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Review

The nexus of geopolitics, decarbonization, and food security gives rise to distinct challenges across fertilizer supply chains

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SUMMARY

Fertilizers are essential for agricultural production and vital to global food security. Nevertheless, the production and use of fertilizers, primarily the nitrogen type, contribute substantially to global greenhouse gas emissions. Meanwhile, fertilizer markets are closely intertwined with a changing geopolitical landscape and disruptions induced by the war in Ukraine. Despite a growing number of studies that have explored these various dimensions of fertilizers, the intricate interdependencies across these different variables along global fertilizer supply chains remain insufficiently examined. Adopting a nexus perspective, this review unravels a reshaping of the global fertilizer landscape led by intertwined driving forces, namely the mounting quest for a more secure supply of fertilizers, efforts to decarbonize production with local renewable energy feedstocks, and the pursuit of industrial upgrading and geopolitical goals. The intertwined nature of these trends, this review argues, warrants a distinct agenda of nexus-based research to dissolve socio-political and environmental conundrums for more sustainable global fertilizer supply chains.

INTRODUCTION

The role of inorganic fertilizers in the world's agricultural system has grown dramatically over the past 60 years. Fertilizer consumption has increased more than 6-fold, from 31 megatons in 1961 to 195 megatons in 2021.[1] Of this, 60% is nitrogen-based (N) fertilizer, while phosphorus-based (P) fertilizers and potassium-based (K) fertilizers, the other two major fertilizer types, account for approximately one-fifth of fertilizer use each. Historically, growing fertilizer use is closely related to the intensification of agricultural production around the world. Inorganic fertilizers offer a way to provide additional plant nutrients to the soil to boost crop yields, as nutrient levels decrease over time. According to studies in the United States, 40% to 60% of agricultural yields can be attributed to the use of inorganic fertilizers.[2] Hence, many scholars consider inorganic fertilizer use an important element in guaranteeing food security and meeting the United Nations (UN) Sustainable Development Goal 2 "Zero Hunger," a persisting challenge against the backdrop of uncurtailed global population growth.[3–6]

Currently, global fertilizer use is highly uneven across countries and regions. The application of inorganic fertilizer ranges from under 5 kg per hectare of arable land in a number of low-income African countries to over 1,000 kg in countries like Ireland and New Zealand and even exceeding 2,000 kg in Malaysia.[7] Research on the barriers to fertilizer access in low-income countries, especially on the African continent, has identified factors including affordability, lack of rural infrastructure and information, as well as an adverse policy environment as important causes of low fertilizer use.[8,9] Different levels of fertilizer consumption also translate into important variation in the marginal utility of fertilizer use, both across countries and over time.[10,11] While increased fertilizer use has been linked to improved agricultural performance in some countries, the expansion of fertilizer consumption has generated few gains in others.[10]

Excess and inappropriate fertilizer use in many countries also means that significant amounts of fertilizer are not translated into harvested crops but remain partially locked in agricultural soils (in particular phosphorus) or are lost to the environment, with major socio-environmental implications. The flows of anthropogenic nitrogen and phosphorus in the environment are considered as one of nine planetary boundaries defining a "safe operating space for humanity."[12] The latest assessment based on this framework suggests that the boundaries for both elements have been transgressed and are considered to be in the "high-risk zone."[13] Fertilizer use is the central driver of this development, causing nitrogen and phosphorus pollution and the associated degradation of terrestrial and aquatic ecosystems. In the absence of appropriate fertilizer management practices, a large share of the applied fertilizers is not absorbed by the crops and pollutes water systems.[14,15] A key result is the increase in phosphorus and reactive nitrogen inputs into fresh water systems.[16] These excess nutrients bring about environmental impacts such as water eutrophication as well as excessive algal bloom in freshwater bodies.[17]

The large-scale use of fertilizers is also a major contributor to global greenhouse gas (GHG) emissions, resulting from manufacturing (most notably ammonia-based N, as well as P fertilizers) and transport of fertilizers as well as from their application in agriculture. Data have been compiled most systematically for nitrogen-based fertilizers, estimated to have accounted for 1.13 Gt of CO_2e annually. This represents more than 2% of global GHG emissions and approximately 8.3% of farm-gate emissions in the agricultural sector.[14] Of this, approximately 39% was attributed to the manufacturing of N fertilizers, primarily during the process of ammonia synthesis.[18] Transport of N fertilizers adds a further 30 Mt of CO_2e or 2.6% of the total. The largest share of emissions occurs due to fertilizer use, which accounts for annual emissions of approximately 662 Mt of CO_2e or 58% of the total.[14] Excess fertilizer that is not absorbed by the plants is partly converted into N_2O by soil micro-organisms as a by-product of their metabolism, while another part may end up leaching or volatilizing from the site of application, resulting in additional downstream emissions.[19]

These various aspects of fertilizer production and use—its role in global food production as well as its impacts on climate change and the environment—are well-documented in the scholarly literature.[14–17] Nevertheless, the existing academic conversations are restricted in two important ways. First, there has been only a relatively limited discussion on the trade-offs and interrelationships between the different dimensions of fertilizer production and use outlined above. This issue is becoming increasingly pressing as the mounting threat of climate change is giving growing salience to the interaction between these different dimensions. Reducing GHG emissions will require important changes in how fertilizers are produced and used, raising questions regarding the ripple effects on other variables. Second, the literature has been largely silent on how a changing international political economy is affecting the fertilizer industry. While contributions have addressed the impact of rising fertilizer prices on global food security,[3,11,20,21] little has been said about how geopolitical trends are affecting fertilizer markets and vice versa. Increasing geoeconomic rivalry is also raising the salience of these questions: price spikes in the wake of Russia's invasion of Ukraine are a case in point.

This review takes a step toward closing these gaps by proposing a perspective on fertilizers informed by nexus thinking in international political economy.[22] We present a conceptual model that places fertilizers at the center of this nexus, highlighting how it relates to the dimensions of food, climate change, energy and mineral resources, environment, and security. On this basis, we review how key political and economic trends are affecting the future development of the fertilizer sector. We identify three drivers altering the global political economy of fertilizers: a rapidly changing supply structure, increasingly influenced by China; geopolitical competition amplified by the war in Ukraine and growing food insecurity in the Global South; and the decarbonization imperative. While previous contributions have discussed these dimensions separately, this review analyses the important interdependencies across these different variables. It discusses how interactions between the quest for security of fertilizer supplies, the potential to localize renewable energy feedstocks, and the pursuit of industrial upgrading and geopolitical goals are reshaping supply chain governance in the fertilizer sector. The intertwined nature of these drivers, the paper argues, warrants a distinct research agenda focused on fertilizer supply chains along three major lines of inquiry: an interdisciplinary perspective on fertilizer supply chains grounded in nexus thinking; a supply chain perspective that addresses the important roles of both the state and spatial factors in shaping the landscape of fertilizer production; and a grand strategy perspective on fertilizers, which explores the broader geopolitical implications of the sector. Finally, we provide an outlook regarding the broader relevance of the proposed research agenda, beyond the fertilizer sector itself.

