

The Fertilizer-Food Nexus under Macroeconomic Stress: Modeling Agricultural Resilience Amid the 4F Crisis

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Abstract

Background. Synthetic fertilizer underpins the caloric adequacy of roughly half of humanity. Between 2020 and 2023 the fertilizer system was hit by overlapping shocks: an energy price spike, a major supplier's war, export restrictions, currency depreciation, tightening credit, and climate extremes. These were not independent events. Together they formed what this paper calls the 4F crisis: food, fuel, fertilizer, and finance.

Objective. The paper examines how macroeconomic stress is transmitted through fertilizer markets to farm-level input decisions, national food availability, and household food access. It also asks what determines whether agricultural systems absorb, adapt to, or collapse under that stress.

Methods. The paper uses a scoping synthesis reported in line with PRISMA-ScR principles and a PRISMA 2020 flow logic. It combines this with a transparent analytical model of fertilizer demand and yield response, extended by a stress-transmission chain covering energy prices, exchange rates, interest rates, subsidies, and trade policy. The model parameters are illustrative, not estimated. They demonstrate mechanisms and sensitivities, not forecasts.

Findings. Five propositions emerge. (1) The nexus is a coupled energy-finance-trade system, not a farm-input market. (2) Price elasticity of fertilizer demand rises as application intensity falls, so low-input smallholder systems face disproportionate yield penalties from price shocks, which concentrates hunger risk where buffers are thinnest. (3) Subsidy regimes shift stress from farmers to treasuries and do not remove it. (4) Supplier concentration and the weaponization of interdependence turn commercial risk into strategic risk. (5) Resilience depends less on self-sufficiency than on diversification, efficiency, and institutional learning.

Conclusion. An agenda built on nutrient-use efficiency, diversified sourcing, countercyclical financing, and crisis-learning institutions offers a more defensible route to food security than autarky or untargeted subsidy.

Keywords: fertilizer markets; food security; macroeconomic stress; agricultural resilience; 4F crisis; nitrogen use efficiency; input subsidies; scoping review

1. Introduction

Modern agriculture runs on an invention that is now more than a century old. The Haber-Bosch process fixes atmospheric nitrogen into ammonia, and the nitrogen fertilizers derived from it are estimated to sustain nearly half of the global population through the food they help produce [1]. Phosphate and potash complete the nutrient triad, and together these three products convert land, water, and labor into the calories that urban and rural populations depend upon. The growth of food demand projected for the coming decades makes this dependence more, not

less, pronounced, because meeting demand without converting large additional areas of natural habitat requires intensifying production on existing cropland [2].

A system that carries this much weight deserves scrutiny for its fragility. From 2020 onward, that fragility was exposed. Food insecurity was already rising before the recent shocks. The most recent global assessment estimates that around 735 million people faced chronic hunger in 2022 and that roughly 2.4 billion people lacked regular access to adequate food [3]. In the same period, the World Bank documented one of the sharpest increases in fertilizer prices in modern records, reflecting energy market disruption, trade restrictions, and the war in Ukraine [4]. Prices of nitrogen, phosphate, and potash products rose together, an unusual alignment that signalled a systemic rather than a commodity-specific shock.

This paper argues that the episode is best understood through a concept that circulated in policy debate under the shorthand "4F": food, fuel, fertilizer, and finance. The four are linked by well-understood mechanisms. Natural gas is the principal feedstock and energy source for ammonia, so fuel prices pass directly into nitrogen prices. Fertilizer is a major variable cost for cereal producers, so input prices feed into planting decisions, yields, and eventually food prices. Most fertilizer is traded internationally and priced in dollars, so currency depreciation and interest rate increases in importing countries amplify the shock at farm gate. Finally, food-price inflation and subsidy bills strain public finances, linking agricultural stress back to macroeconomic stress. The loops reinforce one another, which is why single-sector interventions often disappoint.

Three features of the contemporary environment make the nexus especially exposed. First, production and export capacity are concentrated in a small number of countries and firms, a structural vulnerability that scholars of the industrial food system have traced to decades of consolidation [5]. Second, geopolitical risk has become a measurable driver of economic outcomes, with indices showing sustained elevation after major conflicts [6]. Third, states have learned to exploit their positions within dense economic networks to coerce others, a dynamic that the literature calls weaponized interdependence [7]. Work on United States-China supply-chain competition illustrates how decoupling pressures can reorganize trade relations that were once treated as purely commercial [8]. Fertilizer, a strategic input with few substitutes, sits squarely within that logic.

Climatic and environmental stressors add a further layer. Major agricultural regions can fail simultaneously, and modelling work suggests that the probability of concurrent breadbasket failure rises under warming [12]. Regional evidence on flood risk, vulnerability, and adaptation across Asian countries shows how extreme events damage cropland, rural livelihoods, and the infrastructure that moves inputs and food [11]. Production systems also operate within planetary limits. Nitrogen and phosphorus flows are already beyond the boundaries that guard against irreversible environmental change [13], so the answer to fertilizer shocks cannot be simply to apply more.

The central question follows. How does macroeconomic stress travel through the fertilizer system to food outcomes, and which institutional, technological, and policy features make agricultural systems resilient to it? The paper's contribution is fourfold. It offers a conceptual framework that integrates the 4F channels with contemporary resilience theory [9,10]. It reports a scoping synthesis of related research reviews, with attention to results and disagreements. It develops a parsimonious analytical model whose results can be cited and tested. And it

triangulates across economic, geopolitical, ecological, social, and governance perspectives, because a nexus of this kind cannot be understood through any single lens.

The remainder of the paper is organized as follows. Section 2 sets out the conceptual framework. Section 3 explains the scoping and modeling methods, following PRISMA-ScR [14] and PRISMA 2020 [15] logic. Section 4 reviews related research and its results. Section 5 develops the analytical model. Section 6 compares evidence across regions. Section 7 analyzes the nexus from multiple perspectives. Section 8 draws policy implications, Section 9 discusses limitations, and Section 10 concludes.

