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Global-to-Local Dependencies in Phosphorus Mass Flows and Markets: Pathways to Improving System Resiliency in Response to Exogenous Shocks

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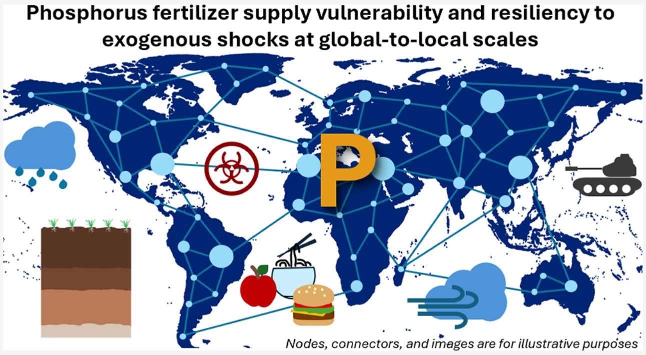
Phosphorus fertilizer supply vulnerability and resiliency to exogenous shocks at global-to-local scales

Nodes, connectors, and images are for illustrative purposes

ABSTRACT: Uneven global distribution of phosphate rock deposits and the supply chains to transport phosphorus (P) make P fertilizers vulnerable to exogenous shocks, including commodity market shocks; extreme weather events or natural disasters; and geopolitical instability, such as trade disputes, disruption of shipping routes, and war. Understanding bidirectional risk transmission (global-to-local and local-to-global) in P supply and consumption chains is thus essential. Ignoring P system interdependencies and associated risks could have major impacts on critical infrastructure operations and increase the vulnerability of global food systems. We highlight recent unanticipated events and cascading effects that have impacted P markets globally. We discuss the need to account for exogenous shocks in local assessments of P flows, policies, and infrastructure design choices. We also provide examples of how accounting for undervalued global risks to the P industry can hasten the transition to a sustainable P future. For example, leveraging internal P recycling loops, improving plant P use efficiency, and utilizing legacy soil P all enhance system resiliency in the face of exogenous shocks and long-term anticipated threats. Strategies applied at the local level, which are embedded within national and global policy systems, can have global-scale impacts in derisking the P supply chain.

KEYWORDS: *food security, phosphate, resilience, recycle, reuse, supply chain, sustainable, water*

1. PHOSPHORUS IS AN ESSENTIAL, BUT GEOGRAPHICALLY LIMITED, NONRENEWABLE RESOURCE

Phosphorus (P) is an essential plant nutrient underpinning the global food system. Most inorganic P fertilizers are sourced from a limited number of phosphate rock reserves globally, with approximately 86% of P rock reserves concentrated in just six countries: Morocco (68%); China (5%); Egypt (4%); and Algeria, Tunisia, and Russia (3% each).[1] By comparison, the 12 member countries of OPEC are thought to control roughly 80% of the world oil reserves.[2] Annual production rates from 2019 indicate that phosphate rock mining is dominated by China (41%), Morocco (16%), the U.S. (9%), and Russia (6%).[1] Similarly, phosphate exports are dominated by a handful of countries: China (20%), Morocco (14%), Russia (11%), the U.S. (8%), and Saudi Arabia (8%).[3] Accordingly, most nations import mineral P fertilizers to support agricultural activities with two-thirds of countries using at least 40% imported P.[4] Although P import ratios are not currently considered drivers of management or policy, P vulnerabilities in fertilizer access (and the associated pricing) may kindle motivations to transition to a sustainable P future by establishing alternate P sources, e.g., local, recyclable sources of P in manure and wastewater/biosolids.[4]

Policies to improve resilience in local food systems have primarily focused on regional market uncertainties and the implications of changing climate and environmental conditions. However, policymakers and resource managers may not fully understand or account for the risks of P fertilizer supply chain disruption and the impact of global market anomalies on local systems. Recent events have shocked the P market, generating higher fertilizer and food prices. In addition to creating food security risks, these global events can also

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increase environmental risks through increased fertilizer manufacturing and crop production intensification in some locations to offset reductions in other locations.

The objective of this Global Perspectives article is to describe underappreciated risks of P market disruption to local and global food production and environmental systems and to offer several examples of interventions that could improve P system resilience and reduce risks of disruption at global and local scales. We focus on U.S.-centric data and examples, but the global-to-local dependencies discussed are relevant to other contexts.

