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Edgar Martín Hernández,
Laval University, Canada
Nugun P. Jellason,
Teesside University, United Kingdom

*CORRESPONDENCE
Will J. Brownlie
wilown@ceh.ac.uk

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Phosphorus price spikes: A wake-up call for phosphorus resilience

Will J. Brownlie[1,2]*, Mark A. Sutton[1], Dana Cordell[3], Dave S. Reay[2], Kate V. Heal[2], Paul J. A. Withers[4], Isabelle Vanderbeck[5] and Bryan M. Spears[1]

[1]UK Centre for Ecology & Hydrology, Edinburgh, United Kingdom, [2]School of GeoSciences, The University of Edinburgh, Edinburgh, United Kingdom, [3]Institute for Sustainable Futures, University of Technology Sydney, Sydney, NSW, Australia, [4]Lancaster Environment Centre, Lancaster University, Lancaster, United Kingdom, [5]United Nations Environment Programme, Washington, DC, United States

Food systems depend on reliable supplies of phosphorus to fertilize soils. Since 2020, a pandemic, geopolitical disputes, trade wars and escalating fuel prices have driven a >400% increase in phosphorus commodity prices, contributing to the current food crisis. The Russia-Ukraine conflict has disrupted phosphate trade further. Concurrently, phosphorus losses to freshwaters, through insufficient municipal wastewater treatment and inappropriate fertilizer use and land management practices, are a significant threat to water quality globally. Despite precariously balanced food and water security risks, nations are largely unaware of their "phosphorus vulnerability" and phosphorus is markedly absent in national and global policies addressing food and water security. Phosphorus vulnerability can be described as the degree to which people/systems are susceptible to harm due to the physical, geopolitical and socio-economic dimensions of global phosphorus scarcity and pollution. Here, we bring the current price spike into focus, highlighting the drivers, policy responses and their consequences. We highlight the need for an integrated assessment of phosphorus vulnerability that considers environmental, socio-economic and climate change risks across scales. We illustrate how reducing phosphorus waste, increasing phosphorus recycling, and wider system transformation can reduce national reliance on imported phosphorus, whilst enhancing food and water security. The current crisis in fertilizer prices represents a wake-up call for the international community to embrace the global phosphorus challenge.

KEYWORDS
phosphorus, price spike, food security, phosphorus vulnerability, eutrophication, sustainability, global-governance

1. Introduction

As an essential plant nutrient in fertilizers, phosphorus is central to food security and societal development. Derived predominantly from phosphate rock, it is converted into a range of fertilizer products including diammonium phosphate (DAP), monoammonium phosphate (MAP) and triple superphosphate (TSP). Around 85% of the phosphate rock reserves are located in five countries: Morocco (70%), China (5%), Egypt (4%) Algeria (3%), and Syria (3%) (Jasinski, 2022). Based on recent annual mining production rates, phosphate rock mining is dominated by four countries: China (39%), Morocco (17%), the USA (10%), and Russia (6%) (Jasinski, 2022). By contrast, nitrogen for fertilizers comes from the atmosphere and can be produced by any country with a sufficient energy supply. In some regions, poor access to mineral phosphorus is already pushing food security targets further from reach (Brownlie et al., 2021). It was previously estimated that 1 in 7 farmers could not afford sufficient fertilizers to meet crop requirements, impacting their ability to produce food (IAASTD, 2009).

In contrast, nutrient pollution through fertilizer overuse and insufficient wastewater treatment, can trigger toxic algal blooms and create coastal dead zones threatening human and animal health (Bajželj et al., 2014). These effects will be exacerbated by climate change. Emerging evidence also suggests that anthropogenic phosphorus enrichment of lakes will contribute to climate change through the greenhouse gas emissions associated with enhanced eutrophication (Downing et al., 2021). Controlling the phosphorus lost to freshwaters from anthropogenic sources globally would cost ∼US$265 billion per year (Johnes et al., 2022). Currently, the economic losses of eutrophication are paid by society through losses of ecosystem services. If phosphorus pollution of the aquatic environment is not reduced in the coming years, the environmental and socio-economic impacts may be irreversible (Carpenter and Bennett, 2011).

It has been suggested that agricultural phosphorus demand may double by 2050, compared with 2006 (Mogollón et al., 2021). This is a consequence of national to global scale demands for food and non-food goods, some of which are destined for international trade (Hamilton et al., 2018). These demands are embedded within national economic development plans and are often not aligned with global sustainability policy agendas. In a business-as-usual scenario, global phosphorus requirements will overtake global phosphorus supply after 2040 (Nedelciu et al., 2020).

No global policy exists for phosphorus. Business as usual for phosphorus ignores the impacts of degraded natural capital on the growth of the green economy (Dasgupta, 2021). It neglects the value of circularity in the anthropogenic phosphorus cycle, where currently <50% of phosphorus wastes/residues are recycled back into the global food system (Brownlie et al., 2021). Finally, it fails to recognize that phosphorus vulnerability is driven, in part, by the international trade of food and non-food goods, creating a novel transboundary context to nutrient impacts across aquatic ecosystems (Hamilton et al., 2018).

