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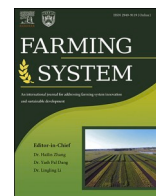
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Nitrogen at the nexus of food, energy and soil security

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ABSTRACT

Global food production relies heavily on fossil-energy-derived nitrogen (N) fertiliser, creating a structural vulnerability to energy and geopolitical shocks. Disruptions rapidly raise fertiliser costs, threaten food production, and disproportionately affect smallholders and import-dependent countries. This paper argues that nitrogen is no longer only an agronomic input or an emissions problem, but a strategic vulnerability at the intersection of food, energy, and soil security. We review what is established in nitrogen science, where uncertainties remain, and why technical knowledge has not translated into enduring improvements in nitrogen productivity. We then propose a leverage-based research and policy agenda: buffering current systems against shocks, improving nitrogen flows within existing production systems, changing feedbacks and incentives, restructuring nutrient and energy pathways, and ultimately redefining agricultural goals around sustained production under lower fossil nitrogen dependence. The central task is not simply to maximise nitrogen-use efficiency, but to build food systems that maintain yield and profitability, reduce exposure to fossil-energy and fertiliser-market shocks, and protect the soil nutrient capital on which long-term productivity depends. Reframing N this way shifts the agenda from isolated technical fixes to coordinated changes in agronomy, breeding, soil biogeochemistry, infrastructure, markets, and policy.

1. Introduction

Global food production rests on a precarious energy foundation. The fuel, fertiliser, and freight systems that underpin modern agriculture share a common dependence on fossil energy and a small number of concentrated supply chains, making them jointly vulnerable to the same geopolitical and market shocks (Quitzow et al., 2025). This structural fragility is often framed as a supply chain management problem, but the disruptions of the past decade, the COVID-19 pandemic, the Russia-Ukraine military conflict in 2022, and the 2026 Strait of Hormuz crisis, reveal that the current food system amplifies energy shocks (Ben Hassen and El Bilali, 2022; Naja et al., 2026).

The Hormuz crisis is the most recent and most direct illustration. Approximately 30–40% of globally traded ammonia and urea transits through the Strait. Disruptions to fertiliser production drives urea prices up by approximately 80% between February and April 2026, while

global fertiliser trade volumes fell by 20–25% during January–April relative to the same period in 2025 (Zereyesus et al., 2022; Williams et al., 2025; Baffes and Temaj, 2026; FAO, 2026). Similar energy and freight pressures also affect phosphorus- and potassium-based fertilisers through mining, processing and transport costs. At farm level, the same shock can simultaneously increase the cost of fertiliser, fuel, irrigation, machinery operation and transport, amplifying its effect on production. These impacts are not distributed evenly. During the global fertiliser crisis between 2019 and 2022, fertiliser consumption across Africa fell by 25%. On already nutrient-depleted soil, this deepened yield risks, slowed soil fertility recovery, and increased exposure to food-price shocks (African Union, 2024).

The Haber–Bosch process transformed twentieth-century agriculture by enabling the high-yielding crop systems of the Green Revolution, but it did so by substituting biological nitrogen (N) cycling with fossil-energy-derived synthetic N, coupling food production tightly to fossil

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fuel markets and centralised global supply chains (Pellegrini and Fernandez, 2018; Billen et al., 2021). Before this transition, farming systems depended more heavily on human and animal labour, locally available biomass and internal nutrient cycling. The shift to fossil-fuel dependency in many industrialised countries occurred within a single generation. In France, for example, this transition occurred within roughly one generation, with fossil fuels increasing from around 10% of agricultural energy consumption in 1946 to around 90% by 1970 (Harchaoui and Chatzimpiros, 2019). This transformation increased production but also increased external energy demand. Across 58 countries between 1961 and 2014, global crop production tripled while embedded energy use per hectare increased by 137% (Pellegrini and Fernandez, 2018).

Agriculture came to account for approximately 2.6% of world primary energy use, while fertilisers increased from 27% to 45% of total agricultural energy inputs over the study period (Pellegrini and Fernandez, 2018). Ammonia synthesis alone now consumes roughly 2% of global energy and generates approximately 1.3% of energy-related CO₂ emissions (Erisman et al., 2008; IFA, 2025). Inorganic fertiliser use reached 190 million tonnes of nutrients in 2023, and synthetic nitrogen is estimated to support food production for about 3.9 billion people, including 1.2 billion of whom depend on imports (FAO, 2025b; Mingolla and Rosa, 2025; Naja et al., 2026). Energy-market disruption can therefore become fertiliser disruption, which can in turn become a food-production shock.

The system is made even more fragile by poor N-use efficiency and poorly buffered N flow. Global cropland nutrient surpluses were estimated at 85 Mt of nitrogen, 7 Mt of phosphorus and 11 Mt of potassium in 2023 (FAO, 2025a). Meanwhile, the long-term focus on fertiliser-responsive agronomy, while lifting yields, has not been matched by equivalent investment in soil organic matter (SOM) cycling, leaving farming systems more dependent on continuous fertiliser inputs and less able to buffer production when those inputs are disrupted (Qiao et al., 2022). The challenge, therefore, is not simply to decarbonise nitrogen supply, improve fertiliser efficiency or promote precision or regenerative agriculture in isolation, but to improve the efficiency, resilience and buffering capacity of nitrogen flows across the food system simultaneously (Field et al., 2026).