2. BLACK SWANS AND DRAGON KINGS: P VULNERABILITY TO EXOGENOUS SHOCKS

Uneven global distribution of phosphate rock and the supply chains to transport P makes P fertilizers vulnerable to "black swans"[5] and "dragon kings"[6]—low probability but high impact events that create exogenous shocks to the P system. In recent years, natural disasters and world events have exposed critical infrastructure in the P system to a series of sustainability challenges. While their very unpredictability makes them difficult to prepare for, they highlight the need to make P infrastructure more resilient.

Evaluations of raw material criticality broadly seek to capture supply risk, vulnerability to supply disruption, and (more recently) environmental implications.[7] Although the impacts of fossil fuel supply risks have been evaluated for decades, only more recently have nonfuel minerals (e.g., rare earth metals) been studied.[7] For example, Erdmann and Graedel's (2011)[7] review identified only one analysis of P criticality. Since then, however, nonfuel minerals have attracted more attention, particularly with respect to circular economies. For instance, phosphate rock has been included on the EU's list of critical raw materials since 2014.[8]

Critical infrastructure is defined as the assets, systems, and networks that underpin society, disruption of which would have debilitating impacts.[9] Critical infrastructure also includes systems-level integration into complex socio-technological networks, which can amplify the impact of local disruptive events to generate broader impacts.[10] Based on this definition, we follow the U.S. National Infrastructure Protection Plan[9] in arguing that P supply and consumption chains constitute critical infrastructure. In our definition of critical P infrastructure, we include phosphate mines, fertilizer processing facilities, transportation networks for raw material and fertilizers, high-density agricultural production systems (e.g., concentrated animal feeding operations [CAFOs] or the U.S. Corn Belt), and waterbodies receiving P-laden discharges/runoff.

These elements of critical infrastructure in the P system are threatened by exogenous shocks stemming from natural disasters and political/economic events. Disasters caused by severe weather events such as Hurricane Ida and the Texas Freeze (both in 2021) have the potential to impact P supply chains[11] by damaging or temporarily shutting down critical infrastructure. Current science on climate change suggests that comparable extreme weather events are likely to become more frequent and not less. Thus, climate change has the potential to dramatically compound P supply risks by impacting several critical infrastructure nodes.[9,11]

Many phosphate processing facilities are in areas where natural hazards, such as hurricanes and coastal flooding, could disrupt production (Figure 1A).[12] In addition, such hazards

