Rebalancing global nitrogen management in response to a fertilizer and food security crisis

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Abstract

Vulnerabilities of the global fuel-fertilizer-food nexus have been revealed by a regional geopolitical conflict causing sudden and massive supply disruptions. Across over- and under-fertilized agricultural systems, nitrogen (N) fertilizer price spikes will have very different effects and require differentiated responses. For staple cereal production in India, Ethiopia, and Malawi, our estimates of N-fertilizer savings show the value of integrated organic and inorganic N management. N-deficient systems benefit from shifting to more cost-effective, high-N fertilizer (such as urea), combined with compost and legumes. N-surplus systems achieve N savings through better targeted and more efficient N-fertilizer use. Globally, there is a need to re-balance access to N-fertilizers, while steering the right fertilizer to the right place, and managing N in combination with carbon through near-term interventions, while striving for longer-term sustainable management. Nationally, governments can invest in extension and re-align subsidies to enable and incentivize improved N management at the farm level.

Full Text

Fuel-fertilizer-food nexus

As a primary yield determinant, nitrogen (N) is needed in massive quantities for production of cereals and other crops. Application of large quantities of soluble N-fertilizer supports high yields, while simultaneously posing an environmental threat through direct and indirect generation of greenhouse gas emissions, spread of invasive species, and degradation of water quality [1]. Fossil fuel energy is the feedstock for fertilizer manufacture. The price of energy-intensive synthetic N-fertilizers has fluctuated greatly over time, closely tracking volatile international fossil fuel supplies and prices[2]. 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). We see this with a staple food crop such as wheat for which a 15% increase in prices would lead to an 8% reduction in wheat consumption, with severe consequences for protein and calorie intake[3].

Geospatial dimensions of N-fertilizer use

Fertilizer use has been a major driver pushing the global N cycle beyond planetary boundaries[4], although contributions are highly spatially variable[5]. Overall, the use of N-fertilizer on global cropland is severely skewed, leading to over-fertilization in some regions and under-fertilization in others[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].

Context for N management

Soil N status is biologically mediated and integrally linked to the C cycle, making N management complex and knowledge intensive. Nitrogen use efficiency (NUE), the proportion of applied N in harvested products, typically ranges from 20 to 55%[8]. Increased NUE can reduce nitrate-N leaching and gaseous N loss from fertilized maize, wheat, and rice fields[9]. In specific contexts, notably high N-input systems, fertilizer advisories have been effective at providing guidance that reduces over-fertilization[10]. There is less scope for gains in NUE in N-deficient systems, where a bigger concern is soil mining, occurring when crop uptake exceeds the amount of N-fertilizer applied[11 7]. In such systems, increased access to N is paramount. Organic matter addition and crop diversification are viable strategies for increasing crop yields, especially where N fertilizer application rates are low[12].

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 in order to boost yields, total production, and rural incomes[13]. In this policy context, global N usage increased by 300% between 1961 and 2019[14]. Input subsidies have played an outsized role in public sector expenditure[15], inadvertently driving pollution[16] and disincentivizing appropriately tailored fertilization[17]. The often modest infrastructure for agricultural research and extension is problematic, given the knowledge intensive nature of managing N for sustainable and environmentally sound crop production[18]. Nonetheless, fertilizer usage in some regions (e.g., sub-Saharan Africa) is widely regarded as sub-optimal[19]with low average application rates attributed, in part, to low and spatially variable economic returns to farm-level fertilizer investments[20]. Advisories that inform local knowledge based on soil conditions, crop yield goals, and market conditions can help improve farm-level profitability and thereby induce greater fertilizer investment[21].

Current crisis

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 challenges. Sudden and massive fuel and fertilizer supply disruptions arising from the Russia-Ukraine war have led to skyrocketing fertilizer prices[22]. 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[23].

Governments need viable solutions to break the fuel-fertilizer-food security nexus and preempt current and future global food crises. To support discussion of policy responses in the context of N-fertilizer crises, this paper estimates N status for three major staple cereals in key production geographies. Specifically, we calculate N balance (surplus/deficit), NUE, N harvest gaps, and potential N savings from management interventions in maize, wheat, and rice in three countries representing a range of biophysical and socio-economic production conditions. The countries and cereal systems chosen encompass production intensification extremes, and are highly relevant to global food security vulnerabilities. Using the best available data, this paper 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. Policy implications of these globally-relevant N management strategies are discussed. Rather than promoting specific interventions, our analysis supports a technology-agnostic approach to N management that is context-based, evidence-driven, and data-enabled.

