Spatially differentiated nitrogen supply is key in a global food–fertilizer price crisis

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A regional geopolitical conflict and sudden massive supply disruptions have revealed vulnerabilities in our global fuel–fertilizer–food nexus. As nitrogen (N) fertilizer price spikes threaten food security, differentiated responses are required to maintain staple cereal yields across over- and underfertilized agricultural systems. Through integrated management of organic and inorganic N sources in high- to low-input cereal production systems, we estimate potential total N-fertilizer savings of 11% in India, 49% in Ethiopia and 44% in Malawi. Shifting to more cost-effective, high-N fertilizer (such as urea), combined with compost and integration of legumes, can optimize N in N-deficient systems. Better targeted and more efficient N-fertilizer use will benefit systems with surplus N. Geospatially differentiated fertilization strategies should prioritize high-N fertilizer supply to low-yield, N-deficient locations and balanced fertilization of N, P, K and micronutrients in high-yield systems. Nationally, governments can invest in extension and realign subsidies to enable and incentivize improved N management at the farm level.

As a primary yield determinant, nitrogen (N) is needed in massive quantities for production of cereals and other crops. Application of large quantities of synthetic N fertilizer supports high yields while simultaneously posing an environmental threat through direct and indirect generation of greenhouse gas emissions (GHGs), spread of invasive species and degradation of water quality[1]. Fertilizer use is essential for high yields but has been a major driver pushing the global N cycle beyond planetary boundaries[2], although effects are highly spatially variable[3]. Overall, the use of N fertilizer on global cropland is severely skewed, leading to overfertilization in some regions and underfertilization in others[4]. N-fertilizer usage in some regions (for example,

sub-Saharan Africa) is widely regarded as suboptimal[5], with low average application rates attributed in part to low and spatially variable economic returns to farm-level fertilizer investments[6].

In high-input agricultural systems, typically in developed and rapidly developing countries, more than half of applied N is lost to the environment, contaminating aquatic, terrestrial and atmospheric systems[7]. In low-input agricultural systems, typically in low-income developing countries, applied N is often insufficient for plant needs and combined management of organic and inorganic nutrient sources is lacking, resulting in stunted plant growth, limited biomass production and carbon (C) sequestration, and poor soil health[7].

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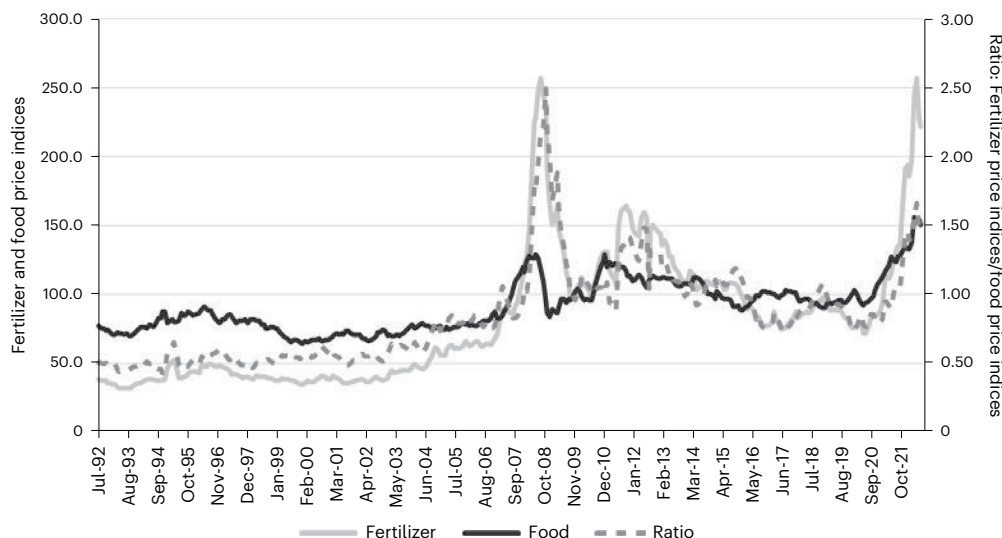
Fig. 1 | Trends in fertilizer and food price indices from July 1992 to June 2022. An index value of 100 corresponds to the 2014–2016 average prices (left axis). For the ratio of fertilizer and food price indices, higher values correspond to lower fertilizer availability (right axis). The monthly fertilizer price index is derived from the international prices of urea and DAP from IndexMundi[70,71]; the food price index is from FAO[72].

Nitrogen use efficiency (NUE) in crop production is the proportion of applied N in harvested products, which typically ranges from 20 to 55%[8] and can be as high as 62% when N content in grain and aboveground straw is considered[9]. Increased NUE can reduce nitrate-N leaching and gaseous N loss from fertilized maize, wheat and rice fields[10]. There is less scope for gains in NUE in N-deficient systems, where a bigger concern is mining of soil N. This occurs when crop uptake exceeds the amount of N fertilizer applied[11]. In such systems, increased access to N is paramount. Organic matter addition and introduction of crops that biologically fix N are viable strategies for increasing crop yields, especially where N fertilizer application rates are low[12].

N-fertilizer production consumes fossil fuel energy, directly contributing to (GHG) emissions[13]. The price of energy-intensive synthetic N fertilizers has fluctuated greatly over time, closely tracking volatile international fossil fuel supplies and prices[14]. This has direct consequences for agricultural production as price spikes in N fertilizer are an important predictor of food shortages, price surges and hunger, as seen in 2008 and 2022 (Fig. 1). This is particularly the case for staple food crops such as wheat, for which a 15% increase in prices would lead to an estimated 8% reduction in wheat consumption, with severe consequences for protein and calorie intake[15].

Sudden and massive fuel and fertilizer supply disruptions arising from the Russia–Ukraine war have led to skyrocketing fertilizer prices[16,17]. This poses a comprehensive threat to agricultural productivity, particularly for farming systems burdened by low NUE or N deficiency. Rising fertilizer and food prices translate into reduced food access and diminished food security for vulnerable populations[18]. In the context of a sudden fertilizer shortage and an emergent food security crisis, durable solutions are needed quickly and at large scale.