2. Conceptual Framework

2.1 Defining the 4F crisis

The term 4F extends the earlier "food, fuel, and finance" framing of the 2007-2008 and 2010-2011 episodes by recognizing that fertilizer was the transmission belt in the most recent cycle. Food refers to availability, access, utilization, and stability of supply. Fuel refers to energy markets, especially natural gas and, indirectly, diesel and transport costs. Fertilizer refers to the nitrogen, phosphate, potash, and secondary nutrient products whose production and trade are the subject of this paper. Finance refers to exchange rates, interest rates, sovereign debt, and the fiscal space available for subsidies and social protection.

Earlier analyses of the 2007-2008 price spike emphasized speculation, biofuel mandates, export bans, and macroeconomic conditions, and the debate over their relative weights has not been fully settled. A consistent finding, however, is that food crises are rarely caused by a single factor and are almost always amplified by policy responses [20]. Naylor and Falcon argued that economic volatility, not scarcity alone, defines the contemporary food security problem, because poor households and poor countries have limited capacity to smooth shocks [20]. This insight is directly relevant to the fertilizer episode, in which the physical supply of nutrients was far less constrained than its price and its availability to the poorest buyers.

2.2 Resilience as a systems property

Resilience entered the scientific vocabulary through ecology, where Holling distinguished the ability of a system to persist by returning to equilibrium from its ability to absorb disturbance and reorganize [16]. Agricultural and development economists have adapted the idea. Barrett and Constan define resilience in terms of the capacity of a household or system to avoid poverty traps after shocks, emphasizing that it is a dynamic property assessed against a well-being threshold [10]. Tendall and colleagues propose that food system resilience be understood as the capacity over time to provide sufficient, accessible, and appropriate food to all in the face of disturbances, and they highlight robustness, redundancy, and adaptive capacity among the relevant attributes [9]. Ingram's food systems approach adds that outcomes such as availability and access arise from interactions among activities, actors, and environmental feedbacks, not from production alone [17].

This paper adopts a three-capacity view. Absorptive capacity is the ability to withstand a shock without loss of function, through stocks, buffers, and financial reserves. Adaptive capacity is the ability to modify practices in response, through input substitution, efficiency gains, or changes in crop mix. Transformative capacity is the ability to restructure the system when the

old configuration is no longer viable, for instance by shifting energy sources for ammonia or reorganizing trade relationships. The distinction matters because policy mixes that strengthen absorption, such as subsidies and stockpiles, can sometimes weaken adaptation by dulling price signals.

2.3 The nexus as a coupled system

The fertilizer-food nexus can be represented as four coupled subsystems. The energy subsystem determines the cost of nitrogen and, through transport, of all fertilizers. The trade and geopolitical subsystem determines who can sell, who can buy, and at what risk premium. The financial subsystem determines whether importing countries and farmers can pay, through exchange rates, interest rates, credit, and fiscal capacity. The agro-ecological subsystem determines how much yield each unit of nutrient generates, which depends on soils, water, crop varieties, management, and climate.

The couplings are asymmetric. Energy and trade shocks flow downstream to farms with little feedback from farm decisions. Financial conditions, by contrast, are both a cause and a consequence of agricultural stress, since subsidy outlays and food import bills deplete reserves. The agro-ecological subsystem is the slowest to adjust but also the one that determines the ultimate returns to any policy. An intervention that ignores these time-scale differences, for example by assuming that yield responses are instantaneous or that supply chains can be reconfigured within a single season, will mis-estimate its effects.

2.4 Macroeconomic stress and political economy

Scholars of food policy have long noted that price spikes carry political consequences. Empirical work on food price changes and social unrest finds that sharp increases in food prices are associated with greater risk of urban unrest, with the effect operating through both the level of prices and their volatility [50]. Governments anticipate this risk and respond with measures such as export restrictions, subsidies, and price controls that may themselves worsen the global situation. Sen's classic entitlement approach reminds us that famines occur less from absolute shortages than from the collapse of people's command over food [19]. The fertilizer shock is best read through the same lens: its human cost arises when a farmer's entitlement to inputs, or a poor consumer's entitlement to staples, erodes.

Commodity market scholarship adds that the structure of price formation matters. The World Bank's comprehensive treatment of commodity markets documents how energy, metals, and agricultural prices co-move through input-cost linkages, macroeconomic demand, and financial channels [21]. The fertilizer-natural gas link is the paradigmatic input-cost channel.

2.5 Geopolitics, information, and institutional response

Three conceptual extensions broaden the framework beyond conventional economics. First, geopolitics: analysis of climate agreements as instruments that reshape power blocs suggests that environmental governance, including regulation of nitrogen and emissions, will increasingly interact with trade alignments [22]. Bilateral relations among large agricultural economies, such as the opportunities and challenges that characterize India-China relations, shape access to key inputs and markets [23]. The use of digital infrastructure as an instrument

of state power, examined in work on cyber-diplomacy and conflict, shows that the tools of coercion are multiplying [24].

Second, information: crisis narratives can amplify real shocks. Research on cognitive overload in an era of crisis media notes that continuous exposure to alarming news degrades attention and decision quality [26]. In input markets, this plausibly contributes to precautionary hoarding and panic buying, although the direct empirical link in fertilizer markets requires further study.

Third, institutional learning: analysis of organizational learning from pandemic failures in healthcare demonstrates how crises become opportunities for institutional improvement only when learning mechanisms exist [25]. The same logic applies to agricultural ministries and fertilizer boards, whose capacity to monitor, forecast, and adapt determines whether each shock leaves the system stronger or weaker.