Results

For India, Ethiopia and Malawi – all developing countries that face pressing food security challenges – 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 [7,24]. In Ethiopia, maize and wheat cropping intensity varies across regions and ecological zones with a negative N balance in many areas[25]. 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[26].

Nitrogen status by country and crop

Our estimates of N surplus or deficit (i.e., difference between N input and N removal) and NUE (i.e., ratio of N-output to N-input) indicate that cereal production systems in these three countries encompass extremes from N surplus to N deficiency to N mining (Figs. 2–4). High N harvest gaps (i.e., 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. Severe N deficiency is widespread in maize production in Malawi, where N mining is prevalent, and across much of Ethiopia, except for the central region which has moderate NUE paired with a high harvest gap.

Surplus N application and low NUE are prevalent in **wheat** production (Fig. 3) across India, with the exception of the N-deficient western semi-arid region (e.g. the Rajasthan), which has medium NUE and a low N harvest gap. 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 generally N-deficient in Malawi with the exception of wheat production by the commercial farming sector, which has moderate to high N inputs.

N surpluses predominate in Indian **rice** production (Fig. 4). In Malawi, N deficiency is much more typical, including prevalent N mining and high N harvest gaps. An Africa-wide meta-analysis estimates that NUE in rice systems ranges from 12 to 21, with a mean value of 14 kg/ha[27]. These values are similar to estimates of NUE in rice of 13 kg/ha in China[28] and 18.4 kg/ha in Asia overall [29].

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 high-N urea fertilizer increased from US$ 483/ton in 2021 to US$850/ton in the first quarter of 2022 and is projected to remain at elevated levels in 2023[30]. Application rates of urea and other N fertilizers have a strong negative response to rising prices [31] and there is a large body of evidence that reduced N fertilizer application negatively affects crop yield, particularly for cereal production [32] .

To anticipate the impact of the fertilizer price spikes in India, Ethiopia, and Malawi, we estimated near-term changes in application rates, based on 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 and 5.8 million tons, respectively, in response to a 1.2 million ton 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 and wheat production by 83 thousand tons. Malawian maize systems are projected to apply 6 thousand tons less urea fertilizer and produce 166 thousand fewer tons, equivalent to US $27 million in foregone 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 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 [33] .

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 management of organic and inorganic N was estimated based on promotion of farm-level use of manure or compost and production of legume crops. 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 one to two year 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 about 10 kg N/ha and net biological N fixation by legumes is estimated to be in the range of 10–20 kg N/ha [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 (i.e., ~ 25% in Ethiopia and Malawi), but the scope is considerably less for N substitution through organic sources in India given high levels of N use there.

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 [34,35]. an added advantage of organic inputs is their residual effects across multiple years[36].

Shifting to **high-N fertilizer types such as urea (46% N)** is projected to result in significant N savings, especially in low-N cereal systems in Ethiopia and Malawi (Fig. 5b). High-N fertilizers generally supply two- or three-fold higher amounts of N per unit of fertilizer compared to compound, multi-nutrient fertilizers, such as **di-ammonium phosphate (18% N**), enabling significant 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 (i.e. urea has a lower unit cost for N than alternative fertilizer blends).

Fertilizer advisories for improved N management appear to offer significant potential N savings in wheat and rice production systems where N over-fertilization 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

Solutions in a crisis

Focusing on globally-important cereal crops, this study confirms the importance of **differentiated approaches** across over- and under-fertilized agricultural systems. Within and across the 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. Since these three countries are indicative of the range of N use in African maize and wheat production[26], our findings suggest that singular interventions are unlikely to lead to improved N management at sufficient scale. This aligns with other studies that identify complex political and socio-technological drivers of N management[18,5]. This study takes the next step and considers the evidence for tailoring N strategies by country, and by cropping system.