Current elevated phosphorus commodity prices are starting to bring phosphorus vulnerability to political and public attention. Phosphorus vulnerability can be described as the degree to which people/systems are susceptible to harm due to the physical, geopolitical and socio-economic dimensions of global phosphorus scarcity and pollution (Cordell and Neset, 2014). It is an interaction between *exposure* (the degree people and food systems are exposed to external shocks like phosphorus commodities price spikes), *sensitivity* (the degree of harm caused by exposure) and the *adaptive capacity* of people and institutions to mitigate harm by reducing exposure or sensitivity (Cordell and Neset, 2014). The components of phosphorus vulnerability are diverse and work at different temporal/geographical scales. For example, water quality degradation resulting from insufficient phosphorus management (i.e., adaptive capacity) is chronic for all nations (Johnes et al., 2022). Spikes in phosphorus commodity prices (i.e., exposure) are episodic with short-term global food security impacts. In economically under-developed countries, phosphorus access issues are an enduring risk to food security (i.e., sensitivity).

The current price spike is raising concern that farmers will not be able to access sufficient phosphorus to produce food using existing farming systems (UN GCRG, 2022; World Bank Group, 2022). As stated by the President of the World Farmers Association, in May 2022 (de Jager, 2022), "*whether in North America or Oceania, even in Ukraine and Russia, the main talk amongst farmers is fertilizers, the availability and the price*."

2. Drivers of global phosphorus price spikes

Three major spikes in phosphorus commodity prices have occurred in the last 50 years, in 1975 (>700%), 2008 (by 800%) (Brownlie et al., 2022a), and 2020-22. In 2008, escalating phosphate prices eventually crashed with prices stabilizing at double that of pre-2007 prices. While it was linked more broadly to the global economic crisis of the time, the specific contribution of different causes of the 2008 price spike remains unclear and likely driven by several interacting factors. These included changing market supply and demand dynamics for agricultural and phosphorus products, instability in energy prices and geopolitical control on exports (International Fertilizer Industry Association, 2011). Long-term (multi-decadal) factors included income growth and dietary changes in emerging economies (e.g., increasing consumption of animal products in China and India, which requires more phosphorus to support); competing objectives for agriculture, in addition to food and feed production (e.g., production of fiber, biofuel feedstock and bio-chemicals); global grain market conditions (i.e., low cereal stocks); and background increases in energy prices (Brownlie et al., 2022a). Short-term (interannual) factors included economic weakness in many countries, export restriction measures, extreme weather conditions and natural disasters (International Fertilizer Industry Association, 2011). Some reports suggest the introduction of a US ethanol policy and increases in food prices in 2008 contributed to increased phosphorus demand (Cordell et al., 2015). Others argue the major contributor was an Indian Government fertilizer subsidy scheme which caused a doubling of fertilizer imports (Khabarov and Obersteiner, 2017). In 2008, China applied an export tax of 100–135% on domestically produced phosphate fertilizers, effectively halting exports (de Ridder et al., 2012). This was driven by an increase in national agricultural production and by concerns that Chinese phosphate rock reserves were being overexploited.

Similarly, a perfect storm of drivers is being attributed to the most recent (2020–22) and ongoing price increase in phosphorus commodities (Cross, 2022):

- Rising fertilizer demand: since 2020, a significant global expansion in agricultural land, supported by government subsidies, has been driven by domestic food security concerns (USDA, 2022). Additionally, strong crop prices since 2020 have incentivised an increase in fertilizer use to maximize yields. Between 2019 and 2021, global phosphorus demand increased by 7.0%, reaching 49.6 Mt, with South Asia and Latin America driving growth (International Fertilizer Association, 2021).

- Phosphate supply disruptions: since 2020, phosphate production in China has been severely impacted by lockdowns and supply constraints; a third of China's phosphate production plants are in the COVID-19 epicenter, Hubei Province. In 2021, US phosphate supply chains were impacted by weather events (e.g., Hurricane Ida and the Texan Freeze), the pandemic and higher input costs.
- Increasing raw material prices: soaring energy costs throughout 2021–22 have increased fertilizer production costs and costs of raw materials and freight (World Bank Group, 2022).
- Geopolitical risks: In February 2022, Russia's invasion of Ukraine and subsequent sanctions imposed by several nations (e.g., Canada, United Kingdom and the USA) and supranational political and/or economic unions (e.g., the EU) took global commodity markets into uncharted territory (UN GCRG, 2022). Whilst nations rally to forge new relationships and domestic policies to protect energy needs, challenges for securing a sustainable phosphorus supply are becoming apparent (World Bank Group, 2022).

3. Short-term responses exacerbating phosphorus exposure

In response to phosphate market disruptions in 2020–22, several governments implemented "knee-jerk" policies to protect domestic markets (Figure 1). In March 2021, the US International Trade Commission determined that the low price of phosphate fertilizer imports from Morocco and Russia had affected the US market and placed tariffs of 9–47% on phosphate fertilizer imports (Quinn, 2021). In May 2021, India increased subsidies for DAP fertilizer by 140% to protect farmers from increasing fertilizer costs. In October 2021, China (the second-largest fertilizer exporter in 2020 by value; US$ 6.57 billion in 2020) stopped all exports further constraining global supply and accelerating price rises. Countries dependent on China for supply (e.g., Australia, India, Pakistan and countries in South-East Asia, and the USA) have been forced to reduce imports or import from elsewhere. In November 2021, Turkey placed export restrictions on phosphate fertilizers further tightening the market. In March 2022, Russia (the largest fertilizer exporter by value; US$ 7 billion) suspended fertilizer exports, asserting sanctions were impacting international shipping. Nevertheless, phosphate prices had already increased substantially before 24 February 2022 (Figure 1). As observed in 2008, multiple short-term government responses designed to protect national interests can simultaneously disrupt global phosphorus trade and increase phosphorus exposure on a global scale. The immediate effects on different phosphate forms also appear to be different, with price changes in phosphate rock lagging several months behind DAP and TSP fertilizers (Figure 1).