Fertilizers at the center of a nexus perspective

A nexus typically denotes a place where independent but intertwined elements of a system meet. A well-known example is the water-energy-food nexus, which became subject to academic and policy debates in the 2010s as part of the Sustainable Development Goals. Although representing distinct systems on their own, water, energy, and food are inextricably linked thanks to multiple interactions between them.[23] For example, agriculture requires water, as does the energy sector, which makes water a crucial element for both food and energy security. Water scarcity may, therefore, pit energy and food against each other. Industry-scale food production, in turn, requires energy and water input, but may lead to land degradation and groundwater depletion.[24] Energy production from large-scale deployment of renewable technologies such as solar or wind farms is land-intensive and may impact the availability of arable land for agriculture.[25] Biofuels as an alternative, non-fossil energy source have been found to impact food security, both because of a change in land use[26] and because of rising crop prices as well as increasing market speculation.[27]

Adding another element to the debate, the World Economic Forum introduced the water-food-energy-climate nexus—albeit with a strong focus on water—to stress the planetary boundaries aspect pertaining to the incumbent growth model.[28] Climate change, an outcome of unabated fossil-fuel consumption, not only impacts irrigation and water availability but, by extension, also food security.

Clearly, changes or developments in one nexus element typically have ripple effects on the others. This makes the dynamic interactions of a nexus akin to a wicked problem,[29] whose dynamics are hard to predict, and where the adopted (policy) measure may change the nature of the problem, inhibiting an objectively optimal outcome. Analytically, nexus thinking helps in understanding the nature of the problem and the dynamics characterizing its embeddedness in bigger, intertwined contexts. It takes a systems approach to analyzing a given sector that also provides room for investigating the economic, political, or social dynamics of this interaction. In policy terms, a nexus approach may help address trade-offs that exist between different policy goals, identifying synergies and enhancing the system's overall resilience.[30]

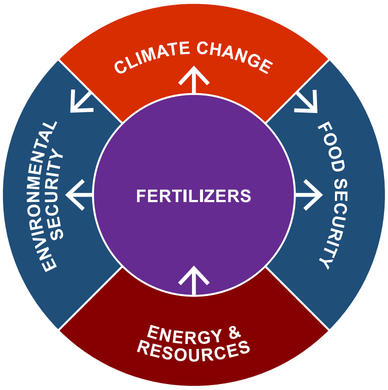


Figure 1. Fertilizers at the nexus of energy and resources, climate, environment, and food security

This figure highlights the central role of fertilizers in the nexus by displaying their interactions with climate change, food security, environmental security, and energy and resources. Fertilizers have an impact on the former three, while energy and resources impact fertilizers; climate change in turn exerts influence on environmental security as well as food security.

The specific nexus we propose here is one defined by food, energy and resources, climate, environment, and security, with fertilizers at its center (see Figure 1). The main elements have already been outlined above: on the one hand, fertilizers rely on energy and mineral resources for their production. On the other, they function as a major input to food production, due to their role in boosting agricultural output. Hence, fertilizer import dependence may imply a risk to food security, particularly as both producer and consumer countries have started to view fertilizers as a strategic commodity and are investing in measures to ensure the security of fertilizer supply. At the same time, fertilizer use has major impacts on environmental quality and the climate. Both represent important dimensions of environmental security, a concept used to define security threats from the individual to the transnational level that result from human-induced environmental pollution and change.[31]

By placing fertilizer at the center of the proposed nexus, we highlight its role in driving impacts along the entire supply chain, from fertilizer production to its use in food production. We highlight how decarbonizing and strengthening circularity in fertilizer supply chains may impact other dimensions within the system. That is, the reduction of GHG emissions from fertilizer production and use present potential synergies and trade-offs, both upstream and downstream. Upstream, for example, it offers an opportunity to substitute imported fossil-based fertilizers with domestic production of so-called “green ammonia” for the production of inorganic “green fertilizers,” utilizing local renewable resources. In contrast to this, potash and phosphate rock—the main feedstocks used for the production K and P fertilizers—cannot be replaced in this manner. It is only through strengthening efficiency and circularity via nutrient use efficiency practices and nutrient recycling (i.e., by recovery from organic waste products) that the demand for these inputs can be reduced.[32]

While these different approaches all offer important synergies among climate, environment, and supply security, in the short to medium term they may also come with higher costs. A case in point is green ammonia where, for the time being, comparably high prices may increase the cost of green fertilizers as an input to food production. Similarly, phosphorus that is recycled from organic wastes may be more costly to obtain than from phosphate rock. Furthermore, the optimization of fertilizer use may not only offer important environmental co-benefits, but also requires approaches to secure crop yields and soil fertility. Finally, each of these elements is embedded in a changing geoeconomic landscape with implications for the nexus system as a whole. As detailed further below, each of the elements constitute moving parts within an evolving nexus system.

The changing fertilizer landscape

Changing market realities and the rise of China

Traditionally, fertilizer production has been strongly influenced by geography. Fertilizer manufacturing has largely been located close to the principal raw materials needed for its production. As a result, the landscapes of production for the three major inorganic fertilizer types differ significantly. Phosphate rock reserves are the most concentrated with more than two-thirds located in Morocco,[33] making the country a major producer and the leading exporter in this market. Canada, Belarus, and Russia are the largest producers of potash fertilizers, due to major potassium reserves in these countries.[34] Finally, nitrogen fertilizer, the largest in terms of total volume of production, requires ammonia as its primary input, which is mainly derived from natural gas. While the nitrogen fertilizer landscape is significantly less concentrated, Russia as a large natural gas producer has traditionally been the largest exporter,[35] and many of the smaller, regional producers of N fertilizers also hold their own natural gas reserves.

However, this traditional landscape has changed significantly over the past decade as China has emerged as the largest global fertilizer producer. It leads global production of both nitrogen and phosphate fertilizers. While China is among the top 10 countries in terms of phosphate reserves, it does not have any significant domestic gas reserves and was traditionally not a major exporter of nitrogen fertilizers. In an effort to ensure self-sufficiency, the country has ramped-up ammonia production, relying mainly on coal as a feedstock. Despite higher production costs and higher CO_2 emission intensity than the natural gas-based production pathway, 85% of China’s ammonia production today relies on coal gasification technologies.[36] As a result, over the past 20 years, China has transitioned from being one of the largest importers to a top exporter of fertilizers (see Figure 2).

