruments like current regulation and incentives could be better targeted to the relevant groups. Incentives should generally encourage reduced use of phosphorus and focus more targeted interventions on environmentally sensitive areas measured against water quality thresholds. While initiatives like rewards for nutrient planning could better connect agricultural stakeholders to phosphorus issues, public awareness raising of the importance of phosphorus in the UK food system could encourage broad buy-in. For example, in the case of carbon, Scottish Water's customers are willing to pay a premium for their water and wastewater services to achieve the environmental outcome of a net zero service. A similar approach could be explored for phosphorus and other nutrients. Overall, greater awareness is needed around the need to rebalance nutrients on land, and this will come most likely through a combination of education, legislation and remuneration. .

[46] a collaboration between Yorkshire Water, Future Food Solutions and others: sustainablelandscapes.uk.com

4.5 Community, Engagement and Awareness

Pathway 5: Engage a broader range of stakeholders in setting direction and progress on achievement of catchment phosphorus targets that allow for local diversity in circular economy development pathways and demonstrate outcomes for public health and well-being (environment, society and economy).

Policy instruments need to be accompanied by a clear 'direction of travel' for multiple stakeholders and different groups in the community. This requires higher levels of public engagement to support establishment of clearer targets. For example, seeking public consensus and acceptance about how their land should be managed and used.

As different communities and sectors have different perspectives and expectations a joint vision is needed, to help organisations identify pathways to meet these targets, to reach a consensus on community values, and on collective responsibility and contribution (not just farmers) to achieving agreed targets.

Although there are some existing efforts between retailers, regulators and farm businesses to work across catchments, more 'whole of system' effort is needed to ensure that people really understand why they are being asked to act. Experience with farmers indicates that a high level of engagement can be required for on-going interest, and considerable farmer involvement is required to ensure adoption of new pilot schemes. For example, Yorkshire Water has worked closely with local farmers for two years, and has secured significant behavioural change in farm nutrient practices, which in turn has improved water quality. More research is now needed to better understand specifically what drove this change, so it can be replicated in other locations. Real-world, field-scale trials could be used as 'living labs' to demonstrate innovations like the potential use of legacy phosphorus, thereby building confidence among farmers and communities in new practices and processes. On-going engagement within communities, will require substantial investment to maintain the social capital essential for success. Further, reciprocity between stakeholders is important, for example while food retailers can significantly influence farmers, farmers need more agency in price-setting of their produce, or to be assured a fair price relative to the costs of production.

Broader stakeholder engagement would encourage a stronger response to consultation on and formulation of future policy and bring the community together on aligned issues. Deeper levers of transformation can be worked upon in continued participatory processes or other forms of sustained stakeholder engagement, to further challenge existing social norms and structures with regards to phosphorus's role in a more sustainable and resilient food system. Participatory stakeholder methods such as serious games, foresight, and backcasting currently applied to other challenges such as climate change, may serve as appropriate approaches[47].

[47] Martin-Ortega et al. 2022. *Are stakeholders ready to transform phosphorus use in food systems? A transdisciplinary study in a livestock intensive system.* Environmental Science & Policy, 131, May 2022, p177-187 www.sciencedirect.com/science/article/pii/S146290112200017X

4.6 Integration, Connections and Networks

Pathway 6: Establish a UK nutrient platform and a 'catchments as living labs' concept linked to information dashboards to drive data sharing among stakeholders, public engagement and cross-scale accountability for phosphorus management (imports, exports, recycling).

Importantly, tackling phosphorus challenges requires a combination of actions not only within individual sectors, but across the range sectors and scales in the UK food system. Cooperation between stakeholders is vital at local and regional scales, to identify and stick to a long-term vision for phosphorus management and for the joint delivery of solutions through collective responsibility, governance and goal-setting. Cooperation and conversations between sectors in the value chain must work in both directions. For example, food supply chains have their own net carbon and sustainability goals, which they cannot achieve without action by farmers. Similarly, creating a viable circular economy means water and waste managers can't just recover phosphorus in the hope that someone will find a use for it: the size and nature of potential end-use markets have first to be identified and evaluated. Different types of farming systems, landscapes and end-users means markets need to be deliberately aligned to supply the right products to the right people.

Knowledge generation and sharing about the UK's phosphorus imports and exports are valuable to create strong information network connections that operate across scales. The inequality in access to such information in some areas needs to change moving forward. Access to high quality affordable advice and information on nutrient management is essential and needs to be centralized in a consistent way for nutrient management planning at a farm and catchment scale.