To support discussion of policy responses in the context of N-fertilizer crises, this paper estimates N status for three major staple cereals in three developing countries that face pressing food security challenges. For India, Ethiopia and Malawi, we calculate N balance (surplus/deficit), NUE and N harvest gaps, as well as the near-term effect of fertilizer price spikes on N application rates and yield. Using the best available data, this study then estimates N-fertilizer savings that could be achieved in these three countries, without compromising crop yield, through implementation of specific N management strategies. The focus here is on interventions that could be implemented immediately in response to a N-fertilizer crisis. By focusing on globally

important cereal crops and selecting countries that encompass a range of biophysical and socio-economic production contexts, our Analysis provides insights that are relevant to crisis response in different regions, as well as for coordinated efforts to address global fertilizer and food supply crises in the future.

Results

Within global smallholder-dominated cereal systems, India, Ethiopia and Malawi represent different fertilizer management contexts ranging from high- to low-input production systems. This study assesses the current status of N management and N harvest gaps as well as the near-term impact of rising fertilizer prices on N application and yield. Further, it estimates potential N-fertilizer savings from regionally targeted interventions in maize, wheat and rice systems. India is a rapidly developing country with intensive cropping systems where high N use and low NUE leads to high N surplus in many areas[7,19]. In Ethiopia, maize and wheat cropping intensity varies across regions and ecological zones, with a negative N balance in many areas[20]. Maize and rice production in Malawi is representative of the highly N-deficient cereal systems that are relied upon by over 100 million people in sub-Saharan Africa[21].

Nitrogen status by country and crop

Our estimates of N surplus or deficit (that is, the difference between N input and N removal) and NUE (that is, the ratio of N output to N input) indicate that cereal production systems in the three countries encompass extremes from N surplus to N deficiency, and from low NUE to high NUE (that is, N mining) (Figs. 2–4 and Supplementary Information 3). High N harvest gaps (that is, the difference between potential and actual N harvest in grain) are observed under both N surplus and N deficiency, and across low and medium NUE and N mining conditions (Figs. 2–4).

Maize production (Fig. 2) exhibits high N surplus and low NUE across the Indo-Gangetic Plains (IGP) and Northeastern India, and modest N deficiency in rainfed areas of central and southern India. Maize area in India is evenly split between N surplus and N deficit and, with ~60% exhibiting low NUE and >75% exhibiting high N harvest gap (Supplementary Information 1), there is huge scope for improved N management. Severe N deficiency in maize production is ubiquitous in Malawi (100%) and widespread in Ethiopia (over 90%) (Fig. 2 and Supplementary Information 1). N mining and high N harvest gaps are
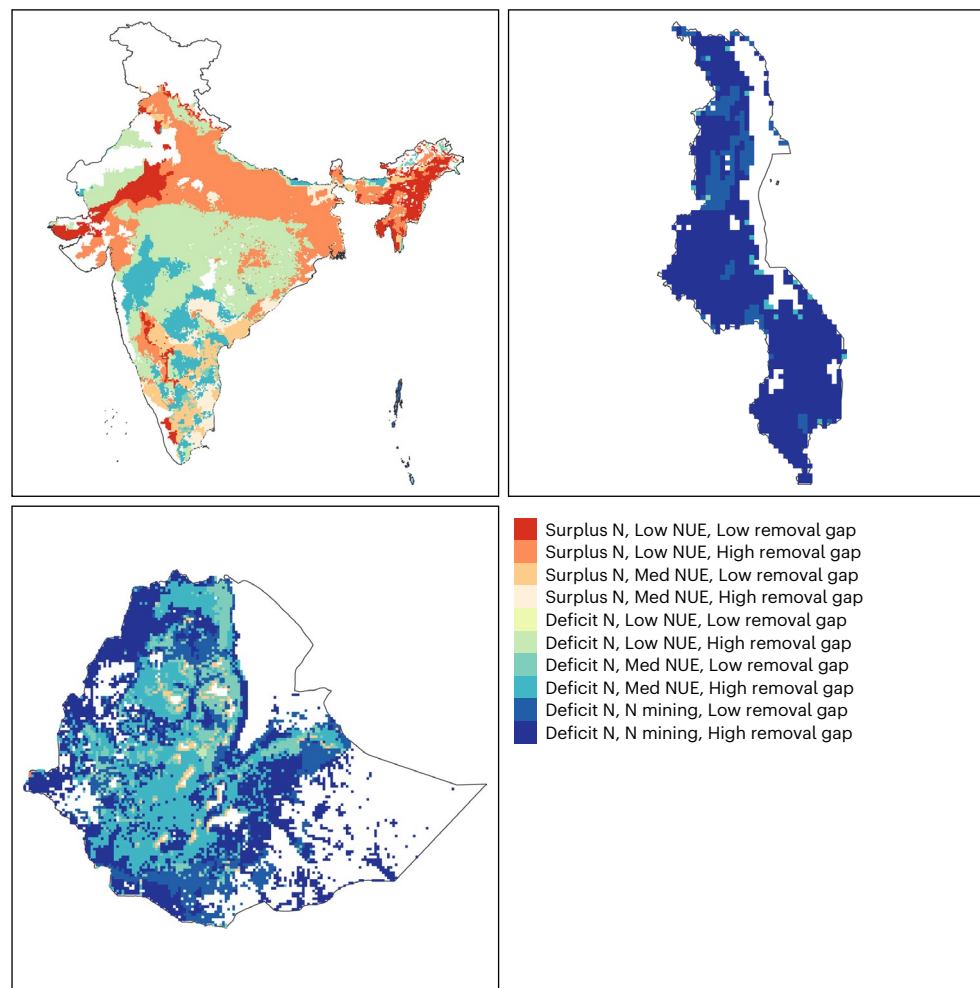
Fig. 2 | Classification of maize areas based on N surplus/deficit, nitrogen use efficiency and N removal gap. Top Left: India. Bottom left: Ethiopia. Top right: Malawi. Classification details are provided in Methods (Spatial distribution of nitrogen balance across countries).

prevalent across maize areas in Malawi. Some maize areas in Ethiopia's central region exhibit moderate NUE paired with a high N harvest gap.

Surplus N application and low NUE are prevalent in wheat production (Fig. 3) across India, except for the N-deficient western semi-arid region (for example, the Rajasthan), which has medium NUE and low N harvest gap. Over 90% of India's wheat area has surplus N application and low N harvest gap (Supplementary Information 1), indicating that reducing N input through improved management is a priority. Nitrogen status varies across Ethiopia's tropical wheat systems, with N mining and high N harvest gaps in warm regions, and medium to high NUE and sometimes surplus N in cool regions. Wheat is a minor crop and is generally N deficient in Malawi, except for wheat production by the commercial farming sector, which has moderate to high N inputs.