In the context of a sudden fertilizer shortage and an emergent food security crisis, durable solutions are needed quickly and at large scale. Our analysis demonstrates that meaningful N-fertilizer savings are achievable in cereal production systems in the near-term and identifies N status as a critical differentiator for intervention objectives. In **N-surplus systems**, N-fertilizer savings can be achieved by increasing NUE, for example, through fertilizer advisories that assist farmers to reduce over-fertilization and loss of N to the environment while lowering production costs[9,24]. In **N-deficient systems**, shifting to high-N fertilizers can offer greater profit:cost ratios, especially for resource-constrained farmers. In countries with variable patterns of N use, like 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].

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. This can be achieved through expanding farmers' access to high-N fertilizers, 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[38]. Extension campaigns show promise for improving fertilizer use in an effective manner, particularly in sub-Saharan maize production. This is a clear example of a N-mining system that can be rebalanced through attention to soil health, integrated organic and inorganic N management, and cost-effective use of high-N fertilizer [39]. 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[40]. Thus, coordinated outreach through public and private sector extension is needed to alert farmers about safe, cost-effective use of high-N fertilizers.

Geo-differentiated approaches are important not only for soil N management, but also for balanced fertilizer investments. The requirement for costly fertilizers that include a full complement of P, K, and micronutrients depends on the geo-location and the cropping system. 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 sub-Saharan Africa, N is the most limiting nutrient for rice production (in 93% of sites tested) followed by P in 60% of sites[41]. In the short term, N is the one nutrient that shows a consistent and profitable crop response in low-yield environments[20]. Thus, increasing access to high-N fertilizer for more cost-effective fertilization of cereal crops is consistent with an evidence-based response to a fertilizer supply crisis. Greater reliance on high-N fertilizer, such as urea, is supportable in the short-term, particularly if paired with site-specific knowledge as part of an integrated organic-inorganic N management campaign. For example, inorganic fertilizer placement and timing and concurrent integrated crop and water management are particularly important for improving NUE in African rice production[27]. In sum, productivity of cereals is highly related to N inputs. Shifting to high-N fertilizer is a strategy that can be deployed rapidly to address a N-fertilizer price crisis and to prevent loss in productivity that could cause widespread food insecurity.

We fully acknowledge that balanced nutrition has indirect as well as direct benefits, such as addressing micronutrient deficiencies and enhancing disease tolerance, which will vary with specific crop and soil requirements. Thus, geo-differentiated management is required over time and space. What has not always been appreciated is that, during a crisis, constraints on time, resources, and logistics hamper the ability of individual farmers and national and regional policy makers to effectively assess options and take action in line with their priorities. Therefore, for cereal production systems where yields are low (e.g., many smallholder farms in Africa), immediately ensuring sufficient supply of N should be the first-order priority. 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[42]. That is, other macronutrient requirements (e.g., K, P) in low-yield environments can be met, in large part, by soil weathering and biological cycling processes and supported through organic amendments and crop diversification [43]. Cost-effective management can thus be achieved through judicious use of high-N inorganic fertilizers combined with biologically-based management.

In contrast to low-yield, rainfed cereals, the requirement in high-yield, intensive cereal systems (e.g, irrigated wheat and rice-wheat double crops in India) is for balanced fertilizer inputs given high nutrient offtake. In these systems, 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 coarse-textured soils[44]. This further illustrates that 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[45]. Taking into account environment and market context is of particular importance where nutrient demand is high, thus intensive cereal production systems achieve substantial benefits from fine-tuned extension advice. Overall, large doses of inorganic and organic fertilizers will be needed to meet macro and micronutrient requirements of high-yield cereal production areas [46].

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. 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 [39,47]. To expand legume production and use of compost, researchers should explore effective agronomic practices, including mechanization options that can facilitate timely incorporation of green manures and other sources of organic inputs. Some promising areas for testing and validation include better delivery of extension messages, improved market infrastructure, and incentives for growing and trading organic nutrients. The functionality and reach of local extension systems, digital advisories, and other services are important for expanding N sources in N-scarce areas as well as for promoting judicious, moderate doses in areas where over-fertilization is prevalent.