A new nutrient platform and IT dashboard could aid data sharing and nutrient management across multiple scales. This nutrient dashboard approach could be trialed within a catchment pilot study to assess the value of the approach. A holistic nutrient management system could support strong connections and integration to deal with the differences in the levels of nutrient planning and management skills, and to support the development of a circular economy. Creating catchments as study sites can help inform governance. For example, utilizing a 'protected sites strategy' could help address phosphate impacts and bring together community and public interest, as well as providing a platform for increased innovation in farming and water treatment.

Integration also needs to occur between parts of the biophysical system: a shared vision for phosphorus could be integrated with carbon and nitrogen roadmaps, as integrated management of these components together offers an opportunity to raise the profile of the phosphorus challenges in addition to the identification of co-benefits. Taking a holistic approach to the biophysical system at the landscape scale is also key: for example, improved soil health is a key lynchpin to achieve multiple sustainability goals, such as optimizing nutrient efficiency, water retention, biodiversity outcomes and flood management[48].

The devolved governance in the UK can pose a challenge for phosphorus governance, such as in the establishment of nutrient hub processing facilities due to potential objections from local government. National scale integration can help turn these challenges into opportunities for the recycling of phosphorus. However long-term challenges like phosphorus require policy-makers to stick to a long-term strategic agenda, and not be diverted by short-term pressures. For example, learning from the water sector, committing to real improvements in river and catchment health (which might not yield results for many years), rather than succumbing to the short-term popular pressure of single actions like cleaning up unsightly wet-wipes littering rivers.

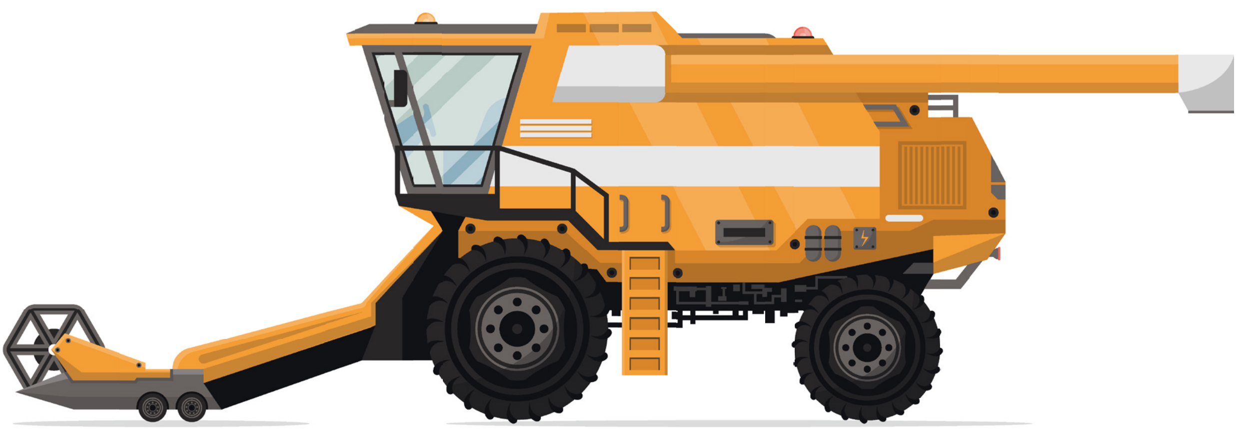
[48] According to a collaborative project in the Humber with Birds Eye, Yorkshire Water and Future Food Solutions, a 1% improvement in soil organic matter can increase water holding capacity in the soil by another 200 tonnes. livingwithwater.co.uk/projects/sustainable-landscapes-humber-project

5 Next Steps

While achieving sustainable phosphorus use in the UK food system is complex, the transition pathways to phosphorus circularity show it is not insurmountable. The food system is made up of many sectors, some more closely linked than others in the phosphorus value chain. While all sectors need to contribute to progress on transition pathways, some sectors, businesses and individuals are already acting. Aligning action on phosphorus with existing sustainability initiatives (such as the sustainability programs of major UK supermarket chains) can help to accelerate system transition. As a first step, each food system sector could produce a phosphorus sustainability action plan, guided by this Strategy. That is, these action plans could seek to:

- Define each sector's status, role, and existing initiatives on phosphorus sustainability;
- Identify the sector's potential contribution to achievement of the transition pathways, including more immediate, short-term actions that may be sector-specific, and longer-term actions that require cross-sectoral collaboration;
- Formulate indicators of success that are specific, measurable, timebound, and can be aggregated to demonstrate progress at regional- and UK-scales. Potential targets for consideration could include: monitoring, evaluation and reporting of the proportion of phosphorus recovered from manures and other wastes and productively reused in agriculture; attainment of zero phosphorus surplus at farm and catchment scale; and the proportion of phosphorus obtained from domestic sources[49].