Geopolitics, the war in Ukraine, and food insecurity

Intensifying geopolitical competition is further adding to these changing market realities, with important knock-on effects for global food production. P fertilizers have long raised concerns about the availability of phosphate rock, a highly concentrated and finite mineral compound.[38] While Morocco controls the vast majority of phosphate rock, China controls 40% of mining, followed by five major countries accounting for an additional 40%.[39] This uneven supply structure is exacerbated by the fact that Morocco’s major fertilizer company, OCP, conducts parts of its phosphate mining and subsequent fertilizer production in the occupied Western Sahara. Moreover, lithium-ion batteries—a key to a successful transition to electric vehicles—have emerged as another important demand source for phosphate rock, placing additional pressure on the resource. Following new Chinese export taxes introduced in 2008 and, related to

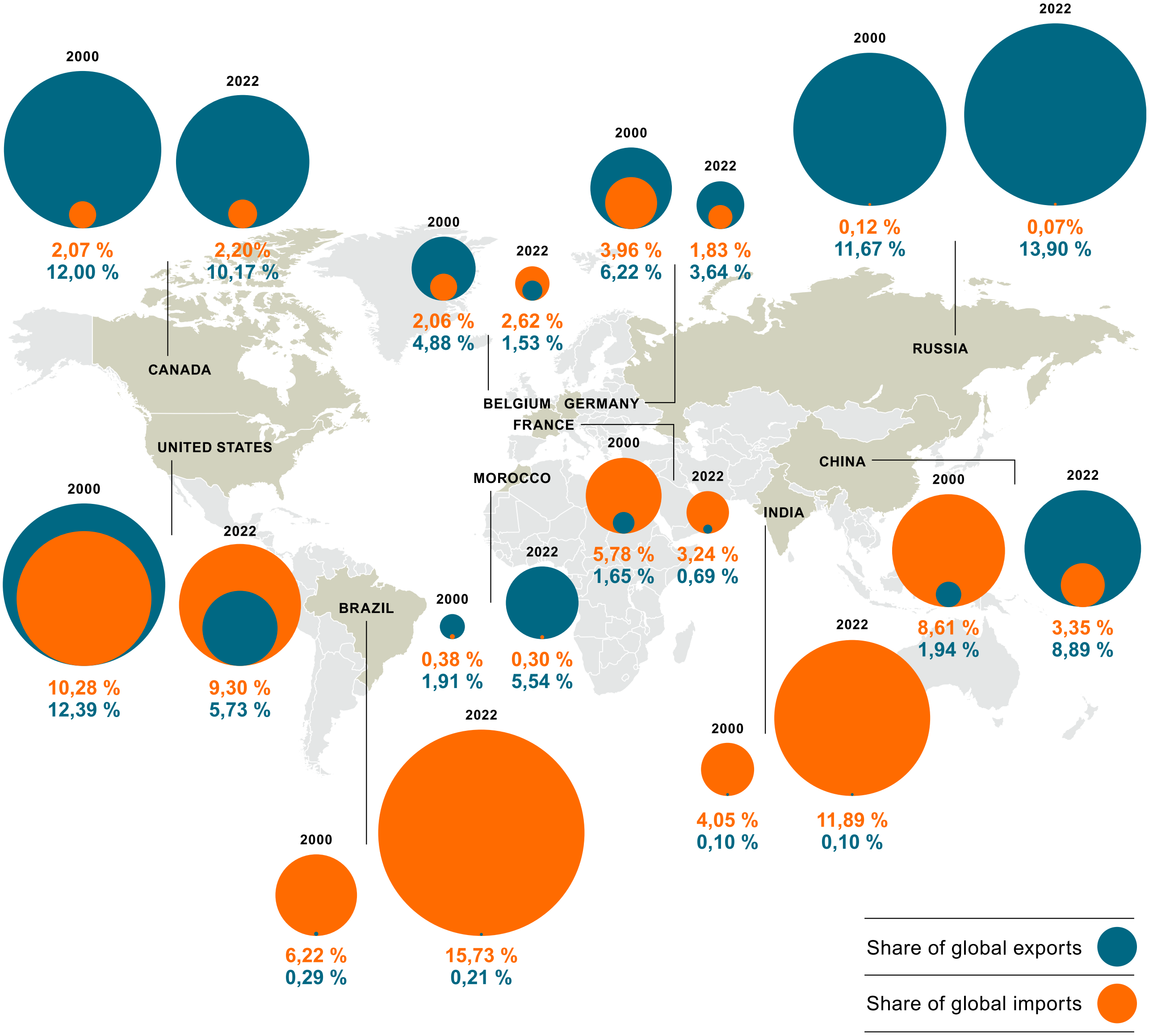
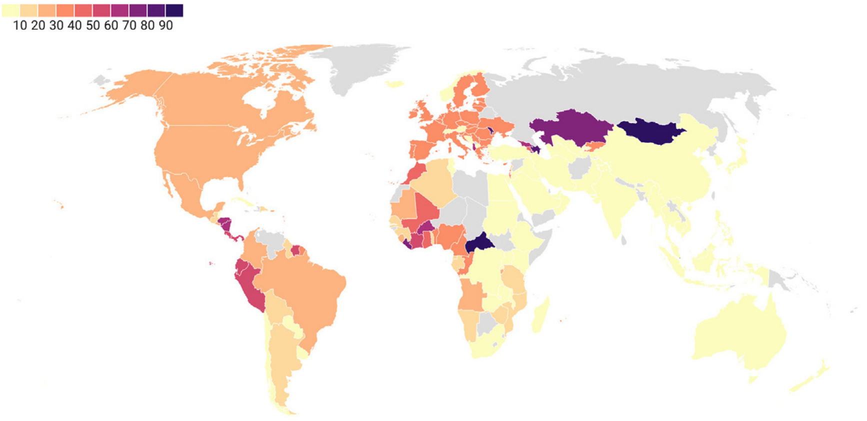


Figure 2. Changing shares of global fertilizer trade, top five exporters and importers in 2000 and 2022
This figure displays the share of global fertilizer exports and imports by trade value for the top five exporters and importers in both 2000 and 2022, based on HS code 31, indicating important shifts in the relative position of different countries in global fertilizer trade. Data from OEC World,[37] http://oec.world.

this, major price spikes in 2008 and 2011/2012, the EU added phosphate to its list of critical minerals and launched the European Sustainable Phosphorus Platform in 2013/2014.[40,41]