Preempting future fertilizer crises

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 at the same time, manage for cost-effective, safe use everywhere. Particularly in N-surplus environments, integrated nutrient management can deliver improved NUE and minimize N loss to the environment. In N-deficient systems, increased access to high-N fertilizer, combined with investment in innovative extension to promote increased organic-N sources and sound soil management, is foundational to meeting food production needs. 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[48,49]. 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.

This paper presents a technology-agnostic, evidence-based approach to tailoring N management solutions to the conditions of specific cereal production systems. 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 [50]. Deeper knowledge about how to increase organic-N sources through enhancing biological nitrogen fixation (BNF) 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].

With appropriate extension support, more farmers can benefit from N management interventions in the immediate term. This is fundamental to cereal productivity, food security, and livelihoods. 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[51]. Promising developments include improvements in extension efficacy through digital tools and bi-directional communication approaches that engage local knowledge and support farmer agency[52]. Medium- and long-term investments in decentralized agricultural research and extension networks can facilitate farmer-led innovation in improved N management.

This paper highlights the urgent need for policies that rebalance N availability and for investment in agricultural technical expertise and extension for improved N management. This is key to keep producer costs minimal while ensuring high crop yields. If improved N management is not tackled, we risk severe negative impacts for cereal production, increases in food prices, and poor nutrition.

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.

Methods

Spatial distribution of current nitrogen balance across countries

Using spatial data on crop N input and output and information on current and potential N harvest, we classified crops in questions in each country based on NUE, N surplus/deficit and N harvest gap (Figs. 2–4). For this, we considered all sources of N inputs into the production areas i.e. synthetic N input [53], manure N[54] residue N[55] atmospheric N-deposition [56], N from mineralization [55], and N fixation calculated by multiplying legume N content with the percentage of it derived from N_2 fixation[57]. We used harvested crop area and crop yield extrapolated from Ray et al.[58] and their corresponding N content[59] to calculate spatial N output at the spatial level. Similarly, we obtained biophysical crop production potential (i.e. yield potential) from the FAO Global Agro-Ecological Zones (GAEZ) v4 data portal (https://gaez.fao.org/). We calculated N surplus or deficit as the difference between N input and output. We estimated NUE using a using a simple mass balance principle using the annual amount of N-input and N-output for each crop [59]. NUE was classified as low ($NUE \leq 30$), medium ($30 < NUE < 90$), or high/soil mining ($NUE \geq 90$) through visual inspection of NUE data. Finally, we calculated N harvest gaps as the difference between potential N removal (i.e. potential yield x N content) and actual N removal. N harvest gap values exceeding global median were considered 'high' whereas those less than global median were considered 'low'.

Estimates of nitrogen fertilizer savings

For each country and crop, we estimated N fertilizer savings under four near-term intervention scenarios: (i) shifts from lower-N inorganic fertilizers to high-N inorganic (urea) fertilizer; (ii) enhanced access to organic-N sources, i.e., promotion of manure and compost use; (iii) biological nitrogen fixation from increased production of legume crops; and (iv) improvements in NUE through fertilizer advisories and farmer training. Values used for calculating N savings (e.g., 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 10% increase in current use) were obtained from multiple sources (Supplementary Information 1). Adoption rates were based on review of literature considering effects of agricultural policies and government and extension investments.

N fertilizer savings were calculated as follows:

(i) N savings through shifts to high-N (SN_{urea}) fertilizer considers N from urea input (N_{urea}) and a 50 percent conversion from non-urea inorganic sources ($N_{nonurea}$), such as diammonium phosphate (DAP), to urea:

$SN_{urea} = N_{urea} + (0.5N_{nonurea}*f_u/f_{nu})* A_c$ (Eq. 1)

where SN_{urea} is 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 crop area (ha).

$N_{urea} = N_r* A_c*A_f * 1000$ (Eq. 2)

and

$N_{nonurea} = NU_r* A_c*A_f * 1000$ (Eq. 3)

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

(ii) Calculations of N-fertilizer savings by integrating organic fertilizer are based on estimates of current crop area under organic-N (i.e., manure, compost, legumes) (Supplementary Information 1) 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:

N_{mc}= A_{fm}*A_c*M_r*M_c*1000 (Eq. 4)

where A_{fm} is the fraction of specific crop area fertilized with manure, M_r is rate of manure application (kg/ha), M_c is manure N content (%).