4. Short-term actions to confer resilience to phosphorus exposure

It is a matter of shared global interest to reduce unpredictable phosphorus price volatility. There are many opportunities for action. For example, international diplomacy could encourage countries to lift phosphorus export restrictions and avoid new ones. Current restrictions are estimated to be impacting 20% of the global fertilizer trade and threaten more than 50% of the fertilizer supply for 24 countries (Hebebrand and Laborde, 2022). Whilst elevated prices persist, governments would be well-advised to review financial support for farmers in tandem with support to optimize on-farm nutrient use efficiency (Masso et al., 2022). It can be argued that the international community has a moral responsibility to support lower-income countries to access sufficient phosphorus to maintain domestic food production (Kahiluoto et al., 2021). Where international aid is appropriate, it should aim to avoid contributing to inflation, and for countries under severe economic stress, financial support may be grant-based to minimize further debt creation (Hebebrand and Laborde, 2022).

A further opportunity for governments is to explore how International Commodity Agreements can be used to protect food security in developing economies with high market exposure (Oehl, 2022). This could be driven by a "fair and equitable benefit-sharing" approach, following examples adopted for other natural resources including marine resources, land use, forest and water management, food production and other extractive activities (Morgera, 2016). Here, we would envisage the application of multilateral and bilateral deals, which could for example secure a stable phosphorus supply to vulnerable nations that do not have domestic phosphorus supplies, in exchange for securing agricultural exports from those vulnerable countries. Such multilateral deals may be moderated through an international organization (e.g., The World Trade Organization). A benefit-sharing approach for the trade of phosphorus may not directly mitigate the effects of phosphorus pollution on the environment. However, benefit sharing of transboundary waterbodies may require upstream water users to better manage their phosphorus pollution to avoid polluting shared water bodies, and in this way mitigate phosphorus pollution. In addition, the development by the financial sector of a sustainable investment strategy for the phosphorus mining/fertilizer sector (e.g., as established for the fossil fuels sector) could help enable fair and ethical supplies of affordable phosphorus fertilizers for use where it is needed (Schütze et al., 2017).

However, to mitigate the impacts of phosphorus pollution and future phosphorus price spikes, strategies that deliver long-term resilience to phosphorus vulnerability are required.

5. Building long-term resilience to phosphorus vulnerability

We highlight three opportunities that could build long-term resilience nationally and internationally to phosphorus price volatility and regional food and water insecurity (Figure 2).