Geopolitical conflict with Russia and its ally Belarus has also amplified concerns around N and K fertilizers. Following the all-out invasion of Ukraine in 2022, interruptions of export routes via the Black Sea resulted in sharp increases in fertilizer prices. While prices have subsequently gone down, they have remained unpredictable.[21,42] In addition, the United States and the EU have imposed sanctions on individual Russian oligarchs in the fertilizer industry following the invasion of Ukraine in 2022 as well as on fertilizer trade with Belarus following a wave of scaled-up repression in 2020.[43] Both China and Russia have enacted temporary export restrictions on fertilizer exports at different stages in 2021 and 2022.[21,44] These interventions have led to major adjustments in trade flows in global fertilizer markets. China's share of global exports dropped from over 13% in 2021 to under 9% in 2022, while India has emerged as the largest single buyer of Russian fertilizers, more than doubling its share of imports from Russia since the onset of the war. To ensure alternate trade routes, Russia is now planning to build new export infrastructure to replace ammonia transit to Ukrainian export ports via the Togliatti-Odesa ammonia pipeline.[45] Despite these recent developments, one-sided dependence on N and K fertilizer imports from Russia and Belarus remains pronounced in a host of countries around the world, providing potential geopolitical leverage to the two countries (see Figure 3).

Panel A: Nitrogen-based fertilizers



Panel B: Potassium-based fertilizers

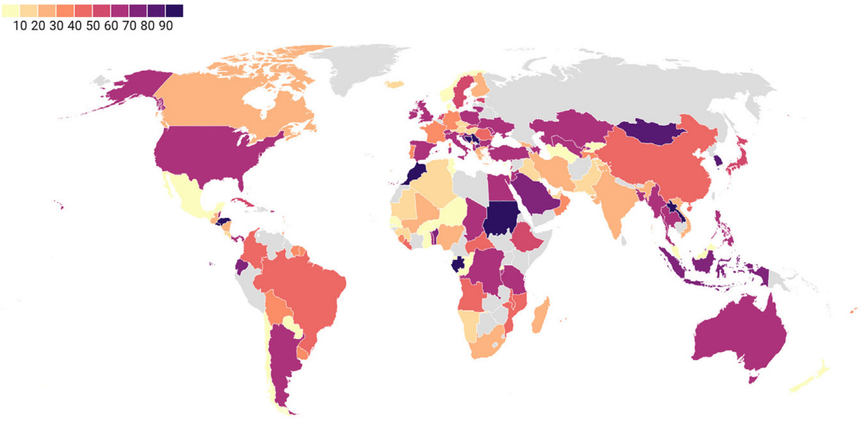


Figure 3. Share of fertilizer imports from Russia and Belarus (2018–2020)

(A and B) The shading of countries in this figure indicates the share of nitrogen-based fertilizer (A) and potassium-based fertilizer (B) imported from Russia and Belarus in the respective country during the time period 2018 to 2020. A higher share of imports translates into a higher degree of dependency on these two countries in the fertilizer sector. Based on Glauber and Laborde.[20]

These changes are creating pressures for key players to ensure the security of fertilizer supply within a sector that—with the notable exception of China—had been largely working on the basis of free market principles. While more fundamental changes in the geography of fertilizer production will take time to emerge, there are also first signs that countries are developing dedicated strategies to secure domestic fertilizer supplies. Following the invasion of Ukraine, the European Commission issued a dedicated communication in September 2022 on "ensuring availability and affordability of fertilisers."[46] Among other things, it has granted member states exemptions under its State Aid rules, enabling a number of countries to hand out subsidies to national fertilizer companies in order to maintain production despite rising feedstock (i.e., natural gas) prices.[47] Similarly, the United States has launched a 250 million USD investment program to boost domestic fertilizer production.[48] Brazil, a major producer and exporter of agricultural goods with a significant dependency on fertilizer imports, has responded with the launch of a national fertilizer strategy to boost domestic production and what the government has called "fertilizer diplomacy."[49]

Rising fertilizer prices resulting from the war in Ukraine have also significantly exacerbated food security challenges in low-income countries in the Global South. While most attention has gone to alleviating rising prices for food commodities, fertilizers play an important part in ensuring a reliable and affordable food supply. According to estimates, a doubling of fertilizer prices translates into a 44% increase of food prices.[50] In particular, countries in Latin America and Africa suffer from high degrees of fertilizer import dependence, exposing them to external supply shocks. In many low-income countries, import dependence is coupled with low levels of fertilizer use per hectare of cultivated land. Africa is emblematic of this. While the continent accounts for 17% of global cropland area,[51] African farmers only account for approximately 4% of fertilizer use.[52] Crop yields are also correspondingly low, a key driver of food insecurity on the African continent. Africa is the lowest consumer of synthetic fertilizers yet exports significant amounts. Eighty-five percent of fertilizer exports from major African fertilizer producers, such as Morocco, Nigeria, and Egypt, go to other world regions, most importantly South America and Europe (see Figure 4).

This points to structural imbalances and infrastructure bottlenecks that prevent fertilizer production across the continent from reaching farmers, hindering increased food production. Worse even, fertilizer use in Africa has declined in recent years.[52] Among other factors, this is related to increasing interest rates that have driven up financing costs for farmers.[21] Another factor is the way investments in large-scale fertilizer production are underwritten. Financing new production capacity requires long-term offtake agreements for significant volumes of future fertilizer production. As a result, a large share of fertilizer output is reserved for exports at fixed prices, while small, domestic offtakers are exposed to volatile global markets.

In the volatile market environment following the invasion of Ukraine, major powers have started utilizing fertilizer supplies as foreign policy tools to pursue "soft-power" goals. As an example, despite (or as a way of shifting attention from) its role in the disruption of food and fertilizer supplies, Russia is demonstratively increasing its engagement with countries in the Global South on food security issues. In 2022, it donated 260,000 tons of fertilizers to Africa via the UN's World Food Programme.[54] The EU has considered but ultimately decided against measures to bolster fertilizer production in countries of the Global South.[55]

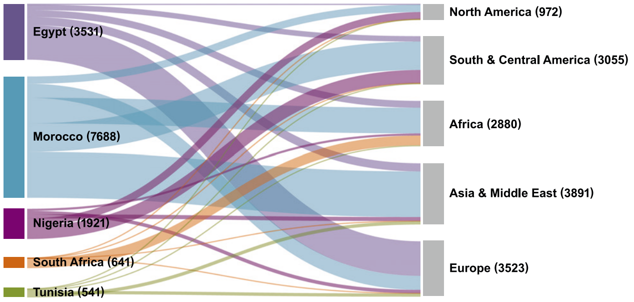


Figure 4. Export flows of five largest African fertilizer producers by region of destination, trade value in million USD, 2021