Furthermore, support from government is important to ensure that action to achieve phosphorus circularity is co-ordinated and integrated across sectors and scales. Multi-actor platforms, have proven successful throughout the world in bringing stakeholders together to share knowledge and resources, and coordinate action on sustainability initiatives (e.g. European Sustainable Phosphorus Platform[50]). The establishment of an industry-led, government-supported phosphorus nutrient platform could be an initial step towards improved governance of phosphorus in the UK.



[49] Such targets would need to be deliberated and agreed to by key sectors involved.

[50] www.phosphorusplatform.eu

6 RePhoKUs Resources

The following include some of RePhoKUs reports, papers, short films and media.

Reports

Withers, P.J.A., Rothwell, S.A., Forber, K.J. and Lyons, C. (2022). Re-focusing Phosphorus Use in the Wye Catchment. RePhoKUs Project Report, Lancaster University doi.org/10.5281/zenodo.6598122

Doody, D., Rothwell, S.A., Martin-Ortega, J., Johnston, C., Anderson, A., Okumah, M., Lyon, C., Sherry, E. and Withers, P.J.A. (2020)., Phosphorus Stock and Flows in the Northern Ireland Food System, RePhoKUs project report

Okumah, M., Martin-Ortega, J., Chapman, P.J., Lyon, c., Novo, P. 2019. Behavioural impacts of Northern Ireland's Funded Soil Sampling and Training Schemes 2017-2019. A RePhoKUs project report. wp.lancs.ac.uk/rephokus

Short films and animations

Phosphorus in the UK Food System: risks and opportunities (6:20 minutes)31st July 2021 www.youtube.com/watch?v=YdbHlxdo9sw

Improving farm productivity and environmental outcomes in Northern Ireland: Through Effective Stakeholder Engagement – The case of phosphorus (8:48 minutes) 4th May 2021 www.youtube.com/watch?v=YiYDWf_6ZHk

The Phosphorus Story (8:59 minutes) 3rd March 2020 www.youtube.com/watch?v=8Ia_KKj-UN0

PHOSPHORUS: A local journey in a global cycle (4:32 minutes) 11th October 2019 www.youtube.com/watch?v=dgPHPgCSt3A

Scientific articles

Rothwell et al. 2022. A new direction for tackling phosphorus inefficiency in the UK food system, Journal of Environmental Management. V314 (2022) 115021.

Martin-Ortega et al. 2022. Are stakeholders ready to transform phosphorus use in food systems? A transdisciplinary study in a livestock intensive system. Environmental Science & Policy, 131, May 2022, p177-187

Yuille et al. 2022. UK government policy and the transition to a circular nutrient economy. Sustainability, 14, 3310.

Lyon et al. 2022. Exploring adaptive capacity to phosphorus supply 2 and water quality challenges in catchments. Environmental Science and Policy 136, 225-236.

Olagunju et al 2021, Dynamic relationships among phosphate rock, fertilisers and agricultural commodity markets: Evidence from a vector error correction model and Directed Acyclic Graphs, Resources Policy, 74, 102301.

Okumah et al 2021, The role of experiential learning in the adoption of best land management practices, Land Use Policy, 105, 105397.

Brownlie et al 2021, Global actions for a sustainable phosphorus future, Nature Food, 2, 71-74.

Rothwell et al 2020, Phosphorus stocks and flows in an intensive livestock dominated food system, Resources Conservation and Recycling, 163, 105065.

Forber et al 2020, Plant-based diets add to the wastewater phosphorus burden, Environmental Research Letters, 15, 094018.

Okumah et al 2020, Revisiting the Determinants of Pro-Environmental Behaviour to Inform Land Management Policy: A Meta-Analytic Structural Equation Model Application, Land, 9 (135).

Lyon et al 2020, Five pillars for stakeholder analyses in sustainability transformations: The global case of phosphorus, Environmental Science and Policy, 107, 80-89.

Withers et al 2020, Towards resolving the phosphorus chaos created by food systems, AMBIO, 49, 1076-1089.

Withers 2019, Closing the phosphorus cycle, Nature Sustainability, 2, 1001-1002.