In Indian rice production areas, N surpluses predominate (over 95%) (Fig. 4 and Supplementary Information 1), and low NUE (nearly 80%) and high N harvest gaps (about half of rice area) are prevalent, indicating the need to improve NUE and to increase rice yields. In Malawi, N deficiency is much more typical, including prevalent N mining. By analysing 50 yr trends in NUE of world cropping systems, ref. 22 reported that NUE in India is decreasing over time, reaching down to ~30% in 2010.

Impacts of the current crisis

In the current fertilizer crisis, we have seen prices doubling over very short time periods. For example, the price of urea (high-N fertilizer)

increased from US$ 483 ton[−1] in 2021 to US$850 ton[−1] in the first quarter of 2022 and is projected to remain at elevated levels in 2023[23]. Application rates of urea and other N fertilizers have a strong negative response to rising prices[24] and there is a large body of evidence showing that reduced N fertilizer application negatively affects crop yield, particularly for cereal production[25].

To anticipate the impact of the fertilizer price spikes in India, Ethiopia and Malawi, we estimated near-term changes in application rates on the basis of price elasticity estimates for urea and resulting effects on yield (Supplementary Information 2). In India, total maize and wheat production is expected to drop by 2.67 million tons (Mt) (9.3% of total production in 2020) and 5.8 Mt (5.4% of total production in 2019), respectively, in response to a 1.2 Mt decrease in total urea application (212 thousand tons for maize and 987 thousand tons for wheat). In Ethiopia, a projected decrease of 8.6 thousand tons in total urea application (4.1 thousand tons for maize and 3.5 thousand tons for wheat) would reduce maize production by 92 thousand tons (0.9% of 2020 levels) and wheat production by 83 thousand tons (1.5% of 2020 levels). Malawian maize systems are projected to apply 6 thousand tons less urea fertilizer and produce 166 thousand fewer tons (4.5% of 2020 production). Malawi rice N use is modest and relative to maize, is not expected to be negatively impacted by N fertilizer price increases. Potential production declines of high magnitude are thus predicted for maize everywhere and for wheat in India and Ethiopia. The rapidity of these production losses underscores the vulnerability of cereal
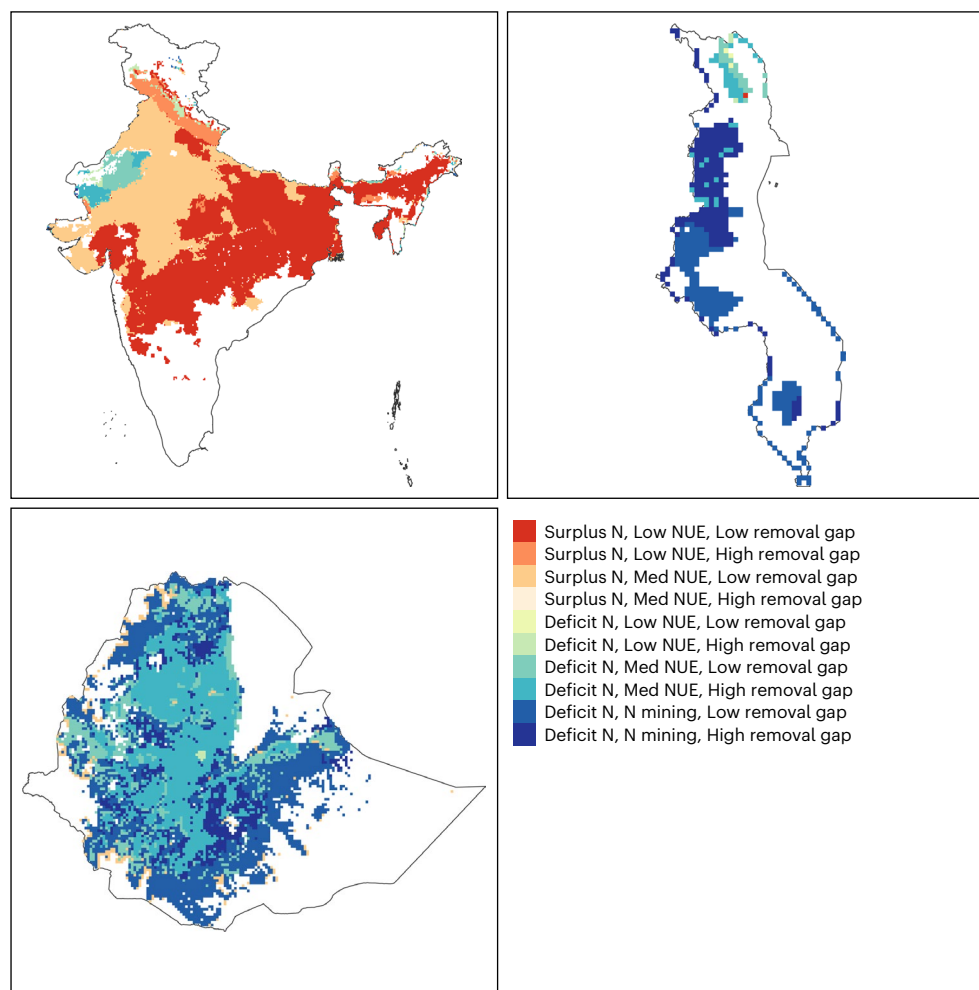
Fig. 3 | Classification of wheat areas based on N surplus/deficit, nitrogen use efficiency and N removal gap. Top Left: India. Bottom left: Ethiopia. Top right: Malawi. Classification details are provided in Methods (Spatial distribution of nitrogen balance across countries).

production systems to N inputs as well as the severe food security implications of the current fertilizer crisis. This is particularly concerning for countries that are heavily dependent on local production of staple cereals[26]. These estimates assume that crop area allocations remain at current levels. We recognize that changing input and output prices could induce shifts in cropping patterns, where land is allocated to N self-sufficient legumes which are less dependent on highly expensive fertilizer inputs. Furthermore, some governments may enact policies to attenuate the transmission of price spikes directly to farmers.