This figure depicts export flows for all synthetic fertilizers grouped under code 562 in the UN Standard International Trade Classification, revealing the significant share of fertilizer exports from Africa to other world regions. Data from UN Comtrade.[53]

Instead, it has joined the US-led Global Fertilizer Challenge to alleviate fertilizer supply shortages through measures in support of more efficient and sustainable fertilizer management.[56]

The imperative of decarbonization

A third major driver of changes in the fertilizer landscape concerns the imperative of decarbonization. Decarbonizing fertilizer production essentially means replacing the main feedstock in ammonia production, that is fossil fuels (for most countries, natural gas), with carbon-neutral, renewable hydrogen.[57] This, however, comes with significant costs. By some estimates, the costs of producing so-called green ammonia with renewable hydrogen are still more than twice those of conventional processes, based on 2020 gas prices,[36] that is, pre-energy crisis data. Costs are expected to come down, and volatile gas prices certainly alter the economic case for renewable-based ammonia. Still, cost differentials may persist for some time to come.

However, decarbonization also comes with potential benefits. Countries poor in fossil fuels may render their production independent from imports. States currently unable to produce nitrogen fertilizers on a competitive basis, due to their lack of natural gas resources, may see their competitive advantage change dramatically in a net-zero economy. The scaling-up of green hydrogen technologies will offer countries with high solar or wind potential an important competitive advantage. This may create new self-sufficiency opportunities for large nitrogen fertilizer consumers (such as India or Brazil) but also for countries that have until now specialized on only one type of fertilizers given their mineral endowments.

A case in point here is Morocco, which, on the basis of its vast phosphate resources, has developed a large phosphate fertilizer industry. Access to low-cost green ammonia production could not only allow the country to reduce ammonia imports for its production of ammonium phosphates used in the production of fertilizer blends, but also widen its product profile. This could allow Morocco's flagship OCP Group to increase its market dominance by entering market segments for additional fertilizer types, thus increasing the country's geopolitical leverage. Natural gas producers, on the other hand, could free up volumes for export. Algeria, for example, a key gas supplier to the EU, is facing increasing domestic energy demand, which may dwindle exports going forward. Decarbonizing nitrogen fertilizer production can help stop the downward trend in the country's export potential.[58] Egypt, an emerging natural gas producer facing similar upward pressure in domestic energy demand, may benefit from additional export capacity going forward.

Indeed, incumbent fertilizer producers may see the need to decarbonize exports as the EU moves to implement its carbon border adjustment mechanism (CBAM) on carbon-intensive products. Fertilizers, one of the products included in the initial phase of CBAM implementation, will likely see decreasing competitiveness on the European market when coming from countries that so far fail to effectively price carbon.[59] To ensure market access at competitive prices, CBAM will represent an important factor in assessing the costs and benefits of decarbonizing production.

At the same time, countries rich in renewable energy resources may see an opportunity in entering the fertilizer market by way of building on green ammonia production. A market with significant upward potential, green ammonia is seen as a central pillar of the net-zero pathways of large economic blocs.[60] A number of green hydrogen partnerships between EU member states and African countries such as Namibia are meant to scale up the nascent market and may, by extension, entice the emergence of new fertilizer producers. A co-benefit clearly lies in employment opportunities and value creation that come with fertilizer production freed of fossil fuels. Indeed, the development of fertilizer production may well offer an entry point for low- and middle-income countries to enter the field of green hydrogen production and, potentially, exports.

Finally, decarbonizing the sector also requires reducing synthetic fertilizer use, helping to mitigate CO_2 emissions from the sector. This offers important synergies with the reduction of excess nitrogen and phosphorus in the environment. The overuse of synthetic fertilizers in many parts of the world is considered to be reaching a level that risks serious disruptions of the earth's biogeochemical flows and constitutes a transgression of one of nine so-called planetary boundaries.[13] Hence, the promotion of sustainable fertilizer management practices and corresponding regulations to ensure appropriate levels of inorganic fertilizer use represent an important entry point for addressing the twin challenges of climate change and disruptions of biogeochemical flows in the earth system. Moreover, nutrient recycling as part of broader nutrient use efficiency management practices can have the added benefit of reducing dependence on fertilizer imports, not only for N but also for P and K fertilizers.

Given large differences in average fertilizer use, the scope of these strategies will differ significantly across countries and regions.[11] In China, for instance, where farmers use approximately 3.6 times the global average of inorganic fertilizers per hectare of arable land, the government has begun to embark on a strategy to reduce fertilizer use.[61] In many African countries, by contrast, fertilizers remain out of reach to significant numbers of smallholder farmers, requiring strategies to boost access in an effort to increase crop yields.[8,9]

Geopolitics of fertilizers: Three lines of inquiry

The three drivers outlined above are transforming the landscape of fertilizer supply. Rising geopolitical tensions are translating into increasing government intervention in fertilizer markets, both on the supply and the demand side. While political steering