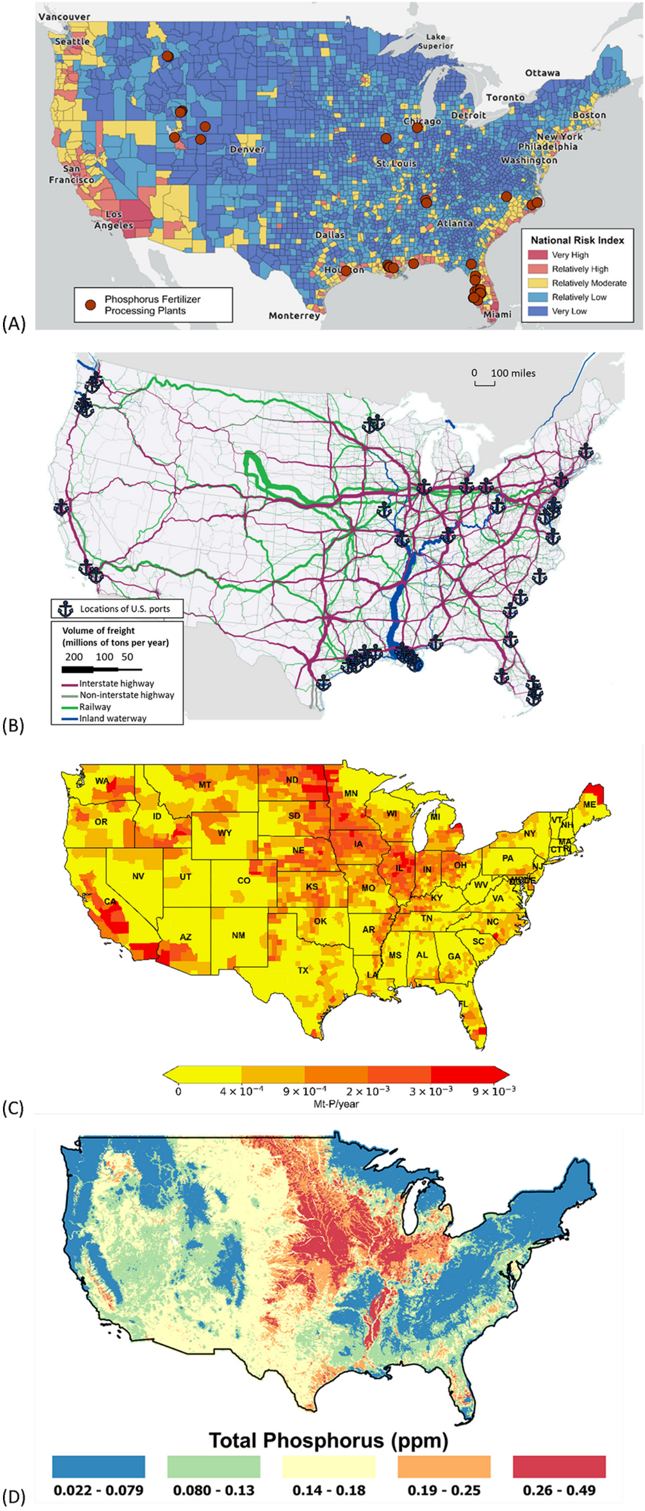


Figure 1. (A) Active and retired P-phosphate processing plants in the conterminous U.S. (data from McFaul et al. (2000);[18] Nelson et al. (2021)[19]) mapped against the National Risk Index (data from U.S. FEMA).[12] The National Risk Index is a composite rating used to inform planners, managers, and decision makers at local-to-national levels about the risks from 18 natural hazards (avalanche, coastal flooding, cold wave, drought, earthquake, hail, heat wave, hurricane, ice storm, landslide, lightning, riverine flooding, strong wind, tornado, tsunami, volcanic activity, wildfire, and winter weather).[12] (B) Major freight transportation networks that could be used to transport raw materials and fertilizer (modified from U.S. DOT reports).[20,21] (C) Agricultural production systems illustrated by annual rates of P

Figure 1. continued

application from rock phosphate fertilizer (data from the Nutrient Use Geographic Information System).[22] (D) Total P concentrations for the gridded stream network shown as seasonal averages of winter, spring, summer, and autumn data at a spatial resolution of 30 arc-seconds (approximately 1 km) (data from Shen et al. (2019),[23] (2020)[24]).

can also interrupt transportation systems, including ports and freight networks, which are critical infrastructure for distributing P (Figure 1B). For example, phosphate is a major export from the Port of Jacksonville (FL), and fertilizer products are distributed throughout the U.S. Southwest from California's Port of Hueneme.[13] Thus, disruptions due to natural hazards could adversely affect agricultural production. Moreover, evidence suggests that climate change and the associated increase in extreme weather events may exacerbate P losses from agriculture or stormwater runoff (Figure 1C),[14,15] increasing P inputs to environmental waters (Figure 1D) and spurring eutrophication, highlighting an even greater need to conserve P in areas experiencing extreme weather events. As the U.S. set a national record for the number of natural disasters and climate catastrophes in 2023,[16] there is a pressing need to secure P supplies in areas experiencing extreme weather events and to enhance P supply chain resiliency while also protecting environmental water quality via regulatory strategies accounting for P inputs from both point and nonpoint sources. Natural disasters are not the only source of risk to infrastructure, as the recent catastrophic collapse of the Key Bridge in the Port of Baltimore (MD) demonstrates. While not a major hub for phosphate or P fertilizer trade, the Port of Baltimore receives the largest share of urea ammonium nitrate imports along the U.S. Atlantic coast.[17]

Beyond natural hazards, political instability and policy choices can also introduce cascading disasters, which can compound risks and introduce more uncertainty into the P supply system. For example, the Russia−Ukraine war impacted P trade flows and markets when Russia (the largest phosphate rock exporter by economic value in 2021 at $293M, followed by Egypt at $97M)[25] claimed that sanctions following its invasion of Ukraine impacted international shipping, and subsequently suspended fertilizer exports.[11]

Policy making can also deliver shocks to the P system, where trade disputes offer an additional illustration of complex interdependencies disrupting the P fertilizer supply chain. For example, since 2020, the U.S., China, and other countries have engaged in protectionist trade policy decisions, which have contributed to P fertilizer price surges not observed since the 2008 financial crisis. In early 2021, the U.S. Department of Commerce, in response to appeals made by the U.S. fertilizer producer Mosaic, imposed tariffs of 9−47% on phosphate fertilizer from Russia and Morocco based on an assessment that the companies producing this fertilizer were being unfairly subsidized by their respective governments. These tariffs were appealed to the U.S. International Trade Commission with political pressure applied by representatives of major crop commodity groups and by U.S. politicians from agricultural states. In November 2023, the U.S. Department of Commerce retroactively decreased the duties on Moroccan phosphate (from 20% to 2%) but raised the duty on Russian producer PhosAgro from 9% to 29%. To our knowledge, while P imports and exports are governed by World Trade Organization rules (with few quantitative restrictions), member states still tend to use [typically low][26] tariffs as a preferred response to unfair trading practices rather than resorting to other remedies.