Near-term interventions for improved nitrogen management
To inform responses to the fertilizer crisis, evidence from the literature was used to estimate N-fertilizer savings from near-term interventions in major cereal systems in India, Ethiopia and Malawi. Integrated organic and inorganic N management was estimated by considering manure and legume N inputs along with N fertilizers (Fig. 5). To consider the potential for improved N availability from organic sources, N supply from manure and legume integration was assessed on the basis of analysis of the current state and future prospects through promotion of these technologies (Supplementary information 3). The effect of reallocating public subsidies to more cost-effective, high-N fertilizers was estimated by quantifying the extra N that could be made available through lower unit cost of N supply relative to currently subsidized low-N fertilizer types. Increased N-fertilizer use efficiency was estimated as the effect of fertilizer advisories prescribing

improved fertilizer management strategies. This study is based on evidence of achievable shifts in N management practice over a 1–2 yr time frame for a modest proportion of cropped area (10%). We did not assess interventions with longer time horizons or large investment requirements, such as precision agriculture, mechanization or deep placement of fertilizer.

Production systems in all three countries are projected to save on N fertilizer from adoption of integrated organic and inorganic N management, with especially large total savings possible in Indian rice production (Fig. 5a). The feasibility of this strategy is conditioned by the availability and accessibility of organic-N sources. In Africa, for example, current manure inputs are estimated to be ~10 kg N ha^{-1} and net biological N fixation by legumes is estimated to be in the range of 10–20 kg N ha^{-1} (ref. 11). Our analysis estimates short-term N savings from a 10% increase in area manured and cropped with legumes—a feasible increase over the short term based on data gathered through household surveys. Over the medium to long term, with research investments, this could be increased substantially. We have, however, assumed that short-term legume production/expansion will not be limited by soil phosphorus (P) supply or poor market infrastructure, which could be limiting factors for widespread adoption of legumes. If achieved, these organic inputs could reduce the need for a substantial proportion of current inorganic N-fertilizer use in Africa (that is, ~25% in Ethiopia and Malawi), but the scope is considerably less for N substitution through organic sources in India, given the high levels of N use there.
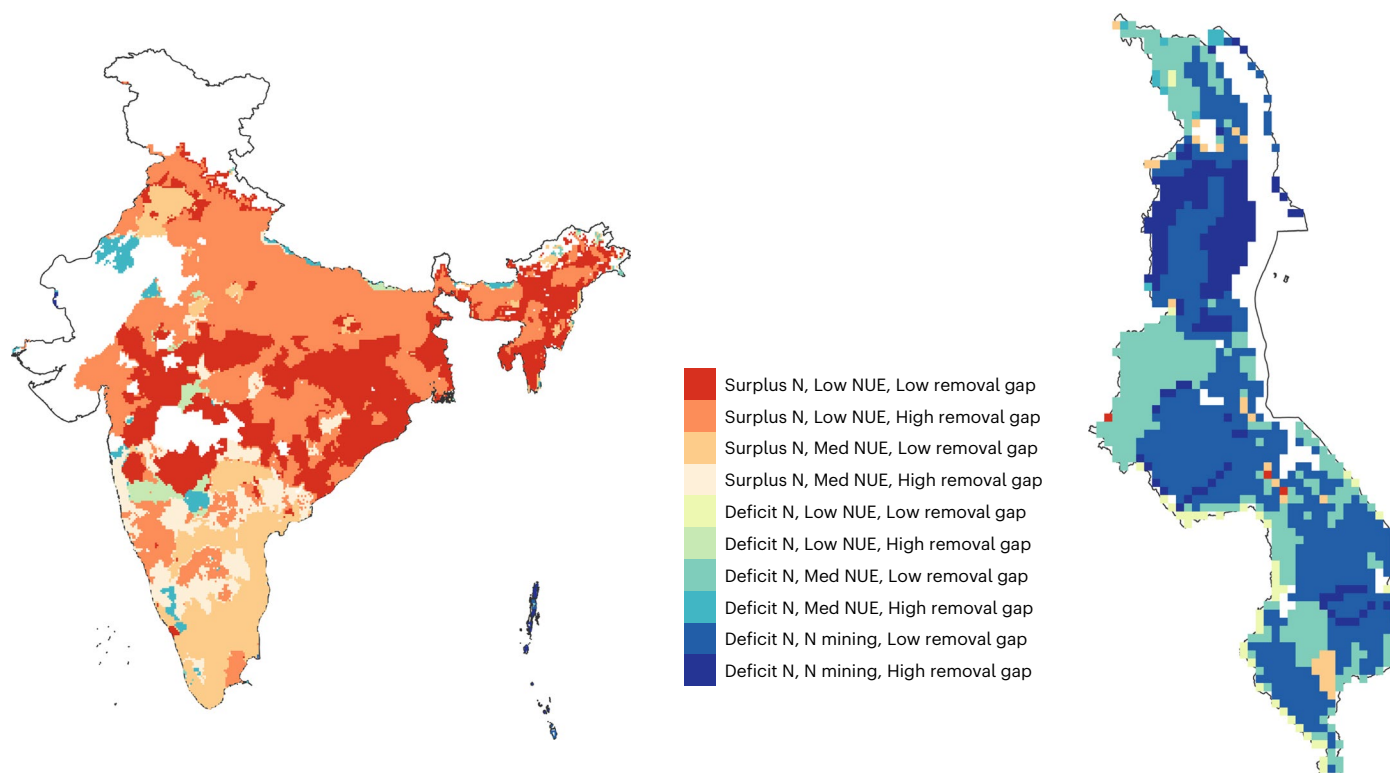
Fig. 4 | Classification of rice areas based on N surplus/deficit, nitrogen use efficiency and N removal gap. Left: India. Right: Malawi. Classification details are provided in Methods (Spatial distribution of nitrogen balance across countries).

Organic inputs are not only sources of additional N, but also affect NUE. Combined organic and synthetic N inputs improve NUE and lower the total N input required to achieve yields equivalent to those from high fertilizer-N alone[27,28]. An added advantage of organic inputs is their residual effects across multiple years[29].

Shifting to high-N fertilizer types such as urea (46% N) is projected to result in substantial N savings, especially in low-N cereal systems in Ethiopia and Malawi (Fig. 5b). High-N fertilizers generally supply 2- or 3-fold higher amounts of N per unit of fertilizer compared with compound multinutrient fertilizers such as diammonium phosphate (DAP, 18% N), enabling notable cost savings. This analysis is consistent with 25% of current N requirements being met by shifting from a low-N fertilizer, such as 18%-N DAP, to a high-N content fertilizer such as 46%-N urea, without incurring additional expense (that is, urea has a lower unit cost for N than alternative fertilizer blends). (See Discussion below regarding spatial targeting of blended fertilizers in cereal systems.)

Fertilizer advisories for improved N management appear to offer important N savings in wheat and rice production systems where N overfertilization is common, such as in the irrigated rice–rice and rice–wheat systems in India, which typically receive high doses of soluble inorganic N. However, fertilizer advisories are of modest N-saving value in cereal systems where N use is low to moderate.