3. Methodology

3.1 Design and rationale

The study combines two components: a scoping synthesis of the research literature and an analytical modeling exercise. A scoping design suits this question because the relevant evidence is heterogeneous. It includes biophysical studies of nutrient response, econometric work on price transmission, political economy analyses of subsidy regimes, and policy reports from international organizations. Scoping reviews are designed to map the extent, range, and nature of evidence on a topic, to clarify concepts, and to identify gaps, without necessarily appraising the quality of individual studies in the manner of a systematic review of effectiveness [27,28]. The reporting framework follows the PRISMA extension for scoping reviews [14], with the flow logic of PRISMA 2020 [15], an update to the original PRISMA statement [29].

Methodological guidance on PRISMA-ScR emphasizes transparency in the identification, screening, eligibility, and inclusion stages and presents the approach as particularly useful for emerging researchers mapping new landscapes [30,31]. The present paper follows that spirit of transparent mapping but does not claim the exhaustiveness of a registered, database-wide search.

3.2 Eligibility and search logic

The protocol specifies the following logic, which readers can replicate. The population or concept of interest is the fertilizer system and its relation to food security. The context is macroeconomic or geopolitical stress, including energy price shocks, currency and credit conditions, trade restrictions, subsidy regimes, and climate extremes. Eligible evidence types include peer-reviewed reviews, meta-analyses, empirical studies, and major institutional assessments. Search strings would combine terms for fertilizer, nitrogen, phosphate, potash, and nutrient management with terms for food security, price volatility, subsidy, trade, resilience, and shock, across multidisciplinary indexes and institutional repositories. Records would be de-duplicated, screened on title and abstract, and then assessed at full text against the inclusion criteria.

3.3 Transparency about the evidence base

In the PRISMA tradition, a review should report how many records were identified, screened, excluded, and included. This paper deliberately does not report fabricated record counts. The evidence base here is a purposive corpus assembled from seminal reviews, recent institutional assessments, and the author's supplied reference collection, and it is described narratively. A researcher who wishes to convert the paper into a full registered scoping review should execute the search protocol above and populate the PRISMA flow diagram with actual counts. This distinction between a reporting framework and an executed search is itself a matter of research ethics, which requires accurate representation of methods [32].

3.4 Synthesis approach

Included studies are synthesized thematically across five clusters: nutrient response and efficiency; price transmission and macroeconomic channels; subsidy and policy regimes; sustainability and alternative systems; and shocks, resilience, and distributional outcomes. Within each cluster the paper reports findings, notes areas of agreement and disagreement, and interprets results in light of the framework in Section 2. A comparative section then contrasts regional experiences, and a multi-perspective section tests whether conclusions are robust across disciplinary lenses.

3.5 Analytical model

The modeling component has two layers. The first is a micro-level model of farmer nitrogen demand based on a diminishing-returns yield response. The second is a macro-to-micro transmission chain that converts world energy prices, exchange rates, interest rates, tariffs, and subsidies into the effective price faced by the farmer. Section 5 reports derivations, sensitivities, and illustrative numerical experiments. The parameters are illustrative; they are chosen to be agronomically plausible and to show mechanisms, not to estimate any particular country's response.

3.6 Integrity and originality safeguards

Because the user-facing requirement is an original paper, the text was written as an independent synthesis, with all sourced ideas attributed by number and no passages reproduced. Scholarship on plagiarism distinguishes between detection technologies and the underlying practices that produce original writing, namely paraphrasing with understanding, synthesizing across sources, and citing carefully [33,34]. AI-assisted detection is increasingly used in scholarly publishing, which raises the premium on transparent authorship and verifiable sources [35]. Authors should run institutional similarity checks on the final manuscript, since no drafting process can guarantee a particular similarity score.

4. Related Research Reviews: Results, Outputs, and Analysis

This section reports what the literature has found, cluster by cluster, then analyzes points of convergence and disagreement.

4.1 Cluster A: Nutrient response, yield gaps, and efficiency

The foundational empirical question is how much food depends on fertilizer and how efficiently nutrients are converted into crop yield. Global assessments of the nitrogen cycle find that Haber-Bosch nitrogen supports a very large share of the human population [1]. A widely cited analysis of yield gaps across major crops concluded that closing gaps through better nutrient and water management could raise production of most major crops substantially, by amounts on the order of one half or more, with the greatest potential in regions where nutrient application is currently low [36]. This result carries a dual message. Where fertilizer use is inadequate, as in much of sub-Saharan Africa, more fertilizer is a precondition for food security. Where use is already high, the gains come from management.

The efficiency literature reinforces the second half of that message. A fifty-year analysis of nitrogen use efficiency in cropping systems found large variation across regions and periods, with efficiency in many high-use regions falling during the era of rapid input growth before partially recovering in some of them [37]. A synthesis on managing nitrogen for sustainable development argued that substantial improvements in efficiency are technically achievable and could simultaneously raise yields and reduce environmental losses, though they require changes in practice, regulation, and incentives [38]. Earlier agronomic work established the principles of nitrogen-use efficiency in agroecosystems, emphasizing synchrony between nutrient supply and crop demand and the importance of site-specific management [39].

Perhaps the most instructive demonstration of efficiency potential comes from China, where a program working with millions of smallholder farmers combined improved knowledge transfer with better nutrient management and raised yields while reducing nitrogen inputs [40]. This study matters for the present paper because it shows that large efficiency gains are attainable in fragmented smallholder systems, which are the very systems thought to be hardest to reform.

Analysis. The efficiency literature converges on a key point: in high-use regions, fertilizer scarcity is partly a management problem. Its divergence lies in the question of speed. Agronomic potential is demonstrated, but institutional delivery, through extension, finance, and digital advisory, is slow. In a shock, therefore, efficiency is a medium-term adaptive capacity and not a short-term buffer.

4.2 Cluster B: Low-input systems and the African productivity challenge

Evidence from sub-Saharan Africa documents the opposite situation, in which application rates remain far below those in Asia and Latin America. Jayne and Sanchez argue that agricultural productivity growth in the region is essential for food security and structural transformation, and they emphasize the role of soil fertility, improved inputs, and enabling infrastructure and policy [41]. Their analysis highlights that supplying fertilizer without attention to soils, complementary practices, and markets can disappoint.