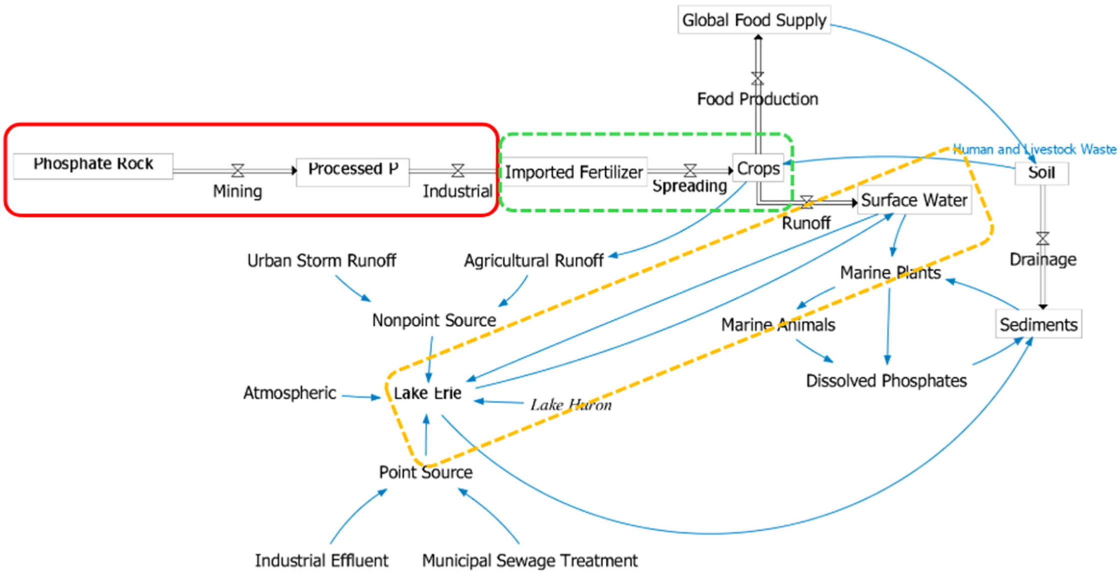
Beyond trade wars, national and transnational regulatory policies can impinge on P flows. That policy can shift dramatically depending on election outcomes and other political shifts. For example, in 2008, a commodity price spike affected markets for fossil fuels, fertilizers, and other related commodity markets at the same time that short-term government responses aimed at safeguarding national interests disrupted the global P trade.[11] More recently, the EU Green Deal aiming to reduce nutrient losses by 50% by 2030, and further efforts to reduce nutrient applications in agriculture, has resulted in political controversy. Recent evidence suggests that we may continue to see higher P fertilizer prices and increased market volatility due to a confluence of policy, market, and environmental factors.[27]

Given the increased likelihood of low probability, high impact global shocks in the future, it is essential to formally incorporate these risks into P assessments and management to better understand where P systems are most vulnerable to disruption and inform risk management plans to promote resiliency as a component of sustainable P management. Moreover, these examples underscore the importance of considering the bidirectional impacts of localized, short-term shocks on global P flows (via natural disasters) and the effects of global market disruption (e.g., trade policy disputes) on local P flows and environmental impact. These global shocks also shape local efforts to manage P at the watershed or community level, affecting the supply and disposition of phosphate rock and P fertilizers, where disruptions ultimately manifest as increased economic burdens on farmers. Decision makers focused on P management and sustainability cannot fully decouple local P management decisions from global market developments and the risks of low-probability but high-impact exogenous shocks because such events necessarily impinge on the availability and price of fertilizer at the local scale. Ignoring these interdependencies and associated risks will result in more vulnerable food systems and may slow the pace of the transition to a more sustainable P future that includes, among other interventions, a more decentralized and circular supply of P fertilizers from recycled P sources.

A key challenge with critical infrastructure is that systems can suffer from "lock-in," wherein the system is constrained in some way that does not adapt to short-term shocks or future needs.[28] Given the relatively small number of P mines and processing plants, P systems are subject to economic and technological conditions that create lock-in and constrain the system, hampering efforts to increase system resilience to both systemic (macroeconomic) risks and local supply chain risks. However, we argue that the economic and technological pressures underlying lock-in for P could help catalyze change through sustained higher market prices and diminished availability of P fertilizers if complemented by policy and strategic public investment.