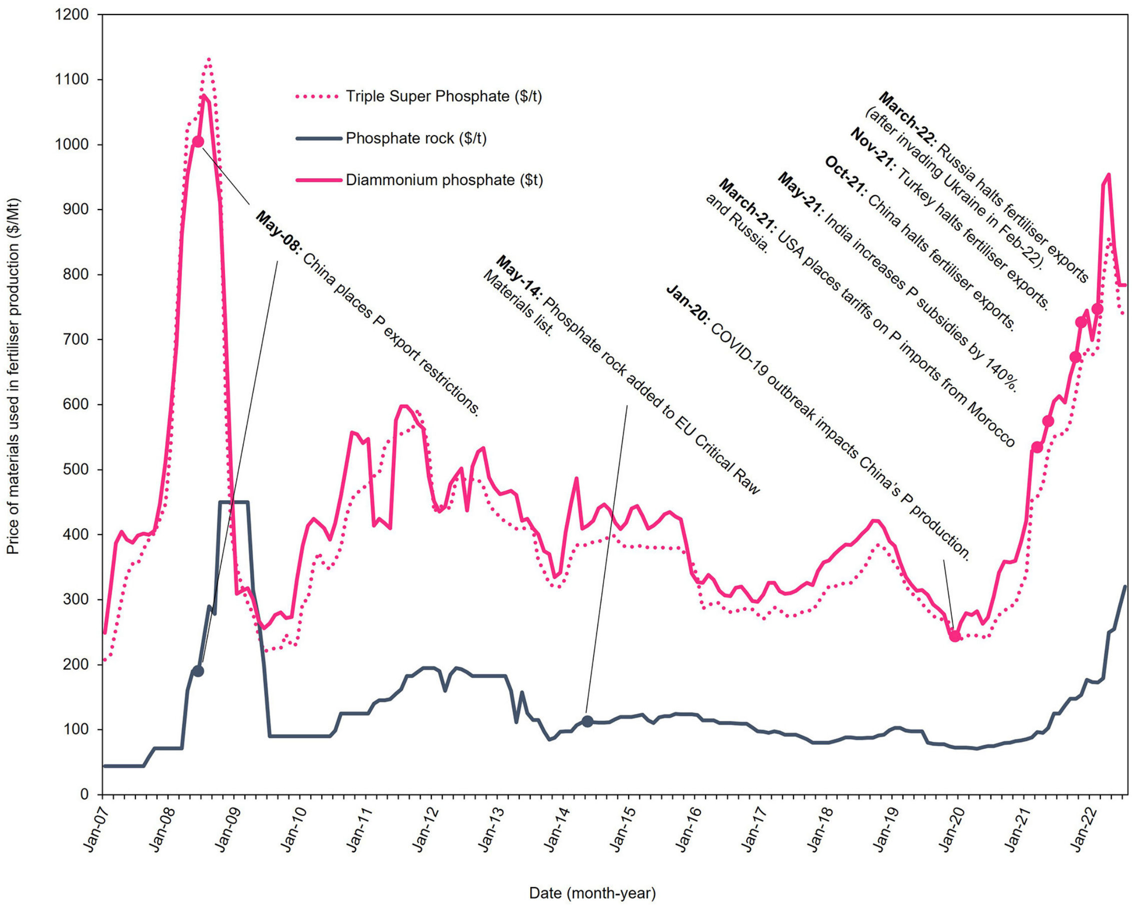

FIGURE 1
The monthly price, January 2007 to June 2022, of phosphorus (P) commodities used in fertilizer production (US$ ton^{-1}): triple super phosphate, diammonium phosphate and phosphate rock. The price of phosphorus peaked in 2008 and increased sharply again in 2021. Key national responses impacting the trade of phosphorus and fertilizer are shown. Data Source: The World Bank (2023).

5. 1. Opportunity 1: Nations commit to the real-time assessment of their phosphorus vulnerability

Barbieri et al. (2022) have proposed a methodology to assess food system vulnerability to phosphorus commodity price spikes. Such methodologies could be further developed to include risks to water security, blue food systems and social development, caused by phosphorus losses along the food-value chain. Such integrated phosphorus vulnerability assessments should be adaptable to diverse national conditions and highlight socio-economic, environmental and climate change impacts (Downing et al., 2021). Relevant activities could build on established work (Nanda et al., 2019), and learn from relevant national and international projects (INMS, 2022). Here, a first step would be to set up systems to identify, collect and monitor phosphorus vulnerability and security indicators as identified in the literature (Cordell and White, 2015). Systems can then be established to warn vulnerable stakeholders of imminent risks associated with phosphorus vulnerability (e.g., looming price spikes and algal blooms).

To give stakeholders early warning of disruption to phosphorus access, it is critical to collect/provide accurate, transparent and current information on phosphorus fertilizer supply, including government or private sector reserves. Initiatives like the IFPRI fertilizer dashboard (IFPRI, 2023), and data gathering, and monitoring efforts provided by the United States Geological Survey (USGS, 2023), International Fertilizer Association (IFA, 2023), AfricaFertiliser (AFO, 2023), and The World Bank (The World Bank, 2023) could be linked to wider agricultural data portals, such as FAOSTAT (FAO, 2023), or information systems such as the Agricultural Market Information System (AMIS, 2023). Importantly, the drivers behind, and implications of, market exposure need to be understood at the national level, ideally employing future projections to inform long-term planning (Yang et al., 2022). The framework for such assessments has been developed for other commodities, for example, the International Energy Agency (IEA, 2023) provides early warnings of market volatility and geographical exposure for energy commodities.

To assess water security risk, integrated sensor networks, earth observation, regulatory monitoring data (e.g., discharge consents), and catchment land-use export modeling can be used to quantify sector-specific phosphorus losses. Ecological and natural capital