Nitrogen has become a strategic vulnerability at the intersection of food, energy and soil security. Here, the Food, Energy and Soil Security Nexus refer to the interdependent feedback system in which food production depends on fossil energy for inorganic fertiliser production, while soil functions as a biological buffer that can either mitigate or amplify energy and supply-chain shocks. Disruptions in energy inputs can compromise fertiliser availability and food security, while declining soil condition (soil health) can increase dependence on external inputs.

This paper argues for a progressive restructuring of how N enters, circulates and is retained in agricultural systems. The agenda is organised by leverage, ranging from actions that buffer the current system against shocks, to those that improve internal nitrogen flows and feedback mechanisms, and ultimately to those that transform the system's underlying goals. The paper first assesses the established body of research on N, examines why persistent inefficiencies have remained difficult to address despite this knowledge base, and then develops a research and policy agenda structured around different levels of leverage. Existing N strategies generally address individual parts of this problem, including fertiliser production and emissions, field-level nitrogen-use efficiency, nutrient recycling, breeding, biological fixation and soil management (Ladha et al., 2020; Mingolla and Rosa, 2025). Previous studies have also examined fertiliser supply-chain vulnerability, energy–fertiliser–food linkages and the uneven effects of N-price shocks across agricultural systems.

This perspective advances that literature in several ways. First, it treats N dependence as a system-level exposure through which energy, trade and geopolitical shocks are transmitted into farm profitability, soil nutrient depletion and food insecurity. Second, it links this external

exposure to the internal resilience of soil and production systems, particularly their capacity to retain, recycle and buffer N when fertiliser becomes scarce or expensive. Third, it introduces a leverage-based framework that distinguishes between interventions that buffer immediate shocks, improve N flows, alter economic and institutional feedbacks, restructure nutrient and energy infrastructure, and ultimately change the goals of agricultural systems.

This framework provides a basis for comparing technologies, management practices and policies according to the vulnerabilities they address, the mechanisms they change, their time horizons and their capacity to reduce structural dependence. It also clarifies the difference between measures that improve the performance of the existing fertiliser-dependent system and those that build resilience by changing the system itself. We first examine what N research has established and why persistent inefficiency has proven difficult to correct, before developing a research and policy agenda organised by leverage.

2. Nitrogen: what is established

The agronomic case for synthetic N fertiliser and its limitations is well established. First, synthetic N fertiliser remains indispensable to current food security. Abrupt reductions, without substitutes or improved targeting, would reduce yields and put food supplies at risk, particularly in cereal systems (Ladha et al., 2020; Köpke, 2026). Second, N management is inefficient across most crops and regions, only about 30–60% of applied fertiliser N is typically recovered by crops, with the remainder lost to the environment, immobilised in soil organic and microbial pools, or carried over to subsequent seasons (Angus and Grace, 2017; Liu et al., 2025; Mingolla and Rosa, 2025). Third, there is no single technological fix. Management decisions that determine N use efficiency (NUE) are shaped by economic opportunity, farmer practice and inherent soil and climatic conditions (Ladha et al., 2005; Pannell, 2017; Li et al., 2018). Fourth, biological N fixation (BNF) is a successful strategy for supplying N to large-scale legume crops (Herridge et al., 2008), including soybean production in Brazil (Telles et al., 2023). Fifth, management is context-specific. Site conditions strongly influence how nutrient, crop and soil management practices affect N recovery, and global syntheses suggest that optimal combinations could substantially increase recovery efficiency, potentially approaching 80% in some scenarios, but not through any universal prescription (Ladha et al., 2005; Udvardi et al., 2021; You et al., 2023).

The challenge, therefore, is not to promote particular management strategies or choose between reducing fossil-derived N and improving efficiency, but to identify combinations of interventions that sustain food production, reduce exposure to fossil-energy and fertiliser-market shocks, and protect the soil nutrient capital on which long-term productivity depends.

3. What remains unresolved

3.1. Nitrogen use efficiency (NUE): essential indicator, incomplete metric

NUE, usually expressed as a ratio between crop output and nitrogen input, is the field's dominant performance metric. But it can be misleading when interpreted in isolation. High NUE may indicate genuinely efficient fertiliser use, but it may also result from low N inputs, reliance on residual or legacy N, unmeasured non-synthetic sources such as biological N fixation and atmospheric deposition, or the mining of soil N reserves (Ladha et al., 2005; Kitchen et al., 2022; Tamagno et al., 2024). Conversely, low NUE may indicate N waste and environmental loss, but it can also occur where systems are rebuilding soil fertility or retaining N for future crop use (Grandy et al., 2022, 2024). NUE is therefore not a single process, but an aggregate outcome of N uptake, crop utilisation, soil N supply, residue management, hydrology, microbial cycling and legacy effects from previous seasons.