P vulnerability is driven by interactions between the degree of exposure to exogenous shocks, sensitivity (or degree of harm caused by the exposure), and the adaptive capacity to mitigate risk by reducing exposure or sensitivity.[29] Policymakers, fertilizer manufacturers, environmental managers, and the agricultural community may under-appreciate the ways in which P vulnerability can be compounded or exacerbated by global supply chain risks such as climate change or environ-

(A) Lake Erie Example



(B) Central Florida Example

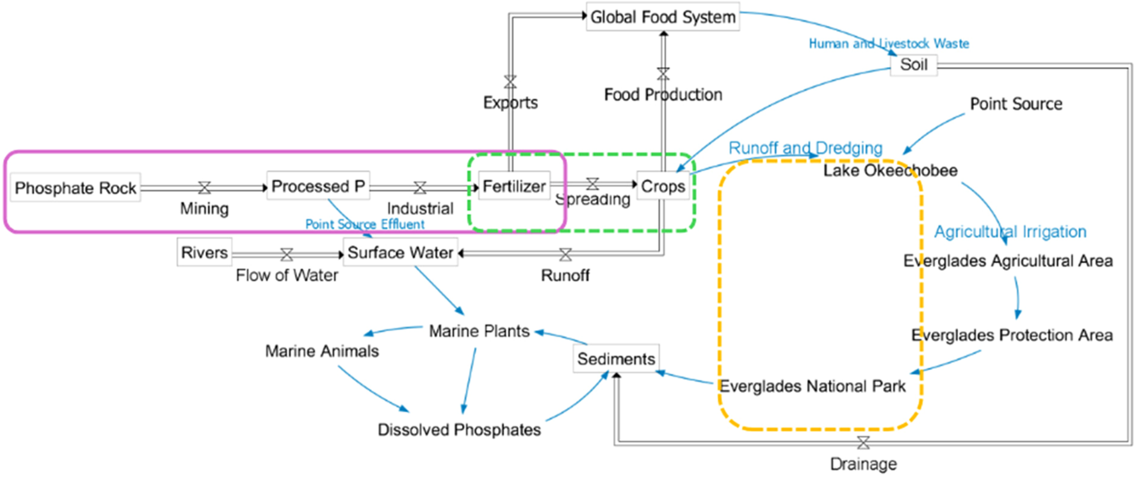


Figure 2. Conceptual illustration of systems dynamics in P flows for two case study regions: (A) Lake Erie and (B) Central Florida. Further description of the models is provided in the Supporting Information. Stocks are represented by text surrounded by an outlined box while flows are hollow tubes with an hourglass symbol representing the valve. Text not in outlined boxes indicates auxiliary variables with a parameter value calculated with basic arithmetic, whereas stocks are calculated using an integral of inflows and outflows, including connections between the global food system and local stocks and flows of P. Solid blue lines are used as dependencies and typically connect auxiliary variables to stocks or other auxiliary variables. Lake Huron is shown in *italics* in panel A to emphasize that it is an input with its own sources and systems for P. Portions of the P flow diagram where risks of supply disruption were transmitted from global to local scales are indicated with a solid red border representing global supply risks, purple border representing local supply risks, green dotted lines representing local fertilizer and food production responses, and yellow dashed lines representing points of vulnerability from increased direct environmental impact.

mental disasters. The general public may be even less aware of the direct human consequences of P scarcity, such as food insecurity, hunger, and geopolitical instability, in addition to the health effects of unabated P pollution.[11,29] If we are to imagine and design a resilient P system, we need to consider design approaches at various scales, including adaptive management,[30] trade-offs between efficiency and resilience,[31] and increased agility and flexibility.[32]

3. IDENTIFYING OPPORTUNITIES TO ENHANCE P RESILIENCY

Decision makers can increase resiliency by identifying P flow bottlenecks as well as building redundancy and reliable alternatives to critical points in the system,[33] such as fertilizer manufacturing and storage facilities and transportation networks. Additionally, identifying sensitive nodes vulnerable to cascade events[10] and considering the net impact (environmental and economic) of international P flows and trade dependencies is also critical for improving P system resilience.

3.1. Global-to-Local Interdependencies and Risk Transmission from P Supply Chains. To conceptually illustrate sources of risk to P supply chains and management in coupled global—local systems, we developed systems dynamics diagrams for two case studies: Lake Erie (LE, Figure 2A) and the Central Florida (CF) region (Figure 2B). These case studies were selected to highlight local risks and interdependencies in P management systems that are inextricably tied to global P and food supply chains. We used these simple diagrams to discuss important feedback loops between the global P supply and local management contexts.