Discussion
### Differentiate responses based on nitrogen status
With fertilizer price spikes threatening substantial near-term reductions in N application and yields of globally important cereal crops, we consider the evidence for tailoring N strategies by country and by cropping system. Within and across three focus countries, our analysis found important variation in the combination of N surplus/deficiency, NUE and N harvest gaps across maize, wheat and rice. Cereal systems in Ethiopia and Malawi suffer from severe N deficiency with high N harvest gap. The majority of rice and wheat fields in India (>90%) receive surplus N application, with most rice fields showing low NUE and high

N harvest gap, and most wheat fields showing low N harvest gap. About half of the maize fields in India shows N surplus with low NUE, while more than 75% of this area shows high N harvest gap.

The effects of N-fertilizer price spikes will materialize quite differently across diverse production systems and our findings suggest that singular interventions are unlikely to lead to improved N management at sufficient scale. This study identifies N status as a critical differentiator for intervention objectives and demonstrates the importance of differentiated approaches across over- and underfertilized agricultural systems. Our analysis shows that near-term interventions for improved N management in maize, wheat and rice production could provide N savings ranging from 7–12% in India and 45–55% in Ethiopia and Malawi. Since these three countries are indicative of the range of N status in African maize and wheat production, differentiated approaches will probably be needed in many cereal-producing countries to effectively moderate the adverse effects of N-fertilizer price spikes, especially given the complex political and socio-technological drivers of N management[3,21,30].

Prioritize nitrogen for low-yield cereal systems
Balanced nutrient fertilizers tailored to specific crop and soil requirements are commonly promoted to increase cereal yields as well as address micronutrient deficiencies and enhance disease tolerance. This intervention can deliver improved NUE and minimize N loss to the environment, particularly in N-surplus environments. Given high nutrient offtake, balanced fertilizer inputs are particularly important in high-yield intensive cereal systems (for example, irrigated wheat and rice–wheat double crops in India). While reliable high-quality supply of blended fertilizers with a full complement of phosphorus (P), potassium (K) and micronutrients is a worthy goal, this has not been achieved at scale in many low-yield cereal-growing regions due to challenges in production, distribution, access and correct usage. In addition, what has not always been appreciated is that, during a crisis, constraints on time, resources and logistics hamper the ability of individual producers
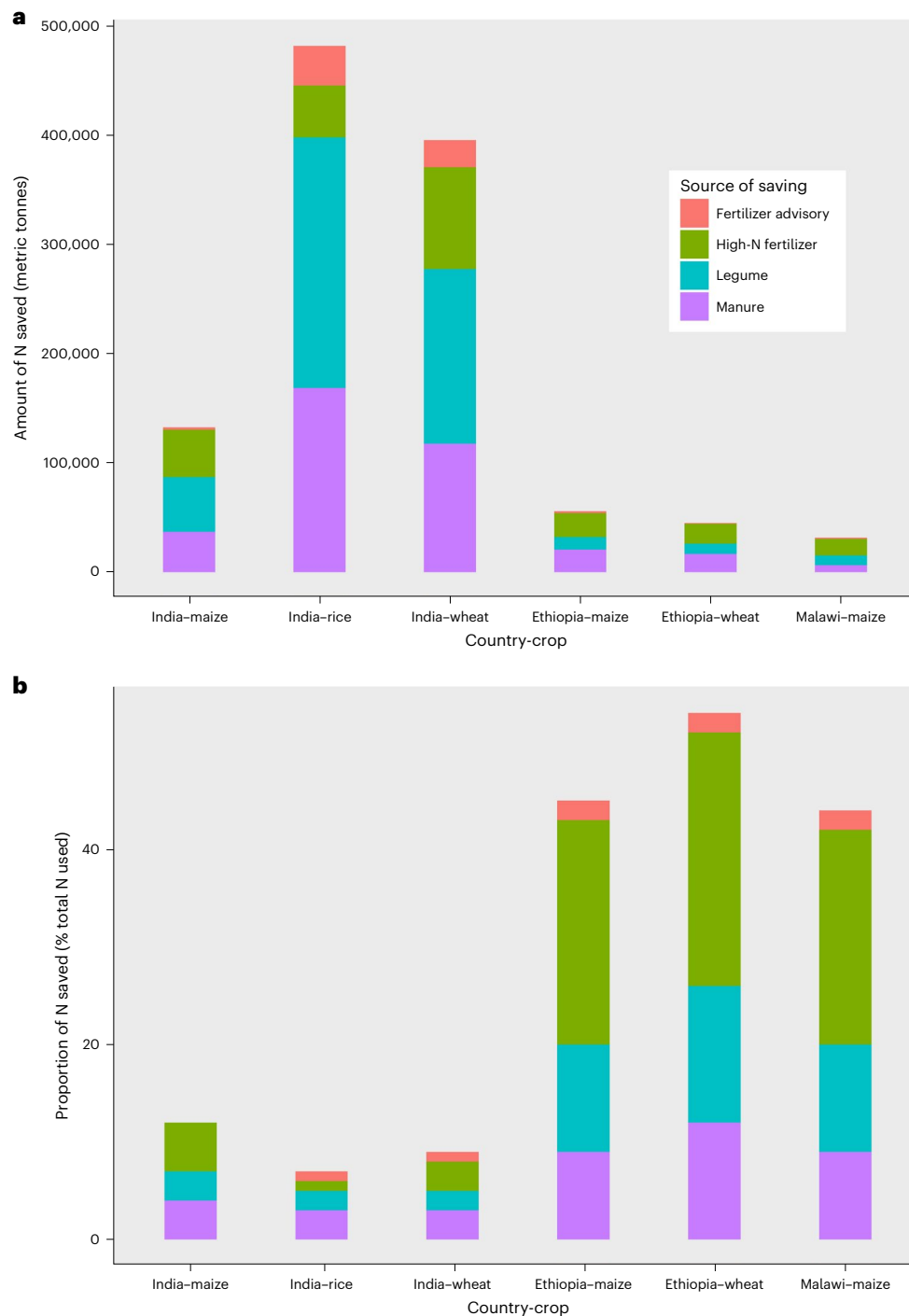
Fig. 5 | Projected N-fertilizer savings from near-term interventions. **a**, Estimated total N fertilizer saved in cereal production systems in India, Ethiopia and Malawi through: (1) promotion of manure use (including compost) and legume production; (2) subsidized access to increased use of high-N fertilizer types; and (3) advisories for improved fertilizer use efficiency. **b**, Proportion of N fertilizer saved relative to N fertilizer used in cereal production in India, Ethiopia and Malawi.

and national and regional policymakers to effectively assess options and take action in line with their priorities.