A more comprehensive assessment should therefore use a range of

complementary indicators, rather than a single NUE value. At minimum, this should include productivity indicators such as productivity and agronomic efficiency; N flow indicators such as N uptake efficiency, N recovery efficiency and farm-gate or field-scale N surplus; environmental indicators including nitrate leaching, ammonia volatilisation and N₂O emissions; and soil indicators including changes in soil organic N, total N and soil organic matter. Economic indicators such as profit per unit of applied N and yield stability should also be considered where data permit. Such a framework captures both the productivity of N use and the fate of N that does not enter harvested products, avoiding the risk that a high apparent NUE masks soil N depletion or environmental losses.

Thus, the goal should not be to maximise apparent NUE, but to increase durable N productivity while minimising environmental losses and protecting soil nitrogen capital.

3.2. Greener fertiliser with more efficient N use?

Low-carbon ammonia, electrified Haber–Bosch, modular production, plasma N and regional fertiliser manufacturing can reduce emissions and geopolitical exposure (Ye and Tsang, 2023; Huang et al., 2025) but they do not address N losses in the field. A green tonne of ammonia, if applied into a poorly functioning soil–crop system, can still be lost through nitrate leaching, ammonia volatilisation and nitrous oxide emissions. While low-carbon ammonia addresses the *Energy–Food* link by decarbonising synthesis, it does not solve the *Soil Security* link; a 'green' tonne of urea applied to a degraded soil still undergoes volatilisation, leaching, and denitrification.

Reducing exposure to fertiliser shocks requires lower demand for synthetic N and stronger biological and soil buffers. Microbial inoculants and other biological inputs offer a potential pathway to reduce dependence on synthetic N fertiliser by improving nutrient availability, plant growth and, in some cases, biological N supply. However, their effectiveness is context-dependent, with field performance varying across crops, soil, climates and resident microbial communities (Li et al., 2022; Shahwar et al., 2023). They are therefore best viewed as complements to legumes, BNF and improved soil management rather than direct replacements for synthetic fertiliser.

This requires renewed investment in legumes, BNF and other biological inputs, nutrient recycling, SOM management, regenerative practices, mixed farming systems and food-system change. Scientifically, this is also attractive because it reconnects N management with soil security, biological function, landscape design and resilience rather than treating fertiliser as a stand-alone input or solution (Smith and Chalk, 2020).

Institutional barriers also make these changes difficult. Current policies often support synthetic fertiliser more strongly than alternatives such as legumes, BNF and nutrient recycling. SOM management and practices that increase soil N stocks also receive limited financial support because their benefits are difficult to measure and reward. Carbon-credit schemes may provide some incentives, but these are often uncertain and primarily focused on carbon rather than soil N. Responsibilities are also divided across energy, agriculture and environmental agencies, making coordinated action difficult (Tamagno et al., 2024). It requires changes in farming systems, markets, labour, infrastructure and risk-sharing arrangements.

3.3. Enhanced-efficiency fertilisers: useful but context-dependent

Controlled-release fertilisers, urease inhibitors and nitrification inhibitors can reduce N losses under the right conditions (Wang et al., 2025; Bandara et al., 2026), but their effectiveness depends on soil type, rainfall, temperature, timing, crop demand, management skill and price. Reviews show that they can reduce volatilisation, leaching, and nitrous oxide emissions in targeted contexts, but performance is variable, and they do not remove the underlying dependence of food

production on manufactured N (Li et al., 2018). Their value is greatest when they are used as part of an integrated N management strategy rather than as a stand-alone technological fix.

3.4. Precision agriculture improves optimisation, not necessarily resilience

The International Society of Precision Agriculture (ISPA, 2024) defines precision agriculture (PA) as “a management strategy that gathers, processes and analyses temporal, spatial and individual plant and animal data and combines it with other information to support management decisions according to estimated variability for improved resource use efficiency, productivity, quality, profitability and sustainability of agricultural production.” In N management, PA supports the 4R concept (right source, right rate, right time and right place) by matching fertiliser application more closely to crop demand. Its main contribution is therefore to improve N allocation within existing fertiliser-dependent systems, particularly where N is over-applied or poorly synchronised with crop demand (Colaço et al., 2024; Ladha et al., 2020).

In large, mechanised farming systems, especially broadacre cereals, cotton and maize, precision N management can combine yield maps, soil management zones, canopy sensing, satellite or drone imagery, crop models, variable-rate spreaders and on-farm strip trials to move from blanket fertiliser rates toward season- and site-specific decisions (Colaço et al., 2024). Its success depends on data density, agronomic interpretation, machinery access and sufficient scale to justify adoption costs. However, conventional PA has largely optimised fertiliser use within existing production systems for productivity.

New Precision Agronomy (NPA) extends precision from input optimisation to extends precision from input optimisation to multi-objective system optimisation in pursuit of *3N Agriculture* (nutrient-balanced, nature-positive and net-zero production) within economic and biophysical constraints (Field et al., 2026; McBratney and Minasny, 2026). For N management, this means optimising combinations of fertiliser, soil N supply, legumes, nutrient recycling, genotype and management rather than fertiliser rate alone. The objective becomes to maintain productivity and nutritional quality while reducing N losses, strengthening soil N buffering and lowering exposure to fertiliser, energy and market shocks.