With an assumption of 10 percent area increase in the adoption of manure, increased N from manure (N_{ma}) in MT was calculated:

Nma = 0.1*A_c*M_r*M_c*1000 (Eq. 5)

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

N_{me}= N_{ma} - N_{mc} (Eq. 6)

(iii) Current legume N input (N_{lc}) in MT was calculated:

N_{lc}= A_{fl}*A_c*BNF*1000 (Eq. 7)

where A_{fl} is the fraction of crop area under legumes and BNF is biological N fixation (kg/ha).

With an assumption of 10% area increase in the adoption of legumes, the increase in N-from legume adoption (Nla) in MT was obtained as:

N_{la}= 0.1*A_c*BNF*1000 (Eq. 8)

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

N_{le}= N_{la} – N_{lc} (Eq. 9)

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

N_{so} = N_{le} + N_{me} (Eq. 10)

(iv) 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[9, 10]. Accordingly, we estimated the effect on NUE and savings of fertilizer-N based on fertilizer advisories being adopted on 10% of fertilized cropland area for each crop and country.

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Figures

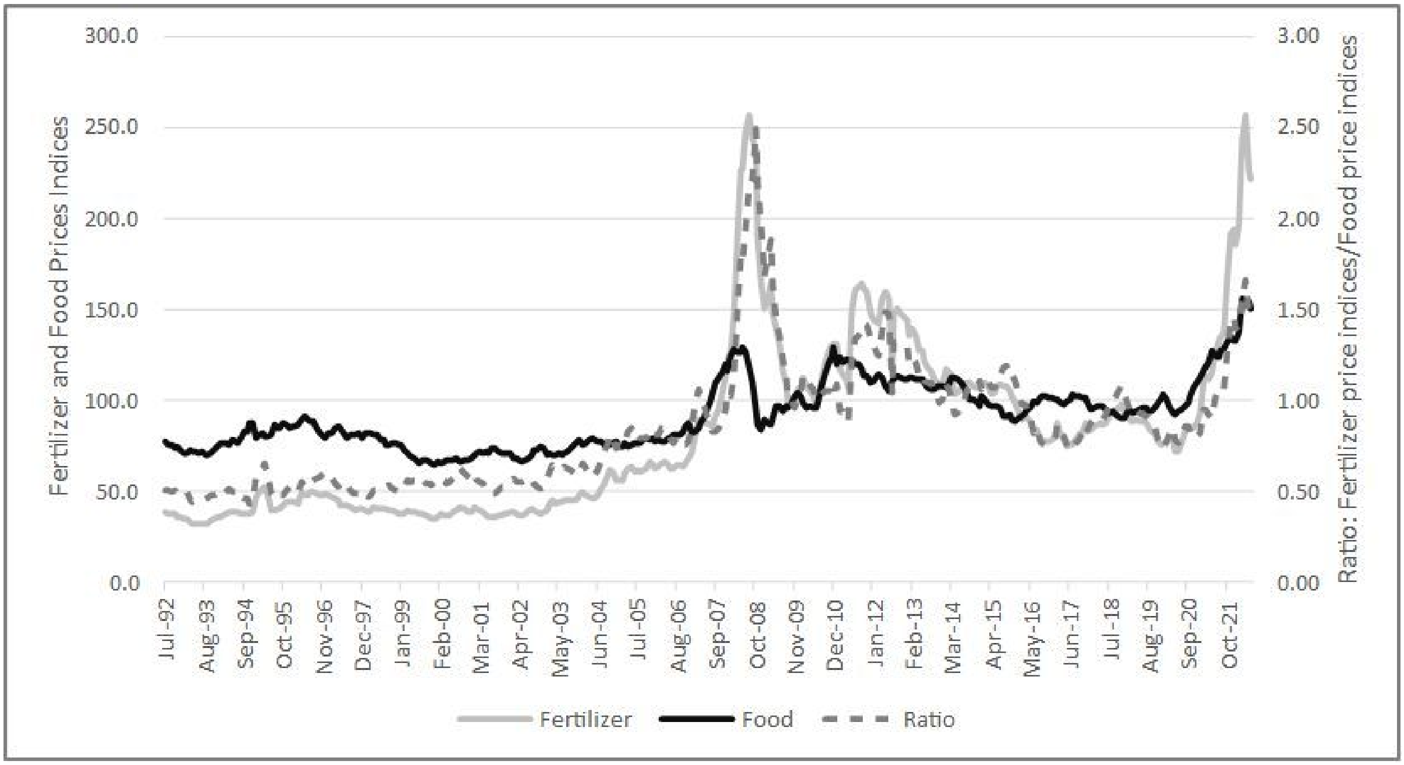

Figure 1

Trends in fertilizer and food price indices from July 1992 to June 2022, where an index value of 100 corresponds to the 2014-2016 average prices (left axis), and the ratio of fertilizer and food price indices, where higher values correspond with lower fertilizer availability (right axis). Sources: Monthly fertilizer price index based on international prices of urea, DAP, potassium, and phosphate (IndexMundi; online data sources). Food price index from FAO.