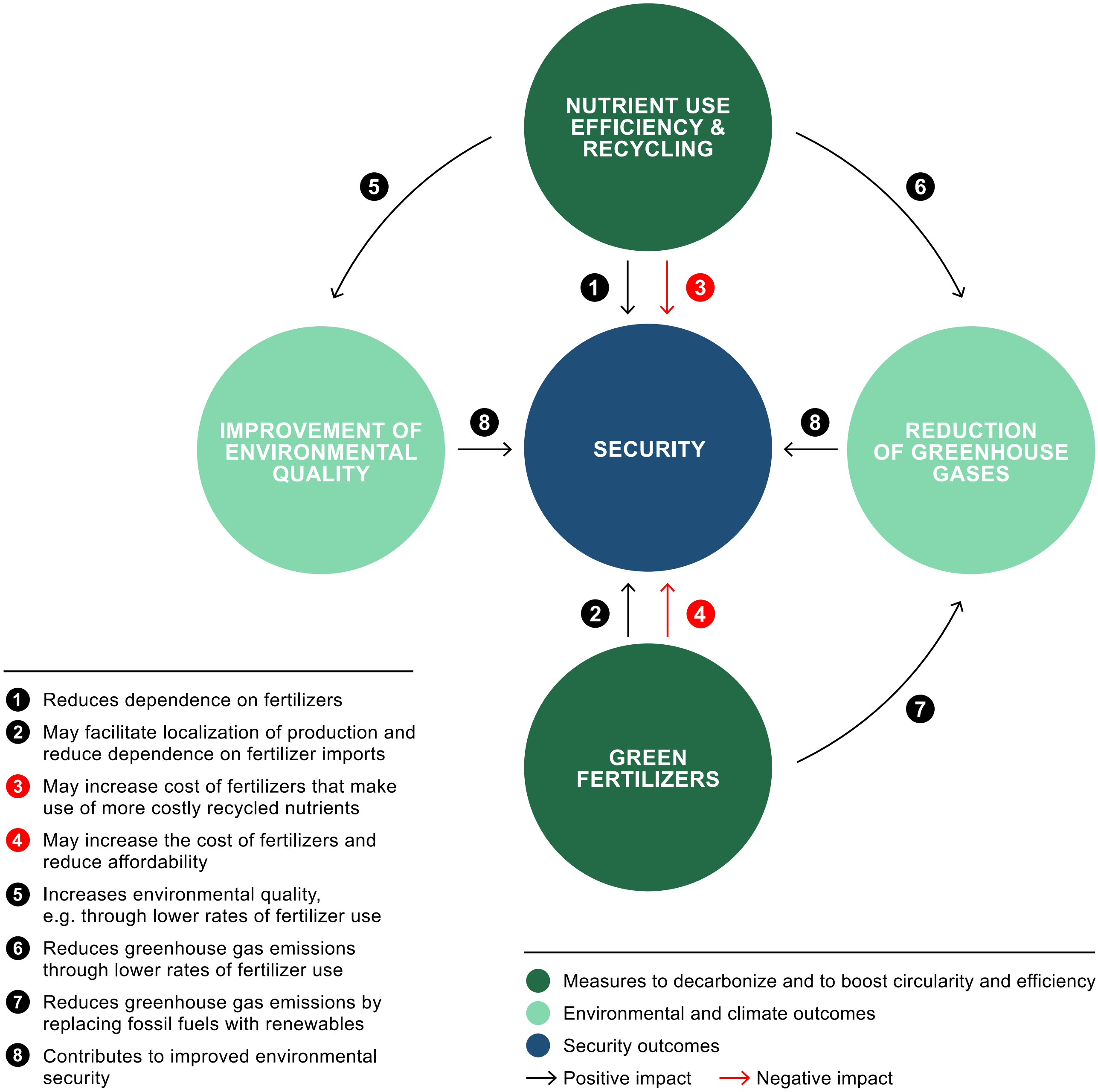


Figure 5. Impacts of decarbonizing the fertilizer sector on security
This figure depicts how the reduction of greenhouse gases in the fertilizer sector impacts security, both directly and indirectly via its role in mitigating climate change and enhancing environmental quality. Black arrows indicate a positive relationship; red arrows indicate a negative relationship.

in the fertilizer sector has been a long-standing feature within China's system of economic governance, the war in Ukraine has brought fertilizers to the attention of policy makers across the globe, most notably in Russia, the EU, and Brazil. Each of these major economic players is pursuing a distinct variant of fertilizer governance, based both on their position in the sector and their specific policy preferences. Moreover, going forward, measures to ensure the security of fertilizer supplies will be strongly intertwined with decarbonization efforts, another driver of political intervention in the sector. Efforts to decarbonize fertilizer production come with the added potential to localize energy feedstocks by switching to renewable hydrogen resources, offering important synergies across the two policy domains. On the demand side, nutrient use efficiency plays a critical role as a pathway to enhance environmental quality, to decrease GHG emissions and to reduce dependence on fertilizer imports. Nutrient recycling provides an additional option for reducing dependence of imported P and K fertilizers, while improving environmental performance. Figure 5 captures the key interactions across these dimensions.

These processes not only raise the political salience of the fertilizer sector as such. They also bring to the fore more fundamental questions of how commodities and their supply chains are being reshaped against the background of new geopolitical realities and the imperative of decarbonization. This warrants a distinct research agenda, offering important new empirical and conceptual insights within a tradition of international political economy research. In the remainder of this paper, we sketch three avenues of inquiry for such an endeavor.

A nexus approach to fertilizer supply chains

First, the changing global political economy of fertilizers merits a research agenda grounded in nexus thinking.[22] Fertilizers can be considered a strategic commodity, due to their cross-sectional nature at the interface of economic development, security, climate change, and the environment. While there are long-standing debates in the international political economy literature on both energy[62,63] and food[64,65] security, fertilizers—situated at the nexus between these two sectors—have not been tackled in this context so far. Indeed, even contributions spanning both policy fields (e.g., Steven et al.[66]) have so far failed to address the role of fertilizers. This relates to a broader gap in the debate on the international political economy of energy, which has largely sidestepped the question of different types of energy uses. Among other things, the gas crisis following the invasion of Ukraine has showcased the role of distinct energy carriers as feedstock for industrial processes. It is not energy per se but natural gas specifically that functions as the primary feedstock for the production of N fertilizers. In the same vein, debates on the decarbonization of so-called hard-to-abate or hard-to-electrify sectors are raising awareness that industrial processes require energy carriers with specific characteristics and the ability to provide specific functions or inputs to industrial production.[60]

Fertilizer production represents an important example in this regard, highlighting the more fundamental point that the concept of energy security—in contrast to food security—represents an intermediate security concern. Ultimately, it is not energy per se but the products and services that energy helps generate that matter for both collective and individual human security. However, as pointed out by Huber,[67] political science research on energy and resources often focuses on what he calls "following the politics," i.e., the places of contention and political struggle. These have traditionally been situated in the spheres of energy extraction and trade rather than their use in industrial facilities for the production of intermediate products or commodities. Yet, changing market and geopolitical realities coupled with the decarbonization imperative warrant a closer look. In the same vein, research on fertilizer supply chains should not limit itself to questions of fertilizer production and trade but also address their use in agriculture. This means integrating the emerging debates on fertilizer supply with discussions on the impacts of synthetic fertilizer use on human health, the environment, and climate.