The higher cost of blended fertilizers is a particular barrier for low-income producers. Evidence from many cereal systems across diverse production geographies indicates that, while N responses are typically large everywhere, P responses are often much lower and much more spatially variable, particularly for areas with relatively low soil fertility (for example, for maize[27] and rice[28] in sub-Saharan Africa). Additionally, while N responses are immediate, P responses are distributed across multiple seasons due to the low mobility of this nutrient in the soil[31,32]. In the short term, N is the one nutrient that shows a consistent and profitable crop response in low-yield environments[6]. In sub-Saharan Africa, for example, N is the most limiting nutrient for rice production (in 93% of sites tested), followed by P (in 60% of sites)[33]. Therefore, for cereal production systems where yields are low (for example, many smallholder farms in Africa), immediately ensuring sufficient access to N should be the first-order priority in a fertilizer supply crisis. On balance, the imperative for supplying other required

nutrients is more modest, given minimal offtake in a moderate-yielding crop and inherent soil nutrient supply capacity[34].

Maintain yield in a crisis through near-term interventions

Our analysis demonstrates that meaningful N-fertilizer savings are achievable in cereal production systems in the near-term through targeted interventions. Promoting integrated organic and inorganic N management is a 'no regrets' N-fertilizer savings strategy. Carbon and N dynamics are interlinked, and organic amendments can supply N to crops and improve N-fertilizer efficiency through enhanced soil C stocks and soil health[35,36]. Soil N status is biologically mediated and integrally linked to the C cycle, making N management complex and knowledge intensive. To expand legume production and use of compost, researchers should explore effective agronomic practices, including mechanization options that can facilitate timely incorporation of crop residues and other sources of organic inputs.

Shifting to high-N fertilizer is a strategy that can be deployed rapidly to address an N-fertilizer price crisis and to prevent loss in productivity that could cause widespread food insecurity. In N-deficient systems, high-N fertilizers can offer greater profit-to-cost ratios, especially for resource-constrained farmers. In geographies and cereal systems characterized by N mining, where soils are N deficient and N inputs are modest, cost-effective means of increasing N supply are critical. In countries with variable patterns of N use, such as India and Ethiopia, redirecting delivery of urea and other high-N fertilizers from N-surplus cropping systems to supply depots in N-deficient areas can stabilize productivity and profitability in a crisis[37].

Soil acidification is a concern when applying high-N fertilizers, but this challenge can be moderated when fertilizer use is combined with lime or organic inputs that harness biological sources of N, modify soil acidity and reduce the risk of fertilizer response variability[35]. Based on fertilizer response trial data, P deficiency and insufficiency of other nutrients can result when urea is used in place of combined fertilizers. In low-yield cereal systems, nutrient requirements (for example, K, P) can be met, in large part, by soil weathering and biological cycling processes and supported through organic amendments and crop diversification[38]. Cost-effective management can thus be achieved through judicious use of high-N inorganic fertilizers combined with biologically based management. Greater reliance on high-N fertilizer is supportable in the short-term, particularly if paired with site-specific knowledge and investment in innovative extension to promote increased organic-N sources and sound soil management. For example, inorganic fertilizer placement and timing, and concurrent integrated crop and water management are particularly important for improving NUE in African rice production[39–41].

In N-surplus systems, N-fertilizer savings can be achieved by increasing NUE, for example, through fertilizer advisories that assist farmers in reducing overfertilization and loss of N to the environment while lowering production costs[10,19]. In specific contexts, notably high N-input systems, fertilizer advisories have been effective in providing guidance that reduces overfertilization[42]. Advisories based on localized soil conditions, specific crop yield goals and market conditions can help improve farm-level profitability[43]. In high-yield intensive cereal systems, large doses of inorganic and organic fertilizers will be needed to meet macro and micronutrient requirements[44], but crop diversification through legume integration can play a role in meeting N demand through biological sources and reducing inorganic fertilizer dependency[12]. Short-season legume integration into intensive cereal production, as illustrated by mungbean in wheat–rice systems, has been shown to be highly effective and N conserving in fine-textured soils, but not in coarse-textured soils[45].

Leverage local mechanisms to increase effectiveness

The functionality and reach of public and private sector extension systems and other services are important for expanding N sources in N-scarce areas as well as for promoting judicious moderate doses in areas where overfertilization is prevalent. With appropriate extension support, more farmers can benefit from N management interventions in the immediate term, with essential benefits for cereal productivity, food security and livelihoods. Extension campaigns show promise for improving fertilizer use, particularly in sub-Saharan maize production where N mining is prevalent[35]. Yet, throughout the developing world, an overwhelming number of agricultural households cannot be served, given inadequate budgets, staffing, transportation, resources and training for extension and other advisory services[46]. Promising developments include improvements in extension efficacy through digital tools and bidirectional communication approaches that engage local knowledge and support farmer agency[47]. Although not yet extensive in developing countries, there is increasing access and use of digital tools and decision support systems for distributing fertilizer recommendations and other agro-advisories[48–50]. Medium- and long-term investments in decentralized agricultural research and extension networks can facilitate farmer-led innovation in improved N management.

Context matters in targeting soil fertility management technologies at fine as well as coarse scales. A systematic review of sustainable intensification technologies provides further evidence of this 'hyper-localization' principle[51]. Viable targeted responses to volatile N-fertilizer supply will depend on an expanded evidence base regarding N status of cereal systems and other contextual factors. As newer technologies such as bio-fertilizers, polymer coatings, nano-urea and precision agriculture generate sufficient field data, these can be integrated into evidence-based analysis[52]. Deeper knowledge about how to increase organic-N sources through enhancing biological nitrogen fixation and other soil-based processes would enable better targeted N management interventions that improve NUE. Mechanization and irrigation are also important long-term investments for improving N efficiency[8].