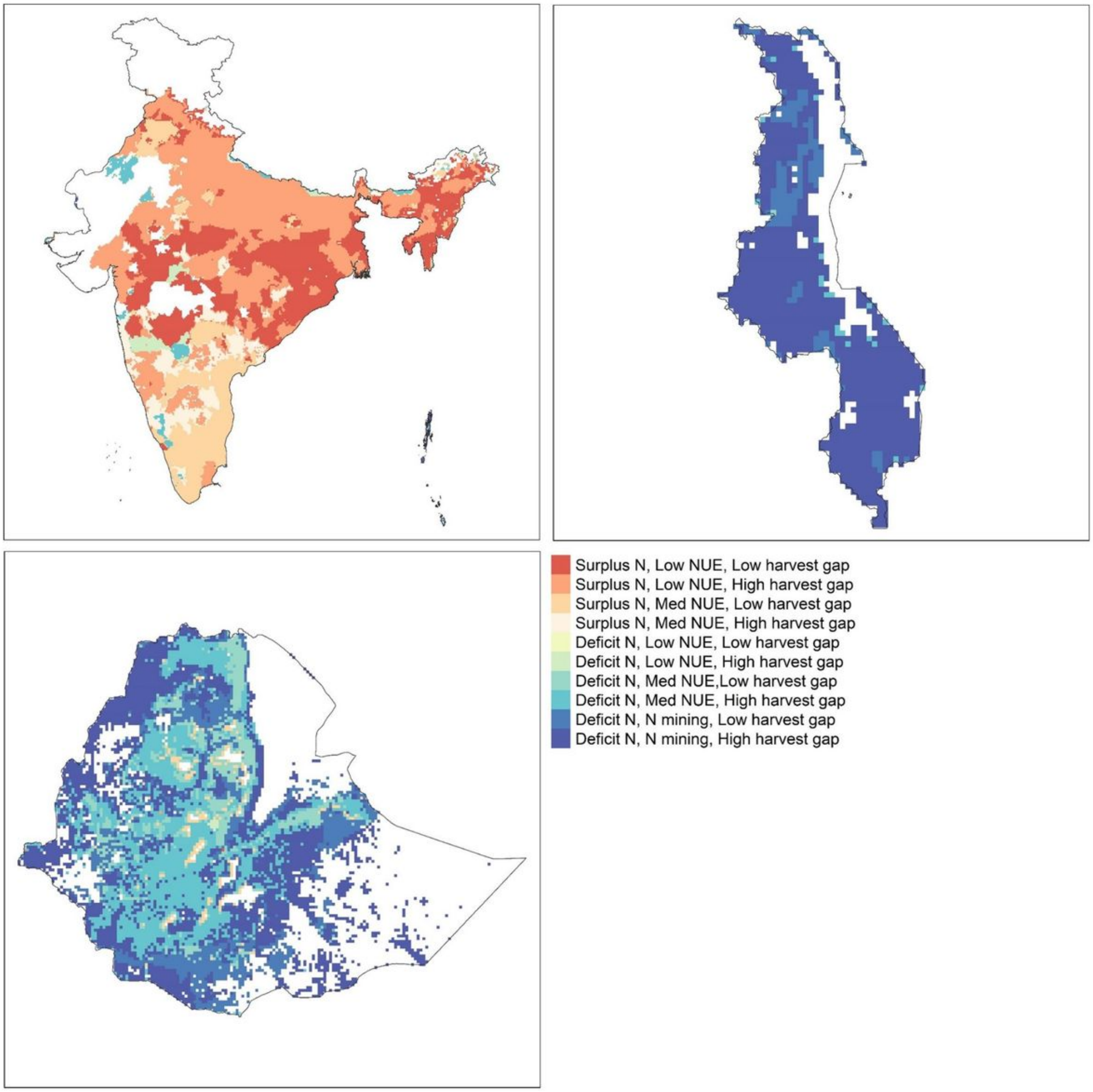

Figure 2

Classification of maize area in India (upper left panel), Ethiopia (lower left panel), and Malawi (upper right panel) based on N surplus/deficit, nitrogen use efficiency, and N removal gap. Classification details are provided in Methods (N use efficiency maps).