The LE region is import dependent for synthetic fertilizer. In this region, the most significant source of P comes from nonpoint sources such as agricultural runoff and urban storm drainage. There are also auxiliary variables for point sources, such as municipal wastewater treatment and industrial effluent. Another large source of P in LE is Lake Huron as water moves via rivers and agricultural dredging from Lake Huron into LE.[34,35]

In the CF system, agricultural dredging and runoff contribute P into Lake Okeechobee, but the CF region also supports mining and fertilizer manufacturing along the central west coast of Florida, together with North Carolina, supplying approximately 75% of the phosphate mined in the U.S.[36] Water from Lake Okeechobee is used for agricultural irrigation in the Everglades Agricultural Area, which drains into the Everglades Protection Area and eventually to Everglades National Park.[37]

For both case studies, we considered a scenario in which the availability of global mined phosphates abruptly decreased by 25% (e.g., through sudden trade policy action and counteraction). In this hypothetical supply disruption example, agricultural input costs increase, the allocation of fertilizers shifts, and agricultural commodity prices rise, exacerbating local food security challenges and P supply chain risks (which would be particularly pertinent in developing countries). Additionally, fertilizer supply chains could respond through the intensification of mining and processing operations in P supply points not impacted by the original disruption, which could increase local environmental risks.

The CF region (Figure 2B) is unique in that local P flows are connected to global markets through both fertilizer and food production systems, with regional P production and consumption choices tied to local water quality risks. In the case of a global supply reduction, mining and fertilizer production in this region may expand to help meet global demand, resulting in heightened and lasting environmental and supply chain risks in the region that will need to be managed, even after P production/processing facilities are retired from production.[19] New, regionally sourced fertilizers, coupled with high global commodity prices caused by fertilizer shortages, could induce agricultural intensification in this system, exacerbating water quality challenges in the Lake Okeechobee region. Human-induced eutrophication of freshwaters in the U.S. alone has been estimated to be at least \$2.2B annually.[38]

The LE system (Figure 2A) could see similar risks from agricultural intensification. Given the global importance of the U.S. Corn Belt region in supporting agricultural trade, higher commodity prices could result in higher fertilizer consumption through management intensification and shifting crop rotation strategies, further stressing regional P imbalances.[39] Such intensification could be necessary in the near-term to alleviate food security concerns of reduced global fertilizer supplies but would amplify local environmental impacts of fertilizer management. For the LE region, agricultural intensification could increase risks of eutrophication and harmful algal blooms plus increase the transport of nutrients downstream. Such intensification could also occur in other parts of the Corn Belt, resulting in higher levels of hypoxia on the Gulf Coast.

Fertilizer and food production anomalies at the local scale can also have broader market impacts at global scales, especially for key export commodities produced in these regions (e.g., corn and soybeans in the LE area), suggesting the presence of local-to-global risk transmission. While these two high-return, high-intensity agricultural systems are unique relative to many regional food production systems, these examples help illustrate the potential transmission of risk from global P fertilizer supply disruption to local contexts and highlight the importance of enhanced P system resiliency and coordination across scales.

3.2. Building Resilience through Internal P Recycling Loops. It is essential to develop strategies that consider environmental, socio-economic, and climate change risks across scales, which can improve long-term resilience to P vulnerability.[11] Enhancing resilience in P systems can help to mitigate the impacts of disasters on volatility in P flows and related P pricing and availability effects. For example, an analysis of cobalt supplies revealed that diversifying resources via a circular recycling system assisted in mitigating price and demand fluctuations of electric vehicles during times of geopolitical crisis.[40] Likewise, opportunities to accelerate the transition to a more circular P economy could build long-term resilience, both at national and international scales.[11] Increased circularity in the P economy includes increased P recycling, which relieves the pressure on primary suppliers during shocks. Developing more efficient P recycling pathways,[41−43] e.g., reuse of P in livestock manure or urban waste, can thus help ensure P supply security by offering a local recyclable P source to reduce reliance on imported P[44−49] while also reducing P losses.

An important component for developing this resilient P strategy is the need to identify and continually assess potentially recoverable stocks, as much of the data currently used to estimate recoverable P is static in time and varies across scales and political units.[50] Importantly, this includes inventories of the chemical species and forms of recovered/recoverable P, as forms and species are often not interchangeable. For example, struvite collected from a wastewater treatment plant cannot serve as a high-grade P source for pharmaceutical use and specific fertilizer types may require specialized machinery for application. Presenting figures for the total recyclable P in a region without this level of detail risks overstating the resiliency that recycling affords.