Farm-level N management is heavily influenced by policy and socio-technological infrastructure. Governments in many countries use subsidies to encourage farmers to apply more fertilizer to boost yields, total production and rural incomes[53]. In this policy context, global N usage increased by 300% between 1961 and 2019[54]. Input subsidies have played an outsized role in public sector expenditure[55], inadvertently driving pollution[56] and disincentivizing appropriately tailored fertilization[57]. As high fertilizer prices strain the ability of governments to maintain existing fertilizer subsidies, evidence-based repurposing of these subsidies could incentivize use of the right fertilizer type in the right places[58,59]. Paradoxically, the disruption caused by a fertilizer supply crisis can stimulate interest in combined use of organic and inorganic inputs that would lead to improved NUE, crop productivity and soil health.

Use evidence-based targeting for cost-effective solutions

In a world where N-fertilizer mismanagement is reinforced by policy and infrastructure at the local level and a volatile fuel–fertilizer–food nexus at the global level, a regional geopolitical conflict has revealed the centrality of N to critical global food challenges. Governments need viable solutions to break the fuel–fertilizer–food security nexus and preempt current and future global food crises. Rather than promoting specific interventions, this paper presents a technology-agnostic, evidence-based approach to tailoring N management solutions to the conditions of specific cereal production systems.

An evidence-based response to a fertilizer supply crisis targets high-N fertilizer and access to this type of fertilizer to locations where crop yields are moderate. This is a cost-effective form of fertilization in such production systems, as N is a primary yield determinant and other nutrients are generally needed in small amounts. In high-yield areas, balanced fertilizer is often required to meet nutrient removal in grain; high-N fertilizer alone is insufficient. Targeting for better management of N can be achieved through deployment of high-N fertilizers to

geospatial locations and crop fields where they can be most efficiently used, especially low-yield regions. This needs to be paired with knowledge about fertilizer placement and timing for efficient utilization, and building an enabling environment for farmers to source organic-N from compost production and legume rotation crops[60].

With more frequent and severe fertilizer and food crises on the horizon, a skillful global response will deploy existing and new strategies that account for important differences among agricultural systems. Given finite resources, solutions should be carefully targeted to specific local contexts, with the near-, medium- and long-term in mind. To safeguard global food security, our challenge is to realign access to N fertilizers so that they are more broadly available in N-starved locations and simultaneously managed for cost-effective safe use everywhere.

Methods

Spatial distribution of nitrogen balance across countries

Using spatial data on crop N input and output (see conceptual framework in Supplementary Information 4), and information on current and potential N harvest, we classified maize, wheat and rice areas in each country on the basis of NUE, N surplus/deficit and N harvest gap (Figs. 2–4).

Estimated NUE, N surplus/deficit and N harvest gaps represent the values at spatial scale for each five arcminute grid cells, considered here as a single field. Total amount of N input to the soil was estimated considering all sources of N inputs into the production areas within a grid cell (Supplementary Information 4 and equation 1). The time-series gridded data on annual synthetic N use in agricultural lands with horizontal resolution of 0.5×0.5 degrees[61] were used to derive grid-specific N application rates. Data on application of N from manure were obtained from a 5-arcminute gridded global dataset[62]. The datasets from the Global Livestock Impact Mapping System (GLIMS) in conjunction with country-specific annual livestock population[63] were used to reconstruct manure N production to agricultural fields. The manure N applied to cropland was developed on the basis of manure management systems in three livestock production systems: rangeland-based systems, mixed rainfed farming systems and mixed irrigated farming systems for cattle (dairy and other cattle), goats and sheep, and poultry and swine (smallholder and industrial systems). Crop residue production was calculated by multiplying crop yield data by a crop-specific residue conversion factor (dry weight ratio of straw to grain). N input from residues was determined by multiplying the estimate of residue production by the residue N concentration (see Supplementary Information 3 for detail) and residue recycling factor (0.39 for Ethiopia and Malawi, and 0.48 for India). Mineralization of N resulting from loss of soil organic C stocks in mineral soils was determined following the Tier 1 approach of IPCC[64]. Gridded data on monthly historical atmospheric N depositions (wet and dry) for 1860–2016 simulated by the National Center for Atmospheric Research (NCAR) Chemistry–Climate Model Initiative (CCMI) were obtained from the Inter-Sectoral Impact Model Intercomparison Project (ISMIP2a). The CCMI models explicitly considered N emissions from natural biogenic sources, lightning, anthropogenic and bio-fuel sources, and biomass burning[53], and are recommended by the Coupled Model Intercomparison Project (CMIP) and the global N_2O Model Intercomparison Project (NMIP) to drive the impact models.

$$N\_input = N\_synthetic + N\_manure + N\_residue$$
$$+N\_mineralization + N\_(atmospheric\ deposition) \quad (1)$$

where N_input is the annual amount of N applied to soil from all sources (kg N ha^{-1}), N_synthetic is the annual amount of N applied to soil from synthetic fertilizers (kg N ha^{-1}), N_manure is the annual amount of N from manure deposited to soil by grazing animals (kg N ha^{-1}), N_residue is the annual amount of N from crop residue from the previous year returned to the soil (kg N ha^{-1}), N_mineralization is the annual

amount of N supplied within soil due to mineralization (kg N ha^{-1}) and N_atmospheric deposition is the annual amount of N deposited from the atmosphere (kg N ha^{-1}).

We used harvested crop area and moisture-corrected grain yield extrapolated from ref. 65 and grain N content[66] to calculate spatial N output. We calculated N surplus or deficit as the difference between N input and output (equation 2):

$$N\_surplus/deficit \left(kg - Nha^{-1}\right) = N\_input - N\_output. \quad (2)$$

We estimated NUE using a simple mass balance principle utilizing the annual amount of N input and N output for each crop (equation 3)[66]. NUE was classified as low (NUE ≤ 30), medium (30 < NUE < 90) or high/soil mining (NUE ≥ 90).

$$NUE = N\_output/N\_input. \quad (3)$$

We obtained irrigated or wetland crop production potential (that is, yield potential) from the FAO Global Agro-Ecological Zones (GAEZ, v.4) data portal[67]. Then, we calculated N harvest gaps as the difference between potential N removal (that is, potential yield × N content) and actual N removal (equation 4). N harvest gap values exceeding the global median were considered 'high', whereas those less than the global median were considered 'low'.