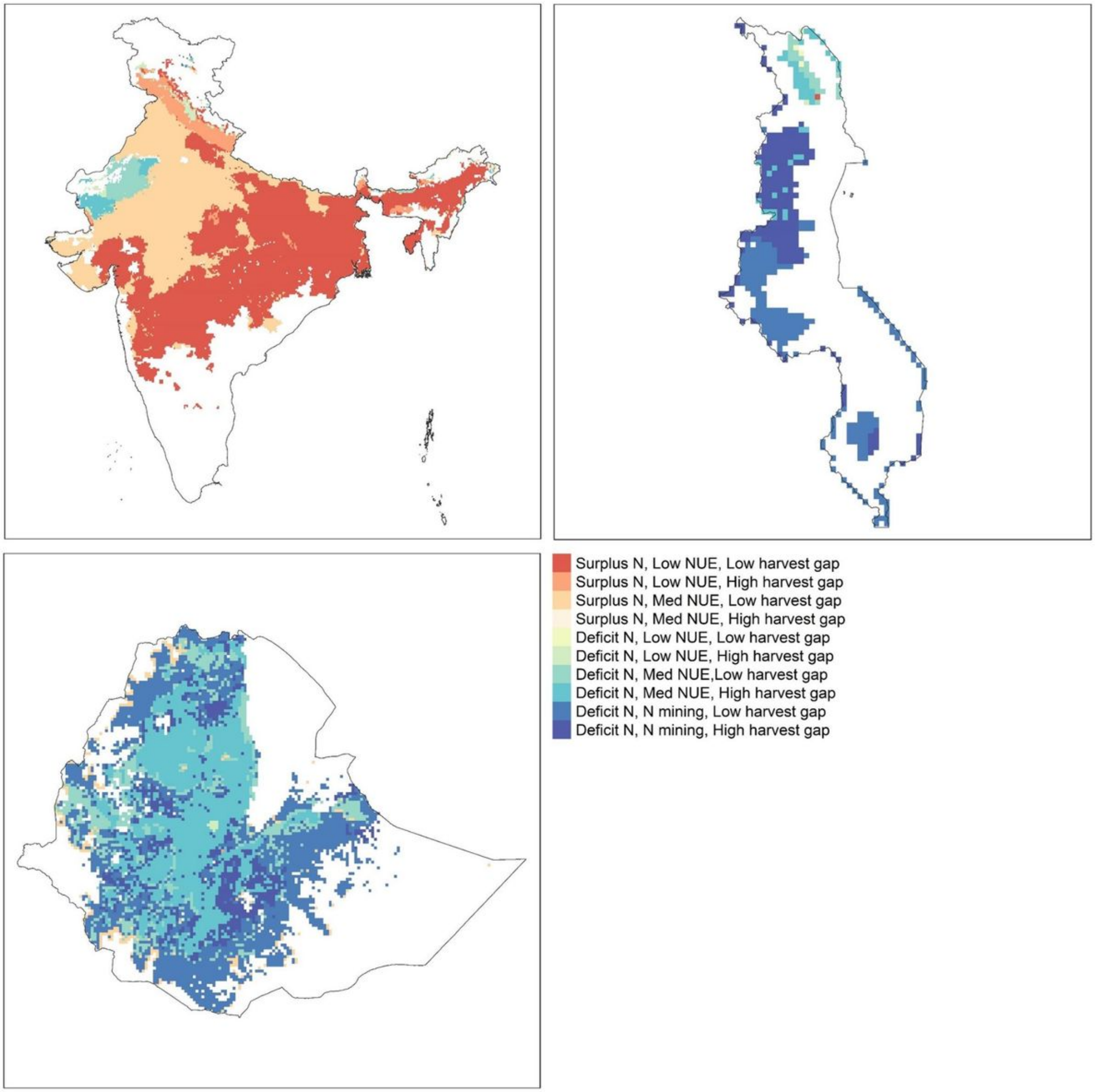

Figure 3

Classification of wheat area in India (upper left panel), Ethiopia (lower left panel), and Malawi (upper right panel) based on N surplus/deficit, nitrogen use efficiency, and N removal gap. Classification details are provided in Methods (N use efficiency maps).