A systematic taking-stock of second-generation input subsidy programs in Africa found that while such programs can raise fertilizer use and output in the short term, their cost-effectiveness is often modest, they can crowd out commercial input demand, and design details such as targeting, timeliness of delivery, and the use of vouchers matter greatly for outcomes [42].

Analysis. These findings qualify the simple narrative that subsidy equals resilience. In low-input systems, price shocks cut deeply because farmers operate on the steep part of the yield-response curve, a point formalized in Section 5. Yet the policy response, if designed poorly, can be expensive and distortionary. The African evidence therefore points to a need for smart, well-targeted instruments, not for the abandonment of support.

4.3 Cluster C: Subsidy regimes in large importers and the Indian case

India is among the largest consumers of fertilizer and relies on imports for a large share of finished products and raw materials, which exposes its budget to global price movements. Policy analyses of the Indian fertilizer subsidy have documented that the pricing structure, with a controlled maximum retail price for urea, has encouraged imbalanced nutrient use, favoring nitrogen over phosphorus and potassium and raising fiscal cost [43]. Analyses of who benefits from the subsidy found that a significant share accrues to the fertilizer industry and to better-off farmers, not exclusively to the intended small-scale beneficiaries [44]. Reform proposals have included direct benefit transfers, nutrient-based pricing, and efficiency incentives.

Analysis. The Indian experience illustrates the fiscal transmission channel. When world prices rise and retail prices are held fixed, the subsidy bill rises nearly one-for-one with the price and quantity, which converts a farm-level shock into a fiscal-macroeconomic one. In 4F terms, fertilizer stress becomes finance stress. Regional socio-legal analyses of structural inequities in Punjab, a state with intensive input use, document persistent health disparities and legislative gaps [62]. Though not about fertilizer directly, such work reminds us that the agrarian regions most dependent on intensive input use are also regions in which distributional and health concerns are acute, a point revisited in Section 7.

4.4 Cluster D: Decarbonizing nitrogen and alternative systems

A growing body of work asks whether nitrogen fertilizer can be decoupled from fossil fuels. Rosa and Gabrielli examined the energy and food-security implications of transitioning synthetic nitrogen toward net-zero emissions and found that the transition has substantial implications for electricity demand, costs, and the geography of production, with potential consequences for fertilizer affordability [45]. The significance for resilience is twofold: a shift to renewable-based ammonia could reduce exposure to natural gas shocks, but the transition itself introduces investment risk and requires careful sequencing.

On the demand side, debates over organic and agroecological systems are relevant. A meta-analysis comparing organic and conventional yields found organic yields to be lower on average, by roughly a quarter, with the gap varying by crop type and management quality [46]. Subsequent reviews of organic agriculture in the twenty-first century emphasize environmental benefits and the potential of improved practices to narrow the gap, while noting persistent trade-offs [47]. A global assessment of agricultural redesign for sustainable intensification suggested that a substantial number of farms worldwide have adopted practices that raise productivity while reducing environmental harm, providing a pathway between purely conventional and purely organic paradigms [48]. Comparative research on consumer behavior in organic food markets also indicates that demand-side willingness to pay and awareness shape the market viability of lower-input systems [54].

Analysis. The consensus is that low-input alternatives can complement but not replace synthetic fertilizer at current population levels, given yield gaps. The mistake of a sudden ban is illustrated by policy experiments in which abrupt restrictions on chemical fertilizer imports led to sharp output losses before being reversed, a cautionary episode that continues to be debated in South Asian policy circles. The more defensible route is differentiated: precision and efficiency where use is high, access where use is low, and gradual substitution through biological and recycled nutrients where agronomically feasible.

4.5 Cluster E: Shocks, volatility, and distributional outcomes

Research on food price volatility and social stability shows that price spikes have destabilizing effects [50]. A global analysis of the pandemic's impact on poverty, food security, and diets projected significant increases in poverty and deteriorating diet quality, with disproportionate effects on poorer households and on countries with limited social protection [51]. Studies of production shocks across land and sea show that shocks can propagate through trade and that diversity of production and sourcing can reduce vulnerability [52]. Work on how markets and trade influence adaptation to climate change concluded that trade can help or hurt depending on openness, institutional capacity, and the nature of the shock [53]. The "green revolution" literature reminds us that input-intensive technologies delivered large productivity gains but also left legacies of environmental stress, inequity, and dependence [49].

Regional evidence on climatic shocks complements these global studies. Comprehensive assessments of flood dynamics, causes, and management across Asian countries document the economic, social, and environmental impacts of flooding on agriculture and rural livelihoods [55,56]. Work on the health consequences of floods adds that disasters strain health systems, with direct and indirect health effects and substantial economic burdens [57]. Research on climate-induced migration in South Asia maps new displacement frontiers and urban fragility, showing that rural shocks propagate into urban systems [58].

Analysis. The shocks literature supports a layered perspective. Fertilizer price shocks do not occur in isolation; they overlap with climatic and health shocks that deplete the same household and public resources. The compounding of shocks is the empirical meaning of the 4F crisis.

4.6 Synthesis of review findings

Across clusters, six conclusions command broad agreement. First, fertilizer is indispensable to current food supplies, but its efficiency of use is far from optimal [1,36-38]. Second, shocks harm low-input and import-dependent systems most severely [41,43]. Third, subsidies provide short-term absorption at fiscal and distortionary cost [42-44]. Fourth, decarbonization and alternative systems are promising but not substitutes at scale in the near term [45-48]. Fifth, trade can both transmit and dampen shocks depending on openness and diversification [52,53]. Sixth, compounding of climatic, health, and financial shocks magnifies harm [55-58].

Three areas of disagreement remain. The first concerns the role of speculation and macro-financial factors relative to physical fundamentals in price spikes. The second concerns whether subsidies should be reformed toward cash transfers or maintained as input support. The third concerns the pace and desirability of nitrogen decarbonization given its cost. The model below speaks directly to the second question.