Precision tools designed for large commercial systems will not, however, address N inefficiency in smallholder contexts, where the constraints are fundamentally different: high costs, land fragmentation, weak advisory services and limited machinery (Mizik, 2022). Small farms under 2 ha account for about 84% of all farms globally, operate only around 12% of agricultural land, and produce roughly 35% of the world's food, while the largest 1% of farms operate more than 70% of farmland (Lowder et al., 2021). Their N problems range from under-application to late application, inability to split applications, degraded soil, poor soil organic matter, limited access to fertiliser at the right time, weak credit and input markets, and limited extension support (Tittonell and Giller, 2013).

Because smallholders face acute land fragmentation, severe credit constraints, and limited risk capacity, high-capital precision machinery is largely inaccessible. For smallholders, the more realistic pathway is therefore low-cost site-specific nutrient management, mobile or advisor-supported recommendations, farmer cooperatives, shared machinery services, soil testing, legume integration, organic nutrient recycling, and integrated soil fertility management (Chivenge et al., 2022).

By contrast, ecological redesign, including agroecological and regenerative approaches, uses practices such as legumes, cover crops, intercropping, organic amendments and integrated crop–livestock systems to rebuild SOM and nutrient cycling, reduce fertiliser dependence and lower emissions (O'Donoghue et al., 2022; Cui et al., 2024). It is, however, slower to implement, less amenable to standardisation, and may reduce yields in already high-performing systems.

3.5. Can cereals fix enough nitrogen?

Cereal crops do host N-fixing bacteria in their rhizospheres, and BNF can be relatively more active in flooded paddy rice systems, but unlike legumes, cereals do not form specialised symbioses that enable to fix atmospheric N at agronomically significant scales. Engineering legume-like N fixation in wheat, rice or maize would be transformative. Recent advances in synthetic symbiosis, N-fixation gene transfer and the discovery of the nitroplast justify sustained public investment in this field (Ladha et al., 2022; Coale et al., 2024; Laidig et al., 2024; Liu et al., 2024; Massana, 2024). However, the literature also cautions against treating cereal N fixation as an immediate solution. Nitrogenase is oxygen-sensitive and energetically expensive, making the integration of N fixation into major cereals without compromising growth, yield or grain quality remains technically challenging. Near- and medium-term gains are therefore more likely to come from breeding cereals with improved N uptake, utilisation, remobilisation, and grain protein formation, supported by advances in the genetic and molecular understanding of N conversion efficiency (Cormier et al., 2016; Teng et al., 2022; Zhao et al., 2023). Biological nitrification inhibition (BNI) offers one promising avenue. Wheat lines carrying a BNI trait from wild relatives suppressed ammonia-oxidising bacteria, slowed nitrification, retained N in the ammonium form, enhanced ammonium uptake, reduced nitrate and nitrous-oxide losses, and used less fertiliser without reducing crop growth or yield. The trait also improved N uptake under nitrate fertilisation and acted synergistically with synthetic nitrification inhibitors, suggesting a potentially scalable way to reduce soil nitrate accumulation and agricultural N losses (Subbarao et al., 2021).

4. Why have efficiency improvements not solved the problem?

The processes governing N uptake, assimilation, remobilisation, soil cycling, and loss pathways are comparatively well characterised. This persistence cannot be explained by scientific uncertainty alone. Nitrogen decisions are made under interacting economic, climatic and policy pressures, and the system often rewards N throughput, the amount of fertiliser applied and the crop growth it produces, more readily than N productivity, measured as grain, protein or profit per unit of N applied (Penuelas et al., 2023). Several structural factors could help explain why this has been so difficult to change.

4.1. Farmers manage production risk

Even where agronomic evidence supports better timing, placement and split applications, farmers often apply additional N as insurance against yield loss, particularly when grain prices are high, seasonal forecasts are uncertain, or late rainfall may create an opportunity for higher yield (Monjardino et al., 2015; Pannell, 2017). This behaviour is reinforced because crops respond visibly to N fertiliser through greener canopies and stronger vegetative growth, even when this does not translate into proportional increases in grain yield, protein or profit. Fertiliser subsidies further weaken incentives to reduce surplus N because private application costs are depressed while environmental costs (nitrate leaching, ammonia volatilisation, nitrous oxide emissions) remain externalised.

4.2. Crop breeding has also reinforced fertiliser dependence

Since the Green Revolution, breeding programmes have selected for high yield under adequate or abundant N, indirectly favouring fertiliser responsiveness over efficiency under N scarcity (Han et al., 2015). This was rational when food shortages were urgent and cheap fossil-derived N was a rapid route to higher production. Over time, however, it tightened the link between food security and energy security, weakened the role of soil as a biological N buffer, and removed the selection pressure that might otherwise have produced crops capable of

performing under N-limited or N-variable conditions.

It remains unclear whether high yield and high NUE are inherently in conflict. Crops that perform well under low N may face physiological limits that constrain their maximum yield under favourable conditions but part of the apparent trade-off may also reflect the history of breeding under abundant N. Landraces and wild relatives contain useful variation in root depth, N uptake, remobilisation and stress tolerance, and the molecular basis of these traits is becoming increasingly well understood (Hawkesford and Riche, 2020). Recent evidence supports this potential: long-term variety trials showed significant genetic gains in NUE in winter oilseed rape and pea, with yield maintained or increased despite stable or declining N inputs (Laidig et al., 2024).