Similar to the security literature, research on the energy-water-food nexus has so far failed to address the arguably important role that fertilizers play in this arena.[24,68] Studies in the field take an integrated perspective on the management of scarce (natural) resources. They have their origin in the debate on integrated water resource management (IWRM), which highlighted the need for a collaborative governance of water across various end-users, most notably food and energy production.[69] The water-energy-food nexus further advances this thinking by addressing multi-directional dependencies, including the impact of water scarcity on energy and food production. Fertilizers have not featured in this debate, as they do not represent an immediate interdependency between water and energy as *resources*. Rather, interdependencies emerge when shifting to a supply chain perspective. Here, fertilizers emerge as an intermediate product in food production, while energy represents an important feedstock for the manufacturing of fertilizers. In other words, rather than considering only direct energy use, a global supply chain perspective shifts the focus to the energy embodied in fertilizers. This is analogous to the debate on virtual water (and water footprinting)[70] and can be seen as a way of extending nexus thinking beyond a discrete geographic area. In this way, the debate on water scarcity has spearheaded a transnational perspective on resource use. Similar concepts have emerged within the debate on climate change, giving rise to the concept of embodied carbon and related methodologies for carbon footprinting.[71,72]

Only recently, however, have these questions assumed political and economic salience beyond the spheres of water and climate policy. As decarbonization policies are beginning to extend beyond power generation and transport to industrial production, the local availability of renewable energy resources is emerging as a tangible competitive advantage for attracting investment in climate-friendly industrial production.[60] The fertilizer sector epitomizes how decarbonization processes are beginning to drive this potential reconfiguration of global industrial supply chains as well as the important opportunities for industrial upgrading this brings. Here the nature of ammonia-based fertilizers as an energy-intensive commodity that is comparatively simple to produce and serves as an input for agricultural production positions the sector at the frontier of these developments in the Global South.

Finally, potassium and phosphorus fertilizers point to the additional nexus between food security and access to mineral resources. Given their reliance on limited, non-replaceable mineral raw materials, this nexus relationship does not provide the same entry points for transformative change in supply chains that nitrogen-based fertilizers offer Rather, the spatial parameters of K and P fertilizer production are not easily changed. Geopolitically, this implies that dependence on the small number of countries where those mineral resources are currently located and processed tends to be sticky. While this dependence can be addressed through strategies of diversification, it cannot be eliminated entirely through the substitution of feedstock, as in the case of ammonia.[40,41] Instead, this underlines the role of efficiency and circularity in managing this nexus relationship. Both reducing the need for K and P fertilizers via nutrient use efficiency and the recovery of unused nutrients via recycling techniques offer important win-win options, combining environmental benefits with increased supply security.[40] At the same time, the introduction of such measures may incur additional cost, at least in initial phases of their application.[32] In sum, the above not only calls for a dedicated research agenda to better understand these interrelationships, both locally and globally, but also policy approaches to catalyze the needed investments for reaping the potential gains of increased efficiency and circularity and for reducing the initial costs of related technologies and practices.

Rethinking supply chain research

The role of geopolitics, decarbonization, and related opportunities for industrial upgrading in the fertilizer sector also present important entry points for better understanding the drivers behind changing political and corporate strategies within global supply chains. As governments and firms seek to reshape supply chains and thereby influence geopolitical dynamics, fertilizers raise important questions regarding governance and power in the industry. The role of supply chain disruptions related to geopolitical events has begun to feature in management-oriented supply chain research, and authors have started to conceptualize the role of different types of vulnerabilities and choke points and their implications for policymakers.[73] Nevertheless, there has been little consideration of how government intervention is beginning to reshape supply chains.[74] Similarly, the growing literature on supply chain resilience takes a firm-centric view focused on approaches and strategies for enhancing the ability to anticipate and respond to supply chain risks.[75] The influence of policy and governance on global supply chains has featured more prominently in the literature on sustainable supply chain management, albeit with a primary focus on how governance and regulation have impacted incremental improvements in environmental and social outcomes.[76,77] Research on how these factors have shaped the configuration and geographic distribution of supply chains has not been a focus.

Questions related to industrial upgrading have been explored in the closely related literature on global value chains (GVC). Similarly, this has focused primarily on firms as actors in value chains. In this context, GVC scholars have dealt with the issue of power by looking at "the ability of one firm in the chain to influence or determine the activities of other firms in the chain" (p. 4).[78] From this perspective, the power of so-called lead firms stems from their ability to control key resources, make decisions about firm entry and exit, and define the terms of suppliers' participation in the chain.[79,80] In a recent addition to the literature, Tups and Dannenberg[81] used the fertilizer sector to demonstrate how lead firms may not only exert power upstream as buyers—as generally depicted in existing value chain research—but also downstream. They analyze how lead firm Yara International, a Norwegian company, has extended its supply chain both horizontally and vertically, offering not only fertilizer products but also crop management knowledge directly to farmers via integrated retail systems and public-private stakeholder platforms. This important addition to the discussion highlights not only emerging linkages between fertilizer supply and use, but also illustrates interconnections between public and private stakeholders precisely at this interface. While Tups and Dannenberg's critical perspective also highlights the political influence that this entails, they remain firmly rooted in a firm-centric perspective.[81]

Nevertheless, their work highlights the urgent need to overcome the largely firm-centric and apolitical perspective that still dominates traditional GVC research, despite some notable efforts to "bring the State back in" by GVC scholars.[82,83] Those that have explicitly tackled the role of government in GVCs focus mainly on how it has acted as a facilitator of industrial upgrading within existing value chains,[84] and, to a lesser extent, in enabling the formation of new industries, like wind or solar energy.[85–87] Research has also explored how domestic business power drives external trade measures, but few works have addressed how government intervention transforms and reshapes supply chains in pursuit of geopolitical goals.

The case of fertilizers makes clear that such forms of political governance are not only rapidly gaining in importance but are closely intertwined with the imperative to decarbonize.[88] In the fertilizer landscape, political actors play key roles at different levels of governance. At the national level, concerns regarding security of supply are giving rise to more activist industrial policy strategies.[89–91] Governments are influencing investment priorities, favoring "national champion" companies and shaping investment conditions more broadly through carbon pricing policies, subsidies, regulations, and even sanctions.[92] This has major implications for how firms are connected across GVCs. At the transnational level, trade regimes, increasingly linked to the decarbonization imperative, are becoming more interventionist. The EU's CBAM is an important case in point, as discussed, with a direct impact on fertilizer trade and investment.[59,93]

In addition, fertilizers speak to the importance of spatiality in supply chains,[11] highlighting how different feedstocks imply not only different types of interdependencies but also different options for their management. This is another important dimension that the existing GVC and supply chain literature has largely neglected in favor of a focus on delocalized, global systems. While some recent literature has started to interrogate the spatial element of supply chains (see for example Coe[94] and Bridge and Bradshaw[95]), the imperative of decarbonization is fundamentally reshaping the factors driving the spatial distribution of production within ammonia-based fertilizer supply chains or GVCs. Meanwhile, mineral resources in K and P fertilizer production imply a much more static spatial distribution. These differences make the sector a particularly important case in point. Changes in the spatial distribution of ammonia-based fertilizer production will depend strongly on the availability of renewable resources for large-scale green electricity production. Because of the importance of advantageous natural endowment factors such as the availability of high-volume, low-cost solar or wind power, other cost-based relocation opportunities are limited. At the same time, because of the significant role played by fertilizers in ensuring national-level food security, states will want to keep a significant portion of the food supply chain, including fertilizers and the ammonia that is essential for its production, within their borders.[96]

Fertilizers in a grand strategy perspective

Finally, from a broader geopolitical perspective, fertilizer supply chains are becoming incorporated into so-called "grand strategy" in the international political economy, serving long-term foreign affairs priorities as part of economic statecraft.[97] As a scholarly conversation, statecraft denotes the orchestrated "use of policy instruments to satisfy the core objectives of nation-states in the international system" (p. 826),[98] deliberately extending the state toolbox from military to economic or informational means of exerting or projecting power. This opens a number of important avenues for academic inquiry into the dynamics and instruments underpinning fertilizers as subject of grand strategy.