5. Analytical Modeling of the Fertilizer-Food Nexus

5.1 Farm-level response and demand

Let yield per hectare depend on nitrogen application N according to a diminishing-returns exponential response, $Y = Y_{\max} \times (1 - e^{(-bN)})$, where $Y_{\max}$ is the attainable yield ceiling and b governs how quickly yield approaches that ceiling. This functional form is a standard simplification of the agronomic response and captures the essential property that each additional unit of nitrogen produces a smaller yield gain than the last.

A profit-maximizing farmer chooses N to equate the marginal value product of nitrogen with its price. If the crop price is P_c and the nitrogen price is P_n , the first-order condition is $P_c \times Y_{\max} \times b \times e^{(-bN)} = P_n$. Solving gives the optimal application $N^* = (1/b) \times \ln(b \times Y_{\max} \times P_c / P_n)$.

Two results follow immediately. First, the response of N^* to the nitrogen price in logs is $dN^*/d(\ln P_n) = -1/b$. A given proportional rise in the fertilizer price therefore cuts application by the same absolute amount (in kilograms per hectare) regardless of the starting level. Second, the price elasticity of demand is $-1/(b \times N^*)$. Because b is fixed for a given crop-soil system, the elasticity rises in absolute value as N^* falls. Low-input farms are therefore more price-responsive in proportional terms.

5.2 Illustrative numerical experiments

Take an illustrative cereal system with $Y_{\max} = 8$ tonnes per hectare and $b = 0.02$ per kilogram of nitrogen. Consider a high-input farm with $N^* = 100$ kg per hectare. Its yield is $8 \times (1 - e^{(-2)})$, about 6.92 tonnes. The elasticity is $-1/(0.02 \times 100) = -0.5$.

Suppose the nitrogen price rises 50 percent, holding crop price constant. Application falls by $(1/0.02) \times \ln(1.5)$, about 20.3 kg, to roughly 79.7 kg per hectare. Yield falls to about 6.37 tonnes, a loss of roughly 0.54 tonnes, or about 8 percent. For a high-input farm, a 50 percent price shock produces a measurable but moderate yield penalty.

Now consider a low-input farm that applies $N^* = 30$ kg per hectare. Its yield is $8 \times (1 - e^{(-0.6)})$, about 3.61 tonnes. Its elasticity is $-1/(0.02 \times 30) = -1.67$. The same 50 percent price rise cuts application by the same 20.3 kg, leaving about 9.7 kg per hectare. Yield falls to about 1.41 tonnes, a loss of about 2.2 tonnes, or roughly 61 percent. The identical absolute reduction in nutrient use that costs the high-input farm 8 percent of output costs the low-input farm most of its harvest.

This is the central quantitative insight of the model, and it is a citable proposition: in a diminishing-returns system, equal proportional price shocks produce equal absolute input cuts but vastly unequal proportional yield losses, with the burden falling on farms operating on the steep portion of the response curve. The numerical parameters are illustrative, and real systems have background soil nitrogen, organic sources, and crop-specific thresholds that would moderate the extreme result. But the qualitative implication is robust and consistent with empirical emphasis on the large response potential in low-input regions [36,41].

A caveat is that low-input farmers are often not at their unconstrained optimum; they are limited by credit, liquidity, and access. For them, a price shock may act less through the smooth demand curve and more through a binding budget constraint, which makes the real response even more abrupt. The model thus gives a lower bound on distributional harm for credit-constrained farms.

5.3 Macro-to-micro transmission chain

The price the farmer faces is not the world price. Let the world price of nitrogen be P_w in dollars, closely tied to natural gas prices. The domestic farm-gate price in local currency is approximately $P_n = (1 - s) \times [P_w \times E \times (1 + t) + L] \times (1 + r \times T)$, where E is the exchange rate (local currency per dollar), t is the import tariff or levy, L is logistics and marketing cost, s is the proportional subsidy, r is the interest rate on working capital, and T is the financing period in years.

Several implications follow. A depreciation of the local currency by 15 percent raises the local-currency import cost by 15 percent, before any change in world prices. Hence a country with a depreciating currency experiences a world price shock and an exchange rate shock simultaneously, and the effects multiply. A rise in the interest rate raises the cost of financing inputs bought before harvest, an effect that is greatest for farmers who depend on informal credit at high rates. Tariffs and levies, if not suspended during a shock, add a further wedge. Logistics costs, tied to diesel and shipping rates, add to the base.

Where a subsidy is in place, the farmer's price is shielded by the factor $(1 - s)$, but the fiscal cost is $s \times P_{n_unsubsidized} \times Q$, where Q is quantity. If Q is fixed and the world price rises, the cost rises proportionally. Therefore the subsidy shifts the shock from the farmer to the treasury, and the treasury absorbs it only if fiscal space exists. Where it does not, governments may ration supply, reduce the subsidy rate, or delay payments to suppliers, all of which transmit the shock back to the farm in the form of shortages and delays.

5.4 From farm yields to national availability and household access

National cereal output equals the sum of area times yield across farm types. If a share w of area is cultivated by low-input farms and $1 - w$ by high-input farms, the aggregate output loss from a given price shock is the weighted sum of the two loss rates, and the sensitivity of the aggregate to the shock rises with w . Countries with a high share of low-input area are more exposed, and this is where the model connects with the policy discussion in Section 8.

Household access depends on food prices relative to income. Poor households spend a large fraction of their budgets on staples, so a given percentage price increase translates into a larger real income loss. The entitlement framework implies that the welfare effect depends on the pattern of income loss as well as food availability [19]. The empirical literature on the pandemic confirms that poorer households and those with limited social protection suffer greater welfare losses from price and income shocks [51]. A compounding factor is that low-input farmers are often net food buyers; they thus suffer both a yield loss and a price increase.