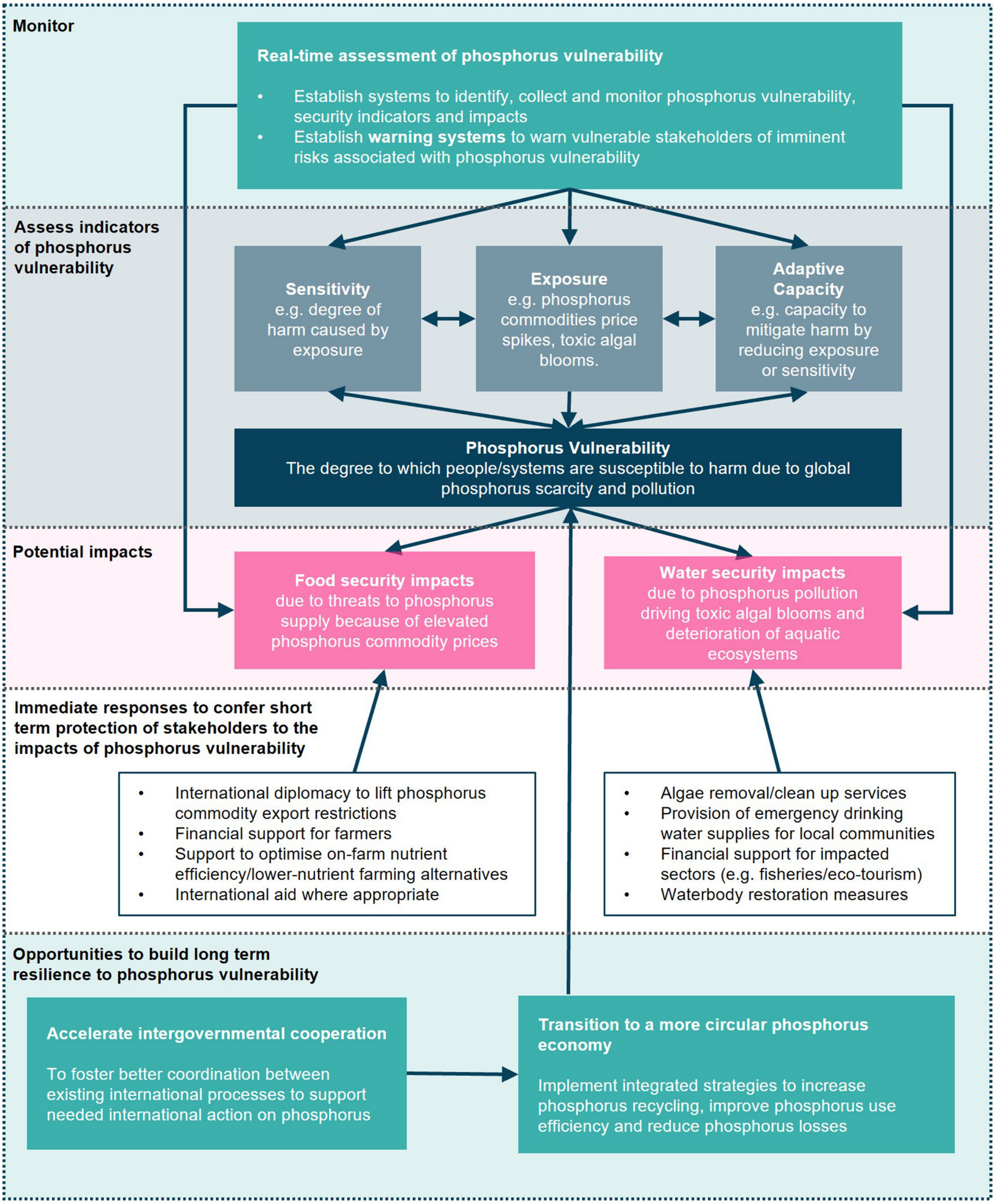

FIGURE 2
A theoretical framework showing short-term responses to protect stakeholders from potential impacts of phosphorus vulnerability and opportunities to build resilience to phosphorus vulnerability in the long term.

targets can be set by linking emissions reduction contributions to ecosystem responses using empirical data and ecosystem modeling tools. Such data could be combined with modeling tools to produce maps (e.g., the "Aqueduct" global water risk tool—World Resources Institute, 2021) to identify where mitigation efforts should be prioritized.

5.2. Opportunity 2: Accelerate a global transition to a more circular phosphorus economy

Efforts to link increasing phosphorus recycling, improving use efficiency and reducing phosphorus losses are necessarily interlinked, all of which can buffer against phosphorus supply risks and reduce phosphorus pollution (Brownlie et al., 2022b). Strategies to improve the circularity of national/regional phosphorus cycles, underpinned by national substance flow analysis, have already been proposed for Brazil (Withers et al., 2018), the EU (van Dijk et al., 2016), the USA (Metson et al., 2016), China (Sattari et al., 2014), Australia (Cordell et al., 2014), and the United Kingdom (Rothwell et al., 2022). A common goal among these plans is to optimize agricultural phosphorus use efficiency across multiple scales (Masso et al., 2022). Options to ensure phosphorus inputs to soils match crop growth requirements include precision agriculture, the use of smart fertilizers (e.g., controlled-release phosphate fertilizer), integrated nutrient management and integrated soil fertility management (including water and weed management). Structural farming measures to reduce erosion and runoff and innovations to improve uptake of residual phosphorus stores (e.g., rhizosphere management and the use of phosphorus efficient cultivars and bio-fertilizers) can reduce phosphorus losses and therefore input requirements. In many cases, the safe recycling of treated animal manures and residues and the use of recycled fertilizers can be increased, with corresponding reductions in mineral fertilizer use. However, we argue that a more integrated systems-based approach is needed to improve phosphorus stewardship *throughout* the food production and consumption chain, not just within agriculture (Metson et al., 2022), and across whole regions (Hamilton et al., 2018).

To achieve this, a paradigm shift is urgently needed in how society deals with residue streams, i.e., shifting from a pollutant focus to an appreciation of valued nutrient resources. With >30 different technologies available to recover phosphorus from residue streams, there are many options available (Kabbe and Rinck-Pfeiffer, 2019).

Emissions and other measurable targets can provide an important means to incentivise and increase phosphorus recycling (Brownlie et al., 2022b). Such initiatives are generally lacking internationally; those that exist are slow-moving, fragmented and confined to more economically developed countries lacking domestic phosphorus reserves. For example, the 2008 fertilizer price spike triggered the EU to place phosphate rock on the EU list of critical raw materials (European Commission, 2014), which, in part, led to innovative legislation to increase the recovery of phosphorus from waste/residue streams in Switzerland, Sweden, Austria and Germany (Günther et al., 2018). However, currently, only Switzerland and Germany have adopted regulations that make phosphorus recovery mandatory, but without corresponding regulations to recycle the phosphorus recovered. More radical change could also be considered. For example, Kahiluoto et al. (2021) have proposed that nutrient-rich sediments and residues could be processed and transported to food-insecure regions using a reverse of the logistics by which phosphate rock and other raw materials were shipped to industrializing countries in the Global North.

At the regional scale, in 2018, the revision of the EU Fertilizers Regulation (EC) No. 2003/2003, aimed to increase market opportunities for developing a circular economy of recycled phosphate fertilizers, while reducing dependence on imported nutrients. In 2020, the European Commission published "The Farm to Fork strategy" underpinning the European Green Deal, which calls for actions to reduce nutrient losses by >50% and to reduce fertilizer use by >20% by 2030. However, many nations lack relevant environmental regulations to support phosphorus recycling in this way, and capital investment remains a significant barrier (Brownlie et al., 2022b). A recently proposed goal for fertilizer products to contain a minimum of 20% recycled phosphorus by 2030 could set a benchmark that demonstrates green commitment across the fertilizer industry (Brownlie et al., 2022b).