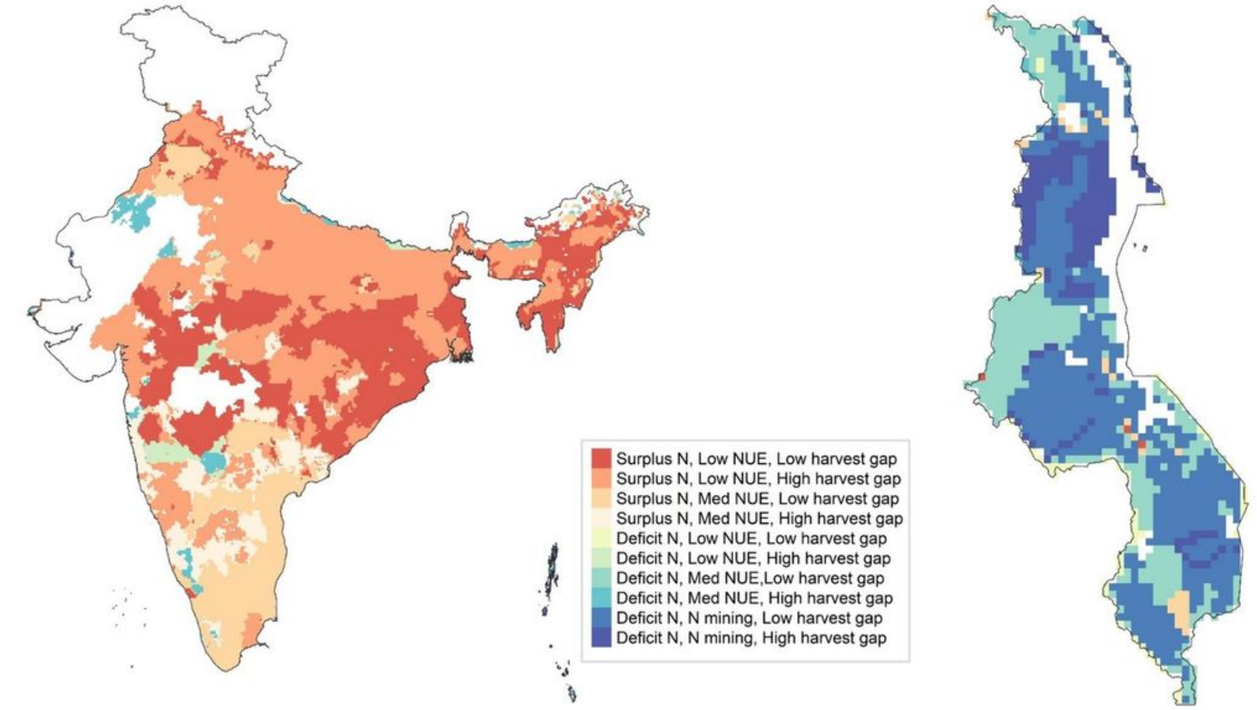

Figure 4

Classification of rice areas in India (left panel) and Malawi (right) based on N surplus/deficit, nitrogen use efficiency, and N removal gap. Classification details are provided in Methods (N use efficiency maps).