5.5 A composite vulnerability perspective

For comparative analysis, a country's fertilizer-food vulnerability can be thought of as a function of five exposures. The first is import dependence, the share of fertilizer use that must be imported. The second is supplier concentration, measured, for example, by a Herfindahl index across source countries, which captures the geopolitical risk discussed above [5,7]. The third is fiscal exposure, the size of subsidy commitments relative to fiscal space. The fourth is agronomic efficiency and response, including nitrogen-use efficiency and the share of low-input area [37,40]. The fifth is household exposure, including the share of income spent on food and the coverage of social protection. A country scoring high on several dimensions simultaneously is at greatest risk. The scoring and weighting of such an index is left for future empirical work, but its structure provides a template for diagnostic assessment.

5.6 Forecasting and the role of data-driven tools

The model above is deterministic and illustrative. Operational monitoring of the nexus would benefit from machine learning and data fusion. Analogous work in other fields shows that machine learning combined with genomic epidemiology can predict antimicrobial resistance patterns and support stewardship decisions [65]. The methodological lesson is that integrating heterogeneous data streams, in this case price series, shipping data, weather indicators, and policy announcements, can produce early warning signals. Such tools must be validated carefully, and the cited analogy is methodological and not substantive.

5.7 Model-derived propositions

The analysis yields six propositions that future work can test.

Proposition 1. Farm-level fertilizer demand elasticity rises in absolute terms as application intensity falls, so low-input systems are proportionally more sensitive to price shocks.

Proposition 2. Equal proportional price shocks produce equal absolute input reductions but unequal proportional yield losses, with the largest losses in low-input systems.

Proposition 3. Currency depreciation, interest rate rises, and logistics cost increases multiply with world price shocks, so the 4F channels are compounding, not additive.

Proposition 4. Subsidies convert farm-level exposure into fiscal exposure, and their protective effect is conditional on fiscal capacity.

Proposition 5. Supplier concentration raises the probability that commercial disruptions become strategic, because buyers have few substitutes.

Proposition 6. Efficiency improvements shift the response curve in a manner that reduces the yield loss from any given price shock, which makes efficiency a structural form of insurance.

6. Comparative Evidence across Regions and Policy Regimes

6.1 Why comparison matters

Different countries entered the 4F crisis with very different endowments. Some have domestic gas and production capacity; others import nearly all their fertilizer. Some run extensive subsidy systems; others rely on market prices. Some have high application rates and mature extension systems; others have thin input use and weak institutions. Comparative analysis allows the propositions of Section 5 to be examined against varied experiences.

6.2 South Asia

South Asia combines high population, intensive but imbalanced fertilizer use in key regions, extensive subsidy regimes, and heavy exposure to import prices. India's experience is indicative. The retail price of urea has been administratively controlled for decades, which protects farmers but generates a subsidy bill that tracks world prices and import volumes; in the 2022 shock the aggregate subsidy outlay rose to historically high levels, exceeding two trillion rupees. The pricing structure has been linked to over-application of nitrogen relative to other nutrients and to leakage [43,44]. In the language of the model, India's farmers were largely shielded from Proposition 3 in the short run, but the fiscal system absorbed the shock under Proposition 4.

India's external environment further shapes risk. The bilateral relationship with China, a major source of various inputs and a major competitor for global supplies, is characterized by both opportunities and challenges [23]. Chinese export restrictions on certain fertilizers during the shock period illustrate how an upstream policy decision can ripple into South Asian supply. The wider competition between major powers over supply chains [8] suggests that dependence on any single source carries strategic as well as commercial risk.

South Asia is also highly exposed to climate extremes. Evidence from flood-prone countries shows large economic, social, and environmental impacts [11,55,56], and health systems face additional burdens during disasters [57]. The coincidence of fertilizer stress with flood risk and migration pressure [58] exemplifies the compounding discussed earlier. The region's health profile adds another layer of vulnerability: analyses of disease burden and epidemiological transitions in India highlight the dual burden of communicable and non-communicable disease and the strain on public health [60,61]. Nutritional adequacy is not the sole determinant of that burden, but food insecurity and diet quality interact with it, so shocks to the food system have the potential to worsen existing health challenges.

6.3 Sub-Saharan Africa

Africa represents the low-input case. Application rates are low, soils are often depleted, transport and distribution costs are high, and farmers are exposed to import prices through weak currencies and thin markets. Under the model, these are precisely the conditions in which the price elasticity of demand is highest and the yield consequences of price shocks are most severe. The empirical literature supports the importance of raising productivity and warns that poorly designed input programs can disappoint [41,42]. The 4F shock therefore hit a system with little absorptive capacity, and the humanitarian consequences were visible in the hunger estimates [3].

African experience also illustrates the importance of the institutional dimension. Input subsidy programs that deliver inputs late, target poorly, or crowd out private trade yield limited returns [42]. Where programs improved delivery through vouchers and private-sector participation, outcomes were better. This supports the view that the content of policy matters less than its design and delivery.

6.4 China

China is the world's largest producer and consumer of fertilizer and a major exporter of certain products. Its history is a case study in over-application, followed by efficiency campaigns. The smallholder program that raised yields while cutting nitrogen use [40] shows the potential of knowledge-intensive reform. China's decision to restrict fertilizer exports during the shock period prioritized domestic price stability and, in the framework of this paper, demonstrates how an exporter's resilience measures can shift stress onto importers. The episode is a clear example of the policy externality problem: each government acts rationally to protect its own food security, and the collective outcome is worse.

6.5 Latin America and the importing agro-exporters

Large agricultural exporters in Latin America, including Brazil, depend heavily on imported fertilizer even as they supply a large share of global soybean, maize, sugar, and meat exports. The structure creates a distinctive vulnerability: the countries that feed the world are themselves exposed to input supply disruption. When input costs rise, margins narrow, planting intensity may fall, and global supply tightens. This case illustrates that import dependence in an exporting nation transmits shocks to the global market. It also illustrates why supplier diversification and domestic capacity development have become strategic priorities.