Importantly, recent breeding research is moving beyond selection for NUE under a single, favourable N regime towards varieties adapted to low or variable N availability, using contrasting-N environments to select for stable yield, N uptake, N remobilisation and BNF (Laidig et al., 2024; Wang et al., 2026). Genomic prediction and multi-trait selection further enable these N-efficiency traits to be combined with high yield and stress adaptation rather than optimising NUE as a single trait (Ceron-Rojas and Crossa, 2022; Wang et al., 2026). This shift towards multi-trait, low-N-adapted varieties is important because improving N acquisition can affect phosphorus uptake, disease resistance, water-use efficiency and grain quality (Hawkesford and Riche, 2020). In dry environments such as Australia, for example, higher N supply can increase yield per unit of water while reducing yield per unit of applied N, creating a trade-off between water-use efficiency and NUE (Norton and Wachsmann, 2006).

4.3. Nitrogen biogeochemistry is more complex than the dominant metric implies

Fertiliser nitrogen does not remain in the form or place in which it is applied. Once it enters the soil, plants, microbes and mineral surfaces compete for it simultaneously (Daly et al., 2021). Microbes can immobilise substantial quantities of inorganic nitrogen within hours to days, routing it into microbial biomass and organic matter pools that remineralise over different timescales to support fertility in the current and subsequent seasons (Zhang et al., 2024). Recent work has therefore reframed soil nitrogen availability as an outcome of interacting plant, microbial and mineral processes, rather than a simple function of fertiliser input (Jilling et al., 2018; Daly et al., 2021; Grandy et al., 2022, 2024). SOM contains far more nitrogen than is added annually as fertiliser, and organic nitrogen pools function simultaneously as both a sink and a source of crop-available nitrogen (Grandy et al., 2024).

Fertiliser and cropping systems therefore need to be designed around these soil processes. The aim should be to retain N within the plant–soil system when crop demand is low, release it as demand increases, and minimise the periods when large dissolved N pools are vulnerable to leaching or gaseous loss (Grandy et al., 2024). However, our ability to measure and predict these dynamics across contrasting soil, climates, crops and management systems remains limited.

4.4. The research and policy space remains fragmented

Plant breeders, soil scientists, microbiologists, engineers, economists, modellers and policy researchers often treat NUE as separate problems. Repeated identification of the same barriers suggests that progress requires institutional as much as scientific change, connecting agronomy, economics, breeding, soil biogeochemistry and policy into a coherent framework in which improved N efficiency is economically rewarding under volatile input conditions.

5. A research strategy organised by leverage

Despite decades of research and policy effort, inefficient nitrogen use remains widespread, suggesting that the problem cannot be solved by

technical improvements alone. Global cropland nitrogen surplus reached 85 Mt in 2023, equivalent to 54 kg N per hectare, while global nitrogen fertiliser use per hectare rose from 54 kg to 68 kg, a 26% increase, between 2002 and 2023 (FAO, 2025a). This provides a quantitative indication of the scale of the challenge: the objective is not only to improve NUE within existing production systems, but to reduce absolute N losses and dependence on fossil-derived inputs while maintaining food and nutritional security. The task is not simply to use fertiliser more efficiently within existing production systems, but also to reduce the exposure of food production to fossil-energy shocks and strengthen the soil processes that retain, recycle and buffer nitrogen. A useful way to organise this agenda is by the depth of change involved: from measures that protect the current system during supply disruptions, through actions that improve nitrogen flows and decision feedbacks, to more fundamental changes in system structure and goals (Table 1).

The feasibility and benefits of these interventions will vary across farming systems. Smallholders may face particular constraints related to land fragmentation, limited credit, labour, input access and market participation, making affordability and implementation feasibility important alongside technical effectiveness.

5.1. Level 1 - buffer the existing system against shocks

At the first level of leverage, research can help buffer the current system against acute disruptions. The scale of this exposure is well documented: anhydrous ammonia prices rose more than fourfold, from US\$290 to US\$1350–1375 per tonne, between June 2020 and January 2022, driven by a sharp increase in natural gas prices (Wongpiyabovorn et al., 2022). More recently, disruption to the Strait of Hormuz

Table 1

A leverage-based research and policy agenda for nitrogen in the energy–food security nexus.^a

Leverage level	Key research and policy actions	What it achieves	Key limitation
1 - Buffer the existing system	Map exposure; strengthen early-warning systems; optimise N allocation under scarcity	Reduces avoidable harm during crises; buys time for deeper interventions	Does not alter fossil-N dependence
2 - Improve flows within the existing system	Refine rate, timing, placement and product choice; build SOM; use sensing and substitution	Reduces losses, costs and emissions within current systems	Bounded by continued reliance on synthetic fertiliser
3 - Reframe the feedback loops	Long-term soil N observatories; comprehensive N accounting (NUE + surplus + SOM + losses); causal modelling	Creates information systems that make inefficiency visible and correctable	Requires investment in monitoring infrastructure and data integration, financial incentives for building SOM
4 - Change system structure	Scale up BNF, legumes, cover crops, circular nutrients; decentralise fertiliser production using renewable energy	Reduces structural dependence on fossil N; diversifies supply and closes nutrient loops	Slower to implement; requires market, policy and infrastructure change
5 - Redefine system goals	Breed crops under low/variable N; engineer N fixation; redesign agroecosystems; extend the N agenda to diets, livestock and food waste	Reorients the entire food system toward resilience and N productivity rather than yield throughput	Longest time horizon; requires coordinated public investment and institutional change