Fertilizers firmly sit at the intersection of economics and national security interests. Their importance for ensuring food security makes fertilizers subject to attempts to use economic commodities for achieving geopolitical ends, in a "war by other means."[99] Net exporters, most notably Russia, have started to utilize fertilizer shipments as an instrument in asserting themselves as partners for countries in the Global South. Importers, by contrast, have come to recognize access to fertilizers and key intermediate products, like ammonia, as important vulnerabilities. At the same time, exports may become subject to geopolitically motivated trade measures. For example, while Western sanctions in reaction to Russia's aggression against Ukraine have deliberately exempted fertilizer exports for their important role in world food supply, Belarus' potash exports indeed have been targeted in the wake of regime-suppressing domestic opposition in 2021, given their importance for the country's economy.[100]

Such patterns have been observed in other strategic commodities, notably oil. In the latter context, O'Sullivan[101] suggested distinguishing between ends, means, and ways of grand strategy. Although securing access to the commodity is the end of state action, control over commodity flows may be a means to coerce adversaries into a desired behavior. Ways, finally, relate to the financial gains from commodities, which may be used for non-market goals. Research from this perspective would add significant granularity to the emerging debate on fertilizer supply chains and their role in marshalling statecraft as part of grand power competition.

Another element lies in the simple but important insight that fertilizer markets are global and deeply intertwined. As Farrell and Newman[102] remind us, (trade) flows may be asymmetric, opening up opportunities to "weaponize" them. For example, potash exports of land-locked Belarus were crucially relying on Lithuania's ports. With these closed due to sanctions, remaining export routes are dependent on Russia, making Minsk exposed to the good will of Moscow. A grand strategy approach would, therefore, crucially need to dissect the upstream, midstream, and downstream segments of the fertilizer supply chain in order to determine crucial nodalities and lopsided interdependencies that may be exploited for geopolitical scheming, both by exporters and importers.

Fertilizer producers and exporters may, as indicated, use the commodity to incentivize or coerce other nations to follow a desired course of foreign policy action, along the line soft or hard power. Statecraft can, however, also alter political costs and opportunities of target countries.[103] This is a matter of political economy and raises important questions regarding the domestic fault lines arising from a changing external market environment (see also Abdelal and Kirshner[104]). Adopting a classic second image reversed argument,[105] grand strategy inquiry may thus link the phenomenon of fertilizer diplomacy back to an analysis of domestic structure. It also allows defining and testing conditions for compliance or successful resistance of domestic leaders with regard to external pressures, notably the level of stateness and the degree to which elites can insulate them from domestic interests.[106] This extends to inquiries into the policy approaches countries opt for in the Global North and the Global South, possibly also as a function of different levels of economic development and, by extension, economic structure.

A grand strategy analysis of fertilizers, finally, reveals important insights into the instruments of economic statecraft as wielded by states. The classics comprise, among others, sanctions, aid, institutionalized economic cooperation, or strategic commercial policy.[107] An interesting field of academic inquiry is regulation and the specific circumstances in which market power can be translated into strategic regulation. Again, energy research has lessons to offer, among other the EU's attempts to design rules with extraterritorial effects, notably in response to Russia's assertive geopolitical behavior.[108] As Kalyanpur and Newman[109] show, it is both the relative economic position of the rule-setting actor and the governance underpinning its markets that are determinants. Particularly when it comes to greening fertilizers, moves to inject sustainability principles into fertilizer supply chains come down to rule-setting power—both in response to the climate change imperative as well as regarding less benign motivations in the shape of green mercantilism.

CONCLUSION AND OUTLOOK

This article outlined how fertilizers and their embeddedness in the nexus of food, climate change, energy and mineral resources, environment, and security raise the political salience of the sector and give rise to a distinct set of challenges at different stages along the supply chain. Yet, it is not entirely unique how geopolitics and decarbonization are driving transformative changes in the sector. Rather, the patterns are arguably akin to other goods exhibiting similar characteristics.

In the case of nitrogen-based fertilizers, these notably include high carbon content, a high strategic importance for broader economic development or for meeting the basic needs of the population, and a relevant degree of (potential) supply chain dependence. While the transformative changes within fertilizer supply chains warrant further investigation in their own right, a better understanding of changes in the sector would also offer an important starting point for comparative research across other carbon-intensive industries. As suggested above, previous research on energy politics has had a strong focus on energy supply.[62,63] While still relevant, transitions within the so-called hard-to-abate sectors are increasing the political salience of the energy-intensive midstream segments within global supply chains. The transformation of these intermediate industries implies a major potential for disruptive structural changes across the global economy. These are likely to both trigger significant modifications in the geography of energy-intensive industrial production—similar to previous industrial revolutions—as well as government and corporate strategies aimed at shaping those changes.

A systematic, empirically driven analysis of nitrogen-based fertilizers alongside other energy-intensive commodities would offer important insights from both a scholarly and policy perspective. Indeed, identifying key commonalities and differences could go a long way in furthering a better understanding of how the interplay between decarbonization and geopolitics is reshaping both economic geographies and the related geopolitical maps.

In a similar vein, due to the absence of substitutes, the more static supply chain configurations for P and K fertilizers exhibit not only important parallels to but also potential interactions with emerging trends within the broader energy transition. The need for phosphorus for the production of lithium-ion batteries is a case in point. More broadly, critical mineral resources have emerged not only as an important bottleneck for the acceleration of the energy transition but also as an important locus of geopolitical competition. Fertilizers and the related mineral resources not only add an important additional layer to this, but highlight the importance of dedicated research focused on the multifaceted benefits of efficiency and circularity within global supply chains.

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AUTHOR CONTRIBUTIONS

Conceptualization, R.Q., M.B., and A.G.; writing - original draft, review and editing, R.Q., M.B., and A.G.; visualization – R.Q., A.G.; supervision, project administration, funding acquisition, R.Q.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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