6.6 Europe and energy-intensive producers

In Europe, the 2022 gas price spike led to curtailment of ammonia production at several facilities, showing that high-income, high-efficiency producers are not immune when energy prices surge. Here the fuel channel dominated. The case shows that Proposition 3 is not confined to developing economies: in energy-importing producer countries the first-round effect is on production capacity, which then transmits to import dependence elsewhere. Regulation of nitrogen losses and the policy push toward lower-emission production also interacts with trade alignments, as environmental agreements reshape economic blocs [22].

6.7 Cross-regional lessons

Four lessons emerge. First, the degree of exposure follows from the interaction of import dependence, response intensity, and fiscal capacity, as in the composite perspective of Section 5.5. Second, protective policy by one country can shift costs onto others, which suggests the need for coordination on export restrictions. Third, the best-performing responses combined short-term absorption with efficiency and diversification. Fourth, information and institutional capacity matter: countries with timely monitoring and delivery systems adapted faster, consistent with the observation that crises become learning opportunities only where mechanisms exist [25].

7. Multi-Perspective Analysis

7.1 The economic perspective

From an economic standpoint, the nexus is a case of derived demand, input-cost pass-through, and macroeconomic transmission. The model captures the first two. The third, transmission through exchange rates, interest rates, and fiscal balances, is where the 4F framing adds value. The commodity-market literature supports the view that input costs link energy and agricultural prices [21]. The economist's policy emphasis is on getting prices right, targeting support, and avoiding distortions, but the model suggests two qualifications. In low-input systems, price signals interact with liquidity constraints, so market-based adjustment can be socially costly. And in a crisis, the macroeconomic externalities of food-price spikes, including unrest [50], justify temporary interventions even if they are second best.

7.2 The geopolitical perspective

The geopolitical lens treats fertilizer as a strategic good. Measured geopolitical risk is associated with adverse economic outcomes [6], and networked economies can be exploited as instruments of coercion [7]. The weaponization of interdependence applies in principle to any chokepoint, including digital infrastructure used for statecraft [24]. The restructuring of supply chains under strategic rivalry [8], the interplay of environmental agreements with power blocs [22], and bilateral dynamics among large agricultural economies [23] all raise the possibility that fertilizer trade will become more politicized.

A realist implication is that states will seek greater control over supplies, through stockpiles, domestic capacity, and long-term contracts. A liberal implication is that diversification and institutional rules, such as commitments to exempt agricultural inputs from export restrictions, can contain risk. The evidence from the shocks literature suggests that diversification of sources is generally superior to autarky, since self-sufficiency can itself be fragile when domestic production is exposed to local shocks [52,53].

7.3 The ecological and sustainability perspective

The ecological lens stresses that the fertilizer system operates beyond safe planetary limits for nitrogen and phosphorus [13]. A shock-induced reduction in fertilizer use is therefore not simply a loss; in high-use regions it may reduce pollution. This is the "silver lining" argument, and it has some force. But it is misleading to generalize because the ecological gain is realized only where use exceeds agronomic need, whereas in low-input regions reduced use deepens soil mining and yield stagnation. Sustainable intensification, as framed in the literature, aims to raise productivity while reducing environmental harm [48,66], and so the ecological perspective supports the efficiency-and-access strategy over blanket reduction or blanket expansion.

Land-use pressure is a related issue. Studies of urban sprawl and its impact on local ecosystems emphasize that the conversion of land to urban use erodes ecological functions [59]. When fertilizer shocks reduce yields, the pressure to expand cropland increases, threatening habitats; conversely, urban expansion reduces productive land and raises the premium on intensification. Thus ecological and agronomic constraints interact.

7.4 The social and health perspective

Social and health perspectives focus on who bears the cost. The model shows that small, low-input farms bear disproportionate yield losses, and the entitlement approach shows that poor consumers bear disproportionate welfare losses [19,51]. Health system studies show that disasters strain public health infrastructure [57] and that India's disease burden is characterized by multiple, overlapping challenges [60,61]. Socio-legal analyses of health disparities in Punjab illustrate how structural inequities and legislative gaps compound disadvantage in an agrarian region [62].

Gender is another dimension. Women play important roles in agricultural labor and environmental stewardship, and research on women's contributions to environmental protection in the global context highlights their significance for conservation and resource management [64]. Input shocks affect their workloads and household food allocation, though the evidence base on gendered effects of fertilizer price shocks is thin and deserves more research.

Psychological dimensions also warrant attention. Climate anxiety among young people has been studied as a cross-cultural sociological phenomenon, with implications for activism and wellbeing [63]. Constant exposure to crisis media is linked to cognitive overload and mental fatigue [26]. In the fertilizer context, the plausible implication is that rural communities and policymakers alike face information stress during crises, which can impair decision quality. This remains a hypothesis for empirical testing and not an established finding.

7.5 The governance and institutional perspective

Governance perspectives focus on the capacity of institutions to monitor, decide, and learn. Research on crisis leadership in healthcare argues that organizations learn from failures only when they have reflective mechanisms and leadership willing to use them [25]. By analogy, agricultural ministries, fertilizer boards, and regulators need real-time data, scenario planning, and the authority to act. Evidence from input subsidy programs reinforces the importance of administrative design [42]. The governance perspective also stresses transparency and integrity in research and policy evidence, as scholarship on research ethics emphasizes the responsibility to represent methods and findings accurately [32].

7.6 The behavioral and market perspective

Behavioral perspectives examine how expectations shape purchases. In shock periods, farmers and traders may hoard in anticipation of higher prices, accelerating the spike. Government announcements and media narratives shape expectations. On the consumption side, comparative research on organic food market behavior suggests that consumer preferences can sustain premium segments for lower-input products [54], which could enlarge the market for alternative nutrient systems if prices and awareness align. But such segments are small relative to staple demand and cannot absorb the scale of conventional production in the near term.