^a Each level builds on lower levels while addressing limitations they cannot resolve. The goal is not to choose among levels but to pursue all five in parallel, with investment weighted toward the higher-leverage interventions that the current system systematically under-produces.

constrained fertiliser exports from the Middle East, which accounted for almost one-quarter of global urea exports in 2024. Urea prices reached US\$725 per tonne in March 2026, nearly 55% above February and the highest level since April 2022 (World Bank, 2026). This vulnerability points to the value of mapping dependence on diesel, synthetic N, and imported fertiliser, particularly where disruptions could coincide with critical planting or fertiliser application periods. Such mapping would identify which crops, regions, supply chains and farmer groups are most exposed when fuel or fertiliser markets are disrupted. Alongside this, early-warning capacity should be strengthened. Integrating natural gas prices, fertiliser trade flows, import dependence, crop calendars, planting windows and local affordability data into monitoring systems would allow input shortfalls to be anticipated before they translate into planting decisions and yield losses.

Under scarcity, N management also becomes an economic allocation problem rather than a purely agronomic optimisation problem. Fertiliser availability, price volatility and climatic uncertainty need to be considered explicit constraints in agronomic decision-making (McBratney and Minasny, 2026). Farmers do not select N rates to maximise NUE; they balance fertiliser and grain prices, rainfall risk, yield response curves and cash-flow constraints (Monjardino et al., 2015; Pannell, 2017). These constraints are particularly important for smallholders, for whom high input prices and limited access to credit can prevent investment in both fertiliser and soil improvement (Tamim et al., 2025). Research strategies should therefore assess N interventions against both agronomic returns and the financial and operational conditions that determine adoption.

The priority is to determine where the next unit of N delivers the greatest marginal return for food security, farm income or nutrition, and where application rates can be reduced with acceptable risk. Where reduced inputs constrain planting, cover cropping offers a productive alternative to fallow, reducing nitrate leaching by 69% (Nouri et al., 2022), reducing erosion by 90% (Du et al., 2022), and contributing to SOM accumulation by 15.5% (Jian et al., 2020). In broader perspective, a global analysis revealed that enhancing soil health, through multiple management practices, could increase crop yields by 7.8 Mt while increase NUE and consequently reducing N surplus by 8.1 Mt worldwide by 2050 (Xu et al., 2025). These measures do not remove the problem, but they can reduce immediate losses, protect vulnerable farmers and prevent a short-term input shock from causing longer-term declines in soil fertility and productive capacity.

5.2. Level 2 - improve flows within the existing system

At this level, the aim is to make fertiliser-dependent systems work more efficiently. This includes improving fertiliser rate, timing, placement, and product choice, while accounting for N sources, residual fertiliser effects, the soil organic nitrogen balance, and N surplus (Ladha et al., 2020). The goal is to synchronise N supply with crop demand, maintain yield, reduce avoidable losses and protect soil N reserves.

SOM should be treated as a core component of nitrogen management because it stores soil N and regulates its release through mineralisation and immobilisation. SOM can increase the capacity of soil to retain and recycle N, potentially buffering crop N supply during temporary fertiliser disruptions, although the magnitude and timing of this buffering depend on mineralisation, immobilisation, climate and crop demand. Practices such as cover crops, reduced tillage, diverse rotations, legumes, manure, compost and digestate should be evaluated under farm conditions and price scenarios. A global meta-analysis found that no-tillage increased surface-soil N by 21%, while optimal nutrient, crop and soil management could increase cropland N recovery efficiency from 48 to 78% (Mondal and Chakraborty, 2022; You et al., 2023). Soil N stocks and SOM should therefore be considered indicators of internal N buffering alongside conventional NUE metrics. These measures can improve the functioning of the existing nitrogen system, but they do not change the incentives that favour high fertiliser use.

Rapid soil and crop sensing can help identify where nitrogen is limiting, where rates can be safely reduced and where losses are likely. For smallholders, however, approaches requiring specialised machinery, dense data or substantial upfront investment may be impractical, making low-cost and scalable technologies important research priorities.

5.3. Level 3 - reframe the feedback loops

Level 3 focuses on why technically sound N management is still not adopted consistently. Nitrogen flows are difficult to observe, poorly valued and only weakly connected to economic rewards. Farmers often make fertiliser decisions without reliable information on soil N mineralisation, residual fertiliser, organic N reserves, leaching, gaseous losses or the profit response to different application rates. As a result, the system rewards fertiliser use and visible crop growth more directly than N productivity, soil N retention or avoided environmental losses. Research should therefore develop decision-support systems that quantify the full nitrogen balance, including surplus, soil nitrogen depletion, leaching, and gaseous losses, and connect these to farm-level profitability metrics. NUE should be reported alongside nitrogen surplus, soil nitrogen balance, SOM trajectory, nitrate losses, ammonia volatilisation, nitrous oxide emissions, yield stability and profit. Long-term soil N observatories, causal N-response models, and decision-support tools should link biophysical N flows to fertiliser prices, grain prices, rainfall risk, and farm profitability.