5.3. Opportunity 3: Accelerate intergovernmental cooperation as a catalyst for change

Delivery of the opportunities outlined above could be further supported by the establishment of an inter-governmental mechanism to foster better cooperation and coordination between existing international processes (Brownlie et al., 2021). The mandates of existing multilateral environmental agreements (e.g., Convention on Biological Diversity, the Aarhus Convention or the United Nations Framework Classification for Resources) are currently too narrow to address the drivers of phosphorus price volatility and support strategies to increase the circular use of phosphorus (Brownlie et al., 2021). Experience with nitrogen points to the need to draw as far as possible on the work of existing bodies and explore opportunities for "Inter-convention Coordination" (Sutton et al., 2021). Such an approach is currently being explored for nitrogen (UNEP, 2019) and is acknowledged in two United Nations Environment Assembly resolutions for Sustainable Nitrogen Management (UNEP/EA.4/Res.14; UNEP/EA.5/Res.2). As highlighted in the second of these resolutions, it is time that nations developed long-term plans to significantly increase nutrient recycling and reduce polluting losses, including phosphorus.

6. Conclusion

Overall, it can be concluded that the current crisis in global phosphorus prices represents a wake-up call on the underlying problems of phosphorus pollution. The price spikes have been triggered by a combination of uncoordinated national decisions and are impacting food security in vulnerable communities and countries, compounding the existing food and energy crises. Whilst several short-term measures could be implemented to alleviate farmer and food insecurity in these nations (e.g., increasing fertilizer subsidies), we argue that investing in longer-term transformative phosphorus initiatives, as described above, would not only create more resilient food and water systems but also reduce the impact of short-term phosphorus risks in the future. The necessary knowledge is already available and being applied by some countries in longer-term plans to build greater resilience to phosphorus vulnerability (Brownlie et al., 2021; Barbieri et al., 2022). However, these green shoots of progress must now be planted across all countries.

Author contributions

WB co-conceived the idea of the manuscript and led the writing of the paper, and collated and conducted data analysis. MS, DC, DR, KH, PW, and IV contributed to writing the paper. BS co-conceived the idea of the manuscript and contributed to writing the paper. All authors contributed to the article and approved the submitted version.

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References

AFO. (2023). *Fertilizer Information in Africa* Available online at: https://africafertilizer.org/statistics/#/en (accessed January 25, 2023).

AMIS. (2023). *Agricultural Market Information System*. Available online at: http://www.amis-outlook.org/ (accessed January 25, 2023).

Bajželj, B., Richards, K. S., Allwood, J. M., Smith, P., Dennis, J. S., Curmi, E., et al. (2014). Importance of food-demand management for climate mitigation. *Nat. Clim. Change* 4, 924–929. doi: 10.1038/nclimate2353

Barbieri, P., MacDonald, G. K., Bernard de Raymond, A., and Nesme, T. (2022). Food system resilience to phosphorus shortages on a telecoupled planet. *Nat. Sustain.* 5, 114–122. doi: 10.1038/s41893-021-00816-1

Brownlie, W. J., Sutton, M. A., Boer, M. A., de, Camprubi, L., Hamilton, H. A., Heal, K. V., et al. (2022a). "Chapter 2. Phosphate rock: resources, reserves and uses," in *Our Phosphorus Future*, eds W. J. Brownlie, M. A. Sutton, K. V. Heal, D. S. Reay, and B. M. Spears (Edinburgh: UK Centre for Ecology and Hydrology), 23–76.

Brownlie, W. J., Sutton, M. A., Heal, K. V., Reay, D. S., and Spears, B. M., eds. (2022b). *Our Phosphorus Future*. Edinburgh: UK Centre for Ecology and Hydrology.

Brownlie, W. J., Sutton, M. A., Reay, D. S., Heal, K. V., Hermann, L., Kabbe, C., et al. (2021). Global actions for a sustainable phosphorus future. *Nat. Food* 2, 71–74. doi: 10.1038/s43016-021-00232-w

Carpenter, S. R., and Bennett, E. M. (2011). Reconsideration of the planetary boundary for phosphorus. *Environ. Res. Lett* 6, 14009–14021. doi: 10.1088/1748-9326/6/1/014009

Cordell, D., Mikhailovich, N., Mohr, S., Jacobs, B., and White, S. (2014). *Adapting to Future Phosphorus Scarcity: Investigating Potential Sustainable Phosphorus Measures and Strategies, Phase II of the Australian Sustainable Phosphorus Futures Project, Prepared by Institute for Sustainable Futures, University of Technology, Sydney, for the Rural Industries Research and Development Corporation.* Canberra: Australian Government.

Cordell, D., and Neset, T. S. S. (2014). Phosphorus vulnerability: a qualitative framework for assessing the vulnerability of national and regional food systems to the multi-dimensional stressors of phosphorus scarcity. *Glob. Environ. Change* 24, 108–122. doi: 10.1016/j.gloenvcha.2013.11.005

Cordell, D., Turner, A., and Chong, J. (2015). The hidden cost of phosphate fertilizers: mapping multi-stakeholder supply chain risks and impacts from mine to fork. *Glob. Chang. Peace Secur*. 27, 323–343. doi: 10.1080/14781158.2015.1083540

Cordell, D., and White, S. (2015). Tracking phosphorus security: indicators of phosphorus vulnerability in the global food system. *Food Secur*. 7, 337–350. doi: 10.1007/s12571-015-0442-0

Cross, L. (2022). *Why Are Fertilizer Prices so High? IFA Market Intelligence Service*. Available online at: https://www.fertilizer.org/Public/News___Events/IFA_Blog/2022_02_07_Why_are_Fertilizer_Prices_so_High.aspx (accessed February 17, 2023).