$$N\ harvest\ gap = potential\ N\ harvest - actual\ N\ harvest. \quad (4)$$

Estimates of N-fertilizer savings

For each country and crop, we estimated N-fertilizer savings without compromising crop yield under four near-term intervention scenarios: (1) shifts from lower-N inorganic fertilizers to high-N inorganic (urea) fertilizer; (2) enhanced access to organic-N sources, that is, promotion of manure and compost use; (3) biological nitrogen fixation from increased production of legume crops; and (4) improvements in NUE through fertilizer advisories and farmer training. An average nitrogen mineralization rate of 40% was used for organic sources[44]. Values used for calculating N savings (for example, country-specific crop area, N-fertilizer application rates, sources of N and total N demand for each crop, enhanced organic-N source estimates based on the 10% increase in current use) were obtained from multiple sources (Supplementary Information 3). Adoption rates were based on a review of literature considering effects of agricultural policies, and government and extension investments. Calculations on N savings associated with promotion and broad use of agricultural advisories on fertilizer rates are presented in Supplementary Information 1 (SI 3) based on the following sources, which reviewed N-fertilizer efficiency associated with advisory use in cereal crops[68,69]:

N-fertilizer savings were calculated as follows:

(1) N savings through shifts to high-N (SN$_{urea}$) fertilizer considers N from urea input (N_{urea}) and a 50% conversion from non-urea inorganic sources ($N_{nonurea}$), such as DAP, to urea:

$$SN_{urea} = N_{urea} + (0.5N_{nonurea} \times f_u/f_{nu}) \times A_c \quad (5)$$

where SN$_{urea}$ is the shift to high-N urea (Mt), N_{urea} is N from urea input (Mt), $N_{nonurea}$ is N from non-urea sources (Mt), f_u is the fraction of N in urea, f_{nu} is the fraction of N in non-urea sources and A_c is the crop area (ha).

$$N_{urea} = N_r \times A_c \times A_f \times 1000 \quad (6)$$

and

$$N_{nonurea} = NU_r \times A_c \times A_f \times 1000 \quad (7)$$

where N_r is the rate of N application (kg ha^{-1}) from urea, NU is the rate of non-urea inorganic fertilizer (kg ha^{-1}) and A_f is the fertilized crop area fraction for a specific crop out of total crop area (A_c).

(2) Calculations of N-fertilizer savings by integrating organic fertilizer are based on estimates of current crop area under organic-N (that is, manure, compost, legumes) (Supplementary Information 3) and increased farmer adoption, resulting in a 10% increase in crop area under organic fertilizers. Note that we refer to manure here with acknowledgement that compost is in some cases included within this term.
Current manure N input (N_{mc}, in Mt) was calculated as:

$$N_{mc} = A_{fm} \times A_c \times M_r \times M_c \times 1000 \tag{8}$$

where A_{fm} is the fraction of specific crop area fertilized with manure, M_r is the rate of manure application (kg ha^{-1}) and M_c is manure N content (%). With an assumption of 10% area increase in the adoption of manure, increased N from manure (N_{ma}, in Mt) was calculated as:

$$N_{mc} = 0.1 \times A_c \times M_r \times M_c \times 1000. \tag{9}$$

The extra N-input from adoption of manure (N_{me}) was obtained as:

$$N_{me} = N_{ma} - N_{mc}. \tag{10}$$

(3) Current legume N input (N_{lc}, in Mt) was calculated as:

$$N_{lc} = A_{fl} \times A_c \times BNF \times 1000 \tag{11}$$

where A_{fl} is the fraction of crop area under legumes and BNF is biological N fixation (kg ha^{-1}).
With an assumption of 10% area increase in the adoption of legumes, the increase in N from legume adoption (N_{la}, in Mt) was obtained as:

$$N_{la} = 0.1 \times A_c \times BNF \times 1000. \tag{12}$$

The extra N input from adoption of legumes (N_{le}, in Mt) was obtained as:

$$N_{le} = N_{la} - N_{lc}. \tag{13}$$

Thus, the increase (savings) from organic N (N_{so}, in Mt) was calculated as:

$$N_{so} = N_{le} + N_{me}. \tag{14}$$

(4) Improvements in NUE and resulting fertilizer savings due to fertilizer advisories were estimated using factors derived from previous studies that measured NUE in response to site-specific nutrient management strategies[10,42]. Accordingly, we estimated the effect of fertilizer-N on NUE and savings on the basis of fertilizer advisories being adopted on 10% of fertilized cropland area for each crop and country.

Reporting summary
Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability
The gridded data on N management challenge categories, country shapefiles used for subsetting and the R script used for plotting are available at https://github.com/noufashub/n-management. Source data for all figures are provided with this paper.

Code availability
The reproducible 'R' code for data analysis and mapping is available at https://github.com/noufashub/n-management.

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Author contributions

S.S. conceptualized, designed and coordinated the work. S.S., T.B.S., J.C., K.A.M., T.S.S. and K.T. collected data. S.S. and T.B.S. analysed the data and interpreted the results. S.S., T.B.S., J.C., C.M.C, S.G, M.L.J., P.M., K.A.M, C.N., K.S., T.S.S., U.S., Z.P.S., K.T. and B.G. contributed to the review of the findings, and to the writing and revision of the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	No software used for data collection
Data analysis	We used MS-Excel 2016 and R (verson 4.2.2). The reproducible 'R' code for data analysis and mapping is available at https://github.com/noufashub/n-management.

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio guidelines for submitting code & software for further information.

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Data files for all the figures and the gridded data on N management challenge categories, country shapefiles used for subsetting and R script used for plotting are available at https://github.com/noufashub/n-management.

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Reporting on sex and gender	N/A
Population characteristics	N/A
Recruitment	N/A
Ethics oversight	N/A

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Field-specific reporting

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Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	We used secondary data on spatial N input and output and FAO's data on potential N harvest to identify priority areas NUE improvement and potential areas to close N harvest gaps. Potential benefit of N management interventions are based on plausible scenario on the adoption of near-term interventions in different countries.
Research sample	We used spatial data on crop N input and output from multiple sources and FAO's GAEZ yield potential data to identify priority areas of N interventions based on N deficit/surplus, NUE and N harvest gaps. We used country level statistics and literature to determine N savings due to adoption of various N management strategies.
Sampling strategy	The study used secondary data and did not require sample size determination or a sampling strategy
Data collection	Authors analyzed secondary data to carry out a scenario analysis so no primary data was collected
Timing and spatial scale	No primary data was collected
Data exclusions	No data exclusion, all the data from the sources mentioned in the method section were used
Reproducibility	The findings can be reproduced accessing the data sources and following the equations and codes in the study
Randomization	Not applicable
Blinding	No primary data collected, so not applicable

Did the study involve field work? ☐ Yes ☒ No

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Methods

n/a	Involved in the study
☒ ☐	ChIP-seq
☒ ☐	Flow cytometry
☒ ☐	MRI-based neuroimaging