Reitzel et al 2019, New Training To Meet The Global Phosphorus Challenge, Environmental Science & Technology, 53, 15, 8479-8481.

Stringer et al 2019, Adaptation and development pathways for different types of farmers, Environmental Science & Policy, 104, 174-189.

Media

Interview with Shane Rothwell and Donnacha Doody by Matt Schulz of the Sustainable Phosphorus Alliance about the Northern Ireland phosphorus substance flow work.

Phosphorus Substance Flow Analysis in Northern Ireland, Sustainable Phosphorus Alliance, 21st October 2020 www.youtube.com/watch?v=N91tu6Q8nFM

Interview with Donnacha Doody by BBC Good Morning Ulster about the technical report on Phosphorus Stocks and Flows in the Northern Ireland Food System. Listen here 00:19 mins

Guardian article citing RePhoKUs's Northern Ireland technical report on Phosphorus Stocks and Flows in the Northern Ireland Food System

Poo overload: Northern Ireland could be forced to export a third of its animal waste, The Guardian, 23rd June 2021 www.theguardian.com/environment/2021/jun/23/poo-overload-northern-ireland-could-be-forced-to-export-a-third-of-its-animal-waste

Farmers Weekly article covering a farmer meeting in the Wye where Shane Rothwell presented RePhoKUs catchment work: Wye catchment farmers vow to limit phosphate losses, Farmers Weekly, 4th August 2021. www.fwi.co.uk/livestock/poultry/wye-catchment-farmers-vow-to-limit-phosphate-losses

Science for the Anthroposcience Podcast, Lancaster University: round table discussion on the phosphorus issue and the work of the RePhoKUs project. Episode 3: Phosphorus, with Phil Haygarth, Paul Withers, Kirsty Forber and Shane Rothwell. anchor.fm/david-tyfield/episodes/Episode-3---Phosphorus--with-Phil-Haygarth--Paul-Withers--Kirsty-Forber-and-Shane-Rothwell-e1fj251

Other useful links

The RePhoKUs project used the FAPRI UK model of UK Agriculture to test the impact of phosphorus shocks on food prices. www.afbini.gov.uk/analysis-agricultural-commodity-markets-fapri-uk-project

Global Food Security Programme: visit the UK cross-government programme on food security research website find out about other related research projects. www.foodsecurity.ac.uk

European Sustainable Phosphorus Platform: bringing together stakeholders and industry to address the phosphors challenge. This website will provide you with nutrient cycling success stories, nutrient cycling R&D stories, further links and resources. phosphorusplatform.eu

Phosphorus Futures: visit the Global Phosphorus Research Initiative website, this initiative undertakes independent, quality, interdisciplinary research on global phosphorus security for future food production. Find out more of what they do here: phosphorusfutures.net

APPENDIX A: Stakeholder engagement in RePhoKUs

This Strategy was developed primarily with the input from over 60 UK stakeholders. The RePhoKUs project engaged UK food system stakeholders across England, Scotland, Wales and Northern Ireland. Three stakeholder engagement processes were conducted to elicit stakeholder views:

Engagement process	Purpose	Number of stakeholders engaged	Time
1. Key informant interviews: semi-structured phone interviews	• Explore how key UK national phosphorus stakeholders perceive phosphorus vulnerability, their current and future potential role • Semi-structured in-depth to allow probing and following leads other RePhoKUs analysis • Inform design and input into the National stakeholder workshop • Identifying/informing stakeholder's capacity to adapt at other scales	30	Sept 2019 & May-June 2020
2. Online interactive survey	• Share preliminary RePhoKUs findings with stakeholders and seek feedback/reactions • Seek stakeholder views on current state of vulnerability and ideal future state for phosphorus in the UK.	25	April 2021
3. Workshop: interactive virtual workshop	• Hear the latest sustainability initiatives and perspectives from key Panellists across the food, agriculture and water sectors. • Share the key findings from RePhoKUs national stakeholder engagement. • Hear participants' sector priorities, initiatives already underway, and barriers/opportunities, that will help shape key policy, technology, market and knowledge pathways to achieve a resilient phosphorus future for the UK's food system. • Form the basis of the UK's first National Phosphorus Transformation Strategy.	47	Sept 2021

Some stakeholders participated in multiple engagement processes. Participants work across the UK food system and phosphorus value chain, including the following sectors:

- Agriculture and Farming
- Environment
- Fertiliser and nutrient production and trade
- Food (including processing and retailing)
- Government
- Water and wastewater