Dasgupta, P. (2021). *The Economics of Biodiversity: The Dasgupta Review*. London: HM Treasury.

de Jager, T. (2022). *International Food Policy Research Institute Event - "Fertiliser Availability and Affordability: Implications for Agricultural Productivity and Food Security"*. Available online at: https://www.ifpri.org/event/fertiliser-availability-and-affordability-implications-agricultural-productivity-and-food (accessed February 17, 2023).

de Ridder, M., de Jong, S., Polchar, J., and Lingemann, S. (2012). *Risks and Opportunities in the Global Phosphate Rock Market. Robust Strategies in Times of Uncertainty*. Hague Cent. Strateg. Stud. No 17 | 12 | 12. Available online at: www.hcss.nl (accessed February 04, 2019).

Downing, J. A., Polasky, S., Olmstead, S. M., and Newbold, S. C. (2021). Protecting local water quality has global benefits. *Nat. Commun*. 12, 1–6. doi: 10.1038/s41467-021-22836-3

European Commission. (2014). *Report on Critical Raw Materials for the EU - Critical Raw Materials Profiles*, 77–85.

FAO. (2023). *FAOSTAT*. Available online at: https://www.fao.org/faostat/en/#home (accessed January 25, 2023).

Günther, S., Grunert, M., and Müller, S. (2018). Overview of recent advances in phosphorus recovery for fertilizer production. *Eng. Life Sci.* 18, 434–439. doi: 10.1002/elsc.201700171

Hamilton, H. A., Ivanova, D., Stadler, K., Merciai, S., Schmidt, J., van Zelm, R., et al. (2018). Trade and the role of non-food commodities for global eutrophication. *Nat. Sustain.* 1, 314–321. doi: 10.1038/s41893-018-0079-z

Hebebrand, C., and Laborde, D. (2022). *Short-Term Policy Considerations to Respond to Russia-Ukraine Crisis Disruptions in Fertilizer Availability and Affordability*. International Food Policy Research Institute Available online at: https://www.ifpri.org/blog/short-term-policy-considerations-respond-russia-ukraine-crisis-disruptions-fertilizer (accessed February 17, 2023).

IAASTD. (2009). *Global Report International Assessment of Agriculture at a Crossroads*.

IEA. (2023). *Data and Statistics*. Available online at: https://www.iea.org/data-and-statistics (accessed January 25, 2023).

IFA. (2023). *IFASTAT*. Available online at: https://www.ifastat.org/supply/Phosphate%20Products/Phosphate%20Rock (accessed January 25, 2023).

IFPRI. (2023). *IFPRI Fertilizer Dashboard*. Available online at: https://public.tableau.com/app/profile/laborde6680/viz/Fertilizer_Dashboard/FertilizerDashboard (accessed January 25, 2023).

INMS. (2022). *The International Nitrogen Management Project*. Available online at: https://www.inms.international/ (accessed February 17, 2023).

International Fertilizer Association. (2021). *Public Summary Medium-Term Fertilizer Outlook 2021-2025. A/21/82*. International Fertilizer Association, Paris, France.

International Fertilizer Industry Association. (2011). *Feeding the Earth: Food Prices and Fertilizer Markets*. International Fertilizer Industry Association, Paris, France.

Jasinski, S. M. (2022). *Mineral Commodity Summaries: Phosphate Rock*. U.S. Geol. Surv, Washington, DC, United States.

Johnes, P. J., Heathwaite, A. L., Spears, B. M., Brownlie, W. J., Elser, J. J., Haygarth, P. M., et al. (2022). "Chapter 5. Phosphorus and water quality," in *Our Phosphorus Future*, eds W. J. Brownlie, M. A. Sutton, K. V. Heal, D. S. Reay, and B. M. Spears (Edinburgh: UK Centre for Ecology and Hydrology), 163–222.

Kabbe, C., and Rinck-Pfeiffer, S. (2019). *Global Compendium on Phosphorus Recovery from Sewage/Sludge/Ash*. Australia: Global Water Research Coalition.

Kahiluoto, H., Pickett, K. E., and Steffen, W. (2021). Global nutrient equity for people and the planet. *Nat. Food* 2, 857–861. doi: 10.1038/s43016-021-00391-w

Khabarov, N., and Obersteiner, M. (2017). Global phosphorus fertilizer market and national policies: a case study revisiting the 2008 price peak. *Front. Nutr*. 4, 22. doi: 10.3389/fnut.2017.00022

Masso, C., Zhang, F., Adhya, T. K., Blackwell, M. S. A., Macintosh, K. A., Johnes, P. J., et al. (2022). "Chapter 4. Opportunities for better phosphorus use in agriculture," in *Our Phosphorus Future*, eds W. J. Brownlie, M. A. Sutton, K. V. Heal, D. S. Reay, and B. M. Spears (Edinburgh: UK Centre for Ecology and Hydrology), 117–162.

Metson, G. S., Brownlie, W. J., Bausch, J. C., Jonell, M., Matsubae, K., Mnthambala, F., et al. (2022). "Chapter 8. Consumption - the missing link towards phosphorus sustainability," in *Our Phosphorus Future*, eds W. J. Brownlie, M. A. Sutton, K. V. Heal, D. S. Reay, and B. M. Spears (Edinburgh: UK Centre for Ecology and Hydrology), 313–342.

Metson, G. S., MacDonald, G. K., Haberman, D., Nesme, T., and Bennett, E. M. (2016). Feeding the corn belt: opportunities for phosphorus recycling in U.S. agriculture. *Sci. Total Environ*. 542, 1117–1126. doi: 10.1016/j.scitotenv.2015.08.047

Mogollón, J. M., Bouwman, A. F., Beusen, A. H. W., Lassaletta, L., van Grinsven, H. J. M., and Westhoek, H. (2021). More efficient phosphorus use can avoid cropland expansion. *Nat. Food* 2, 509–518. doi: 10.1038/s43016-021-00303-y

Morgera, E. (2016). The Need for an international legal concept of fair and equitable benefit sharing. *Eur. J. Int. Law* 27, 353–383. doi: 10.1093/ejil/chw014

Nanda, M., Cordell, D., and Kansal, A. (2019). Assessing national vulnerability to phosphorus scarcity to build food system resilience: the case of India. *J. Environ. Manag*. 240, 511–517. doi: 10.1016/j.jenvman.2019.03.115

Nedelciu, C. E., Ragnarsdottir, K. V., Schlyter, P., and Stjernquist,. I. (2020). Global phosphorus supply chain dynamics: assessing regional impact to 2050. *Glob. Food Sec*. 26, 1000426. doi: 10.1016/j.gfs.2020.100426

Oehl, M. E. (2022). *Sustainable Commodity Use*. Cham: Springer International Publishing. doi: 10.1007/978-3-030-89496-2

Quinn, R. (2021). *USITC Orders Duties on P Imports. Progress. Farmer*. Available online at: https://www.dtnpf.com/agriculture/web/ag/crops/article/2021/03/11/us-imports-phosphate-fertilizer-will (accessed February 17, 2023).

Rothwell, S. A., Forber, K. J., Dawson, C. J., Salter, J. L., Dils, R. M., Webber, H., et al. (2022). A new direction for tackling phosphorus inefficiency in the UK food system. *J. Environ. Manag*. 314, 115021. doi: 10.1016/j.jenvman.2022.115021

Sattari, S. Z., van Ittersum, M. K., Giller, K. E., Zhang, F., and Bouwman, A. F. (2014). Key role of China and its agriculture in global sustainable phosphorus management. *Environ. Res. Lett*. 9, 054003. doi: 10.1088/1748-9326/9/5/054003

Schütze, F., Fürst, S., Mielke, J., Steudle, G., Wolf, S., and Jaeger, C. (2017). The role of sustainable investment in climate policy. *Sustainability* 9, 2221. doi: 10.3390/su9122221

Sutton, M. A., Howard, C. M., Kanter, D. R., Lassaletta, L., Móring, A., Raghuram, N., et al. (2021). The nitrogen decade: mobilizing global action on nitrogen to 2030 and beyond. *One Earth* 4, 10–14. doi: 10.1016/j.oneear.2020.12.016

The World Bank. (2023). *Commodity Markets 'Pink Sheets' Data*. Available online at: https://www.worldbank.org/en/research/commodity-markets (accessed January 25, 2023).

UN GCRG. (2022). *Global Impact of War in Ukraine on Food, Energy and Finance Systems*. Brief no 1.

UNEP. (2019). *Roadmap for Action on Sustainable Nitrogen Management 2020-2022. Implementation of UNEA-4 Resolutions: Follow-up to UNEP/EA.4/Res.14. 2019 Inf. Doc*. Available online at: https://papersmart.unon.org/resolution/uploads/roadmap_for_action_on_sustainable_nitrogen_management_roadmap1.1.pdf (accessed February 17, 2023).

USDA. (2022). *World Agricultural Production*. WAP 4-22. Available online at: https://apps.fas.usda.gov/psdonline/circulars/production.pdf (accessed February 17, 2023).

USGS. (2023). *Phosphate Rock Statistics and Information*. Available online at: https://www.usgs.gov/centers/national-minerals-information-center/phosphate-rock-statistics-and-information (accessed January 25, 2023).

van Dijk, K. C., Lesschen, J. P., and Oenema, O. (2016). Phosphorus flows and balances of the European Union Member States. *Sci. Total Environ*. 542, 1078–1093. doi: 10.1016/j.scitotenv.2015.08.048

Withers, P. J. A., Rodrigues, M., Soltangheisi, A., De Carvalho, T. S., Guilherme, L. R. G., Benites, V. M., et al. (2018). Transitions to sustainable management of phosphorus in Brazilian agriculture. *Sci. Rep*. 8, 1–13. doi: 10.1038/s41598-018-20887-z

World Bank Group. (2022). *Commodity Markets Outlook: The Impact of the War in Ukraine on Commodity Markets, April 2022*. Washington, DC: World Bank. Available online at: https://www.nature.com/articles/s41893-021-00816-1 (accessed February 17, 2023).

World Resources Institute. (2021). *The Aqueduct' Global Water Risk Tool*. Available online at: https://www.wri.org/aqueduct (accessed February 02, 2023).

Yang, Z., Du, X., Lu, L., and Tejeda, H. (2022). Price and volatility transmissions among natural gas, fertilizer, and corn markets: a revisit. *J. Risk Financ. Manag*. 15, 91. doi: 10.3390/jrfm15020091