The objective is to shift feedback so that farmers, advisers, markets, and policymakers reward nitrogen productivity and soil nutrient retention. For resource-constrained farmers, such feedbacks must be supported by accessible extension, credit and risk-sharing mechanisms, because information or incentives alone cannot overcome binding liquidity constraints. Financial investment and incentives should recognise the value of building soil organic matter, not only for climate mitigation but also for lower agronomic risk and better margin protection in shock years.

National policies show different ways of changing nitrogen feedbacks. New Zealand provides a clear regulatory example, with synthetic N application on grazed land capped at $190 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ since 2021 (Ministry for Environment New Zealand, 2021). Denmark provides evidence of longer-term outcomes, with stream nitrate loads declining by 30–52% over 29 years across five agricultural catchments following successive regulations (Petersen et al., 2021). Ireland and the Netherlands have similarly strengthened nutrient planning, application controls, monitoring and measures to reduce losses (European Commission, 2022; Department of Housing Local Government and Heritage, 2025).

5.4. Level 4 - change system structure

Greater leverage comes from changing how N and energy enter, circulate and are retained within agricultural systems. This includes greater use of BNF, legume integration, circular nutrient systems, decentralised fertiliser production and renewable farm energy. Each of them represents a structural departure from the current linear, fossil-N pathway.

SOM should be treated as part of the system's nitrogen infrastructure, alongside biological fixation and nutrient recycling. Grain and forage legumes, cover crops, green manures, and intercrops can introduce biologically fixed N into cereal systems, enhance N cycling in soil-plant system reducing N losses, reduce fertiliser demand, and improve soil N supply for subsequent crops. A systematic review estimated mean N fixation of $87 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ across legume crops under organic management, including $131 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ for fodder legumes and $76 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ for grain pulses (Barbieri et al., 2023). Under Brazilian conditions, Carvalho et al. (2026) reported that legume cover crops can cycle an average of $121 \text{ kg N ha}^{-1} \text{ yr}^{-1}$, with species of the *Cajanus*, *Canavalia*, *Crotalaria* and *Mucuna* genera cycling 155, 142, 133 and

$120 \text{ kg N ha}^{-1} \text{ yr}^{-1}$, respectively. This highlights the potential of biological N inputs, but also the need to assess them at the whole-system level rather than treating fixation as a direct substitute for fertiliser.

Circular nutrient systems are another complementary pathway. Manure, compost, digestate, recovered ammonium, struvite, wastewater nutrients, residues and food waste can help reduce dependence on synthetic fertilisers, but only if the N is retained, recycled and released in step with crop demand. A global assessment modelled decentralised ammonia production as potentially cost-competitive for up to 96% of global ammonia demand by 2030 when transport costs and supply-chain disruption risks are included (Tonelli et al., 2024).

Changes in energy and fertiliser infrastructure are also needed. Green ammonia, renewable hydrogen, plasma-based nitrate production, modular fertiliser systems, on-farm solar, batteries, electric pumps, microgrids and local storage can collectively reduce reliance on natural gas, imported urea and diesel. Plasma-based N fixation is one example, in which electricity activates N from air to produce nitrate-rich liquid fertiliser or plasma-activated water (Huang et al., 2025). These technologies are being developed for field deployment and point toward a future where fertiliser is produced closer to where it is used. However, the objective should not be to create a green version of the same N-intensive system, but to move towards diversified systems that retain, recycle, and regenerate N. Such structural change will be gradual and institutionally demanding, requiring coordinated changes in markets, infrastructure, policy and risk-sharing arrangements. For smallholders, collective approaches such as cooperatives, shared machinery, local nutrient recovery and decentralised input supply may help overcome constraints arising from small farm size and fragmented landholdings.

5.5. Level 5 - redefine the goals of the system

The highest level of leverage involves changing what agricultural systems are designed to achieve. Breeding programmes and agronomic research have traditionally prioritised maximum yield under adequate or abundant N supply. Future systems should instead be judged by their ability to maintain yield, protein, other quality attributes and profitability while using less fossil-derived N, reducing nutrient imbalances and emissions, and strengthening the biological and soil processes that retain and recycle nitrogen (Field et al., 2026). This is the objective of New Precision Agronomy (NPA) to move beyond optimisation of a single outcome towards nutrient-balanced, nature-positive and net-zero production within economic and biophysical constraints (McBratney and Minasny, 2026). The challenge is to optimise combinations of yield, protein and nutritional quality, profitability, soil function, N loss, greenhouse-gas emissions and dependence on external N.

This broader objective changes how breeding, agronomy and soil management are evaluated. Crop improvement programmes should routinely screen germplasm under low, moderate and variable N conditions and across the environments in which farmers operate, particularly where access to fertiliser is constrained. Priority traits include root architecture, N uptake, N remobilisation, grain filling under stress, microbial interactions, biological nitrification inhibition and yield stability under combined water and N limitation. In wheat, for example, introducing biological nitrification inhibition traits from wild relatives could help suppress nitrifying microbes in the rhizosphere, reduce nitrate leaching and nitrous oxide emissions (Subbarao et al., 2021).