When recycling is considered as a strategy to enhance P supply resiliency, one must also consider trade-offs. For example, adoption of fertilizers and soil amendments sourced from manure and wastewater streams may be constrained by farmer acceptance (as they contain not only nutrients but possibly unwanted pollutants). Additionally, as part of sustainable nutrient management, P as well as nitrogen, potassium, and carbon must be considered. Manure is well-recognized for its poor balance of P and nitrogen, which often leads to the overapplication of P when land-applying manure.[51] Manure can either be applied only to meet agronomic P needs, with nitrogen added in a more targeted fashion (i.e., through use of mineral fertilizers or recycled N fertilizer), or it can be treated to remove excess P to avoid creating water quality problems in the name of addressing resiliency challenges. In low-income economies, the cost or operations of manure or wastewater treatment technologies may prove prohibitive, in which case dependence on P recycling (and hence higher input costs) may prove less desirable to agricultural producers than ensuring a resilient supply of mineral fertilizers and improving P use efficiency.

3.3. Building Resilience through Reduced P Dependence via Strategic P Storage, Improved Use Efficiency, and Soil P Utilization.

Avoiding global implications of temporary P supply disruption could require supply side measures to ensure adequate P and fertilizer availability in times of market disruption. Strategic commodity reserves have been deployed in other commodity markets to boost resilience to global shocks, with examples ranging from petroleum reserves to grain and oilseed reserves. Research is needed to evaluate whether strategic P reserves (mined and partially processed or final fertilizers) could improve P resilience and ease market pressures during periods of supply disruption, noting that there is some skepticism of strategic reserves as a supply risk management strategy.[52,53] New research could provide insight into the potential effectiveness of P reserves as a global risk management strategy as well as the form, cost structure, and ideal locations for reserves. There is also a need to understand how governance strategies could be designed to limit inequitable access to reserves so that vulnerable food supply regions can benefit from reserves during periods of disruption.

In addition to increasing supply chain resilience, one potential cost-effective and environmentally sustainable way of ensuring adequate supplies of P is to simply reduce its demand, especially if demand reduction efforts are coupled with risk mitigation efforts on the supply side. One way to reduce the need for P is to use it more efficiently, especially in its predominant use, agriculture. At the production stage, P from low-grade ores, mine tailings, and phosphogypsum byproducts are currently wasted, but could be extracted.[54] Fertilizers can be better formulated through slow-release, soil fixation blocking, and biochemical response induction technologies.[55] Farmers have also adopted a wide variety of best management practices (BMPs) for effective P use to reduce costs, for compensation through government programs, or to improve environmental performance of their systems by keeping P in soils where crops can use it, and out of waterways where it leads to algal blooms.[56−58] However, BMPs alone are not always adequate, e.g., for restoration of eutrophic lakes, BMPs may need to be supplemented by further reductions in internal and external P loads.[59]

Because most mined P is used as fertilizer, an additional way to reduce P use is to improve fertilization regimes. Current P management in agriculture is based on the quantification of the plant-available P by soil analysis and recommendation of fertilizers when the soil P content is below critical levels. However, soil P availability has high spatial variability in agricultural fields and increased P efficiency will require intense use of precision agriculture tools to identify P hotspots and use of precision fertilization to avoid overfertilization in those spots.[60] Additionally, "smart fertilizer" strategies can deliver phosphate at the optimal time by using P sources with lower solubility, wider adoption of controlled materials and nanotechnologies for delivery, and use of granules with inhibitors that reduce P adsorption to soil particles to target increased P fertilizer use efficiency.[61]

P unused by crops during past applications may accumulate in soils, and this stored P is sometimes termed "legacy P" or "residual P".[62] Although legacy P is often discussed as an environmental problem that can exacerbate water pollution, residual P stored in soils can provide a potential reservoir of P that could be harnessed to promote crop growth. For example, some fields are estimated to have sufficient P to support crop growth for several decades.[63,64] Global[65] and U.S.[66] databases of soil P concentrations or soil test P provide starting points for identifying regions where soil P has been banked and may be utilized in the absence of, or with reduced, P inputs. Utilizing these residual soil P stores provides another pathway to reduce the demand. The simplest method in overfertilized agricultural fields is the adoption of drawdown management by halting P fertilization until the legacy P is reduced to agronomically sound levels.[67] However, the residual P forms in soil are often held in pools that are not plant-available and require management strategies to facilitate their utilization.[68] Addressing plant use efficiency and cultivating varieties with enhanced abilities to uptake and utilize bioavailable P, as well as utilization of cover cropping strategies to promote P uptake,[69,70] can contribute to optimizing P utilization in agriculture.[71]