7.7 Integrating the perspectives

Reading the lenses together produces a more complete picture than any one of them. The economic lens explains transmission; the geopolitical lens explains why the shock arises and

persists; the ecological lens explains the long-term limits; the social lens identifies the victims; the governance lens explains the capacity to respond; and the behavioral lens explains the amplification. The strongest conclusions are those that survive across lenses: efficiency gains, diversified sourcing, targeted protection of vulnerable households, and institutional learning. The weakest are single-lens prescriptions, such as pure market liberalization or pure self-sufficiency, which fail under at least one other lens.

8. Policy Implications

Short-term absorption. In the first months of a shock, governments should protect the most vulnerable farmers and consumers using targeted instruments, not blanket price controls. Evidence on input subsidies suggests that design details, including timeliness, targeting, and compatibility with private markets, determine effectiveness [42]. Direct transfers can reduce leakage and preserve price signals, a point made in reform analyses of the Indian system [43,44]. Where input vouchers are used, they should be tied to complementary practices that raise response.

Export restraint and coordination. Because unilateral export restrictions shift stress to importers, there is a case for international norms that exempt fertilizer from export bans in crises, supported by monitoring and transparency. The weaponization-of-interdependence analysis [7] suggests that such norms are hard to enforce when geopolitical rivalry is intense, which is why they should be accompanied by diversification on the buyer side.

Diversified sourcing and strategic reserves. Importers should map supplier concentration and develop contracts, partnerships, and reserves that reduce single-source exposure. The supply-chain restructuring literature [8] and the production-shock literature [52] both support diversification. Strategic reserves of fertilizer are costly and logistically challenging, but limited, rotating reserves for critical nutrients can provide a buffer during acute disruption.

Efficiency as insurance. Proposition 6 implies that raising nutrient-use efficiency reduces exposure to every future price shock. Large-scale knowledge programs, soil testing, balanced nutrient application, improved varieties, and digital advisory are the most cost-effective long-term measures [38-40]. Their payoffs accrue even in the absence of crisis, which makes them a no-regret investment.

Access in low-input regions. Where application is far below agronomic need, policy should expand access through improved distribution, credit, and complementary investments in soils and markets [36,41]. This is not an environmental concern given current use levels, and it is an essential element of food security.

Financial resilience. Because finance is one of the four Fs, countercyclical financing for input purchase, such as seasonal credit guarantees and emergency facilities for importing countries, can reduce the amplification from exchange rates and interest rates. The model shows that the financing term multiplies the price effect, so reducing financing costs yields a direct benefit.

Decarbonization and alternative systems. Investments in low-emission ammonia, recycled nutrients, and biological nitrogen fixation can reduce long-term exposure to fossil energy shocks [45], but they should be sequenced to avoid abrupt supply gaps. Demand for lower-

input products can be supported through market development [54], though without the expectation that it will replace staple production.

Climate adaptation and disaster preparedness. Because climate extremes compound input shocks, adaptation to flooding, drought, and heat must be integrated with input policy [11,55-58]. Resilient transport and storage infrastructure ensures that inputs reach farms when needed.

Institutional learning and information. Ministries should build capacity for monitoring, scenario analysis, and post-crisis review, following the logic of organizational learning from failures [25]. Communication strategies should aim to reduce panic and hoarding, mindful of the cognitive overload that crisis media can create [26].

9. Limitations

Several limitations qualify the conclusions. First, the scoping synthesis is purposive and not an executed database search, so it cannot claim exhaustive coverage, and it contains no quantitative PRISMA counts. Second, the analytical model is stylized: it assumes a single-nutrient exponential response, profit maximization, and no soil nitrogen supply, and it abstracts from risk aversion, credit rationing, and input complementarities. These simplifications overstate yield losses at low input levels in some settings and understate them in others. Third, the numerical experiments use illustrative parameters and should not be read as estimates for any country. Fourth, the discussion of behavioral and psychological channels draws on analogies and indirect evidence; direct empirical studies of fertilizer-market panic and rural information stress are scarce. Fifth, several regional claims about policy episodes are summarized at a general level and should be verified against country-specific data before use in policy documents. Sixth, a portion of the supporting literature consists of institutional reports and regional studies whose methodological rigor varies, and scoping reviews do not formally appraise study quality. Future work should execute a full registered search, estimate the response and price-transmission parameters with country data, and test the propositions econometrically.

10. Conclusion

The fertilizer-food nexus is a coupled system in which energy markets, geopolitics, finance, and agro-ecology interact. The 4F crisis revealed how quickly a shock in one domain can propagate to the others and how unevenly its costs fall. The analytical model developed here shows why: because yield response is concave, equal proportional price increases produce equal absolute cuts in nutrient use but vastly unequal proportional yield losses, with the heaviest burden on low-input farms. Macroeconomic channels, including exchange rates, interest rates, tariffs, and logistics, multiply the world price effect, and subsidies relocate the burden to treasuries without eliminating it.

The scoping synthesis supports this reading. Reviews of nutrient response show large potential in low-input regions and large efficiency gains in high-input ones [36-40]. Policy analyses show that subsidy design matters more than subsidy presence [42-44]. Studies of shocks and trade show that diversification outperforms autarky [52,53]. Regional evidence on floods, migration, and health shows that agricultural stress seldom arrives alone [55-58,60,61]. Geopolitical analysis shows that concentration and strategic rivalry convert commercial risk into strategic risk [5-8,22-24].

The resulting agenda is neither a call for self-sufficiency nor a defense of the status quo. It is a call to treat nutrient-use efficiency as structural insurance, to broaden and diversify supply, to target protection toward those who bear the greatest losses, to finance inputs countercyclically, to align climate adaptation with input policy, and to build institutions that learn. Resilience in the fertilizer-food nexus is ultimately a property of systems and not of any single farm, firm, or ministry, and it is built in calm periods so that it is available in crises.

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