Reducing N inputs, however, cannot be evaluated against yield alone. Grain protein concentration and grain protein yield must also be considered because N is required for both grain production and storage protein accumulation. A global meta-analysis found that splitting N into three or four applications increased wheat yield by 7% and grain protein concentration by 5%, while reducing the negative relationship between yield and grain protein concentration (Hu et al., 2021). Rather than assuming that a fixed reduction in fertiliser can universally maintain both yield and grain quality, the feasibility of reducing external N while maintaining quality will depend on crop, environment, soil N supply and

starting N rate. Strategies that improve N recovery and late-season N supply may therefore offer greater potential than uniform reductions in N rate (Zörb et al., 2018; Hu et al., 2021). Research should therefore evaluate N-saving technologies against a combined outcome of yield, protein yield, grain quality, profitability and N loss, rather than NUE or yield alone.

Redefining system goals also requires redesigning agroecosystems in which soil and biological processes contribute more strongly to N supply and retention. Conservation agriculture, based on reduced or no tillage, permanent soil cover and diversified cropping systems, provides one pathway. Its benefits, however, depend on how practices are combined and managed. Reduced tillage alone may have limited effects on N recovery, whereas integrating residue retention, cover crops, and crop rotation can provide greater benefits (You et al., 2023). Conservation practices can also improve yield and NUE under low-N conditions, but responses depend on N inputs, climate and residue management, and early N immobilisation may constrain performance during transition (Adil et al., 2024). Diversified rotations, particularly those including legumes, can enhance BNF and improve N supply to subsequent crops (Zhao et al., 2022; Cherubin et al., 2025).

Finally, redefining system goals extends beyond the paddock. Live-stock feed demand, food waste, crop choice, biofuels, export systems and diets all shape total reactive N demand. At this level, the central question is what kind of food system can maintain productive and nutritious output while reducing dependence on fossil energy, N losses and depletion of soil nutrient capital. This changes the objective against which N systems are designed, measured and governed—from maximising production under abundant external N to sustaining food production with greater internal cycling, lower environmental cost and greater resilience.

6. Summary

Nitrogen fertiliser sits at the intersection of food security, energy security, and soil security. When fertiliser prices rise or supplies are disrupted, farmers may reduce application, lowering yields and residue returns to soil. Repeated or prolonged shocks can therefore weaken soil organic matter, reduce biological N supply and make production increasingly dependent on external fertiliser.

Although the main processes governing N uptake, cycling and loss are well understood, this knowledge has not yet been translated into production systems that simultaneously deliver productive and nutritious food, farm profitability, low emissions, healthy soil and resilience to disruption. The challenge is therefore broader than improving nitrogen-use efficiency or maintaining yield. It also stems from breeding priorities, bio inputs investments, infrastructure, markets and incentives that have evolved around assumptions of inexpensive energy and reliable fertiliser supply, often rewarding input-responsive production rather than the efficient use and regeneration of nutrient resources.

A leverage-based framework helps distinguish immediate responses from deeper change. Early warning, targeted allocation and improved N use efficiency can reduce damage during a crisis, but they leave the underlying dependence largely intact. Greater resilience requires changing the feedbacks that shape farmer decisions, redesigning nutrient and energy infrastructure, and breeding crops that perform under low and variable N supply. New precision agronomy can help operationalise this transition by extending precision from optimising fertiliser application to optimising combinations of genetics, soil N supply, biological fixation, nutrient recycling and management against productivity, environmental, economic and resilience objectives. Farmer co-design remains essential because labour, timing, capital and production risk ultimately determine whether these options are adopted.

Achieving enduring resilience requires rebalancing the food, energy and soil security nexus by reducing dependence on fossil-energy-derived inputs and rebuilding soil organic capital to buffer food production

against energy and supply shocks. Soil organic matter is a central part of this transition because it retains and recycles N and can buffer crops when fertiliser inputs decline. However, soil organic matter takes years or decades to build. Investment must therefore occur before disruption. Reframing N in this way shifts the agenda from isolated technical fixes towards coordinated changes in agronomy, breeding, soil biogeochemistry, infrastructure, markets and policy. Agricultural systems cannot eliminate exposure to fertiliser and energy shocks, but they can reduce that exposure by investing before disruption in soil nutrient capital, more adaptable crops, diversified nutrient sources and institutions that reward N productivity.

CRediT authorship contribution statement

Budiman Minasny: Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Damien J. Field:** Writing – review & editing. **Maurício Roberto Cherubin:** Writing – review & editing. **A. Stuart Grandy:** Writing – review & editing. **Jagdish K. Ladha:** Writing – review & editing. **Alex B. McBratney:** Writing – review & editing. **Wartini Ng:** Writing – review & editing. **Raj Setia:** Writing – review & editing. **Peng Zhang:** Writing – review & editing.

Declaration of generative AI use

ChatGPT 5.5 was employed to assist with improving the clarity, grammar, and overall quality of the English language.

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