3.4. Building P Resilience via Effective Waste Management in Response to Exogenous Shocks.

Beyond P supply and utilization, a more sustainable P future also relies on addressing vulnerabilities in the "back end" of P flows to protect the environment against the negative impacts of excessive P release into aquatic systems. For example, the former Piney Point, Florida, P processing facility has historically been plagued by leaks and releases of wastewater from the phosphogypsum stacks generated during P production, exacerbated by severe weather such as flooding caused by heavy rain and hurricanes.[72] In a widely publicized event in 2021, the facility released more than 200 million gallons of wastewater containing P and other contaminants into Tampa Bay to reduce pressure on a leak in the containment wall liner, which threatened surrounding communities.[72,73] Considering that there are dozens of P processing plants in the U.S. alone, the environmental threat of such P losses is salient.[19]

4. PATHWAYS TO ENHANCE P RESILIENCE IN RESPONSE TO EXOGENOUS SHOCKS

The global food system hinges on the P fertilizer supply chain, which is vulnerable to low-probability, high-impact shocks that are difficult to predict in advance and can co-occur in ways that compound the human toll of global disaster risks. To enhance P resiliency, we must better account for vulnerabilities in the P system and understand bidirectional risk transmission (global-to-local and local-to-global) from a range of P supply chain components (including mining sites, processing facilities, transportation and distribution networks, and end use locations and impacts). Improving our understanding of the most critical supply chain components in the global P sector and how associated risks affect local managers is a necessary starting point, which will require advances in P flow modeling and systems dynamics frameworks that capture dependencies between global and local scales. Advanced modeling of P flows and P system vulnerability must also account for changing risks driven by both environmental factors (e.g., climate change) and socioeconomic developments. The research community should work to better characterize not only sources of risk now but also how risk factors and spatial dependencies may evolve in the future.

Improved analytics and modeling alone will not help address compounding risks to P flows, however. Exogenous shock response planning will require coordination of public and private actors at all scales of the global economy, from local officials to the UN. Improvements in infrastructure and management are needed to enhance resiliency at local scales, including leveraging a portfolio of strategies to derisk the P supply chain, e.g., strategic P storage, reducing P demand, utilizing legacy P, and leveraging internal P recycling loops. For example, national-level agencies could help advance P resiliency by developing stringent P effluent discharge guidelines for waterways that better account for point and nonpoint P inputs and incentivizing P recovery.

Ensuring that national/regional-level plans (e.g., U.S. National Infrastructure Protection Plan[9] and EU critical raw material list[8]) account for investment in more resilient fertilizer storage and transportation infrastructure as well as strategies to stabilize fertilizer accessibility and use in response to disaster is critical. We recommend the development of national-level resiliency planning frameworks for nutrients, including phosphate. For example, the U.S. has developed a National Climate Resiliency Framework that outlines a set of six objectives and opportunities for advancing those objectives;[74] an analogous framework could be developed to mitigate both shocks to the P supply chain and the effects of P pollution. Additionally, the EU recently adopted the European Critical Materials Act, which calls for setting benchmarks for extraction, processing and recycling of P; streamlining permitting procedures that might obstruct more efficient functioning of supply chains; monitoring and stress-testing the P supply chain; advancing the circular economy; and diversifying imports.[75] Such frameworks can direct and motivate lower administrative units to address more local aspects of resiliency planning (e.g., the U.S. National Climate Assessment provides national policy guidance as well as guidance at the level of 10 regional jurisdictions).[76] National organizations can also support public investment or new public-private partnerships to improve data infrastructure for monitoring and modeling the spatial and temporal distribution of P flows in human and natural systems and to better understand risks and interdependencies between global and local P flows.

At the international level, the scientific community has called for better global governance of P resources through: 1) the establishment of a UN body to make an independent, global, and readily available assessment of phosphate rock reserves to replace the current system, which depends heavily on national and industry self-reporting without formal validation; and 2) the development of recommendations for financial disclosure information, akin to the G20s Task Force on Climate-related Financial Disclosure, that can help companies and investors price risks to the phosphate supply chain when making investment decisions by providing transparency relative to phosphate-related risks and opportunities.[77] A path forward to improve P system resilience will require both public and private investment and buy-in, which starts with improved information on global-to-local and local-to-global scale dependencies, risk transmission, risk management strategies on both the P supply and consumption sides, and distributional implications of alternative P management or infrastructure investment choices.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.estlett.4c00208.

Additional detail on case study model development (PDF)

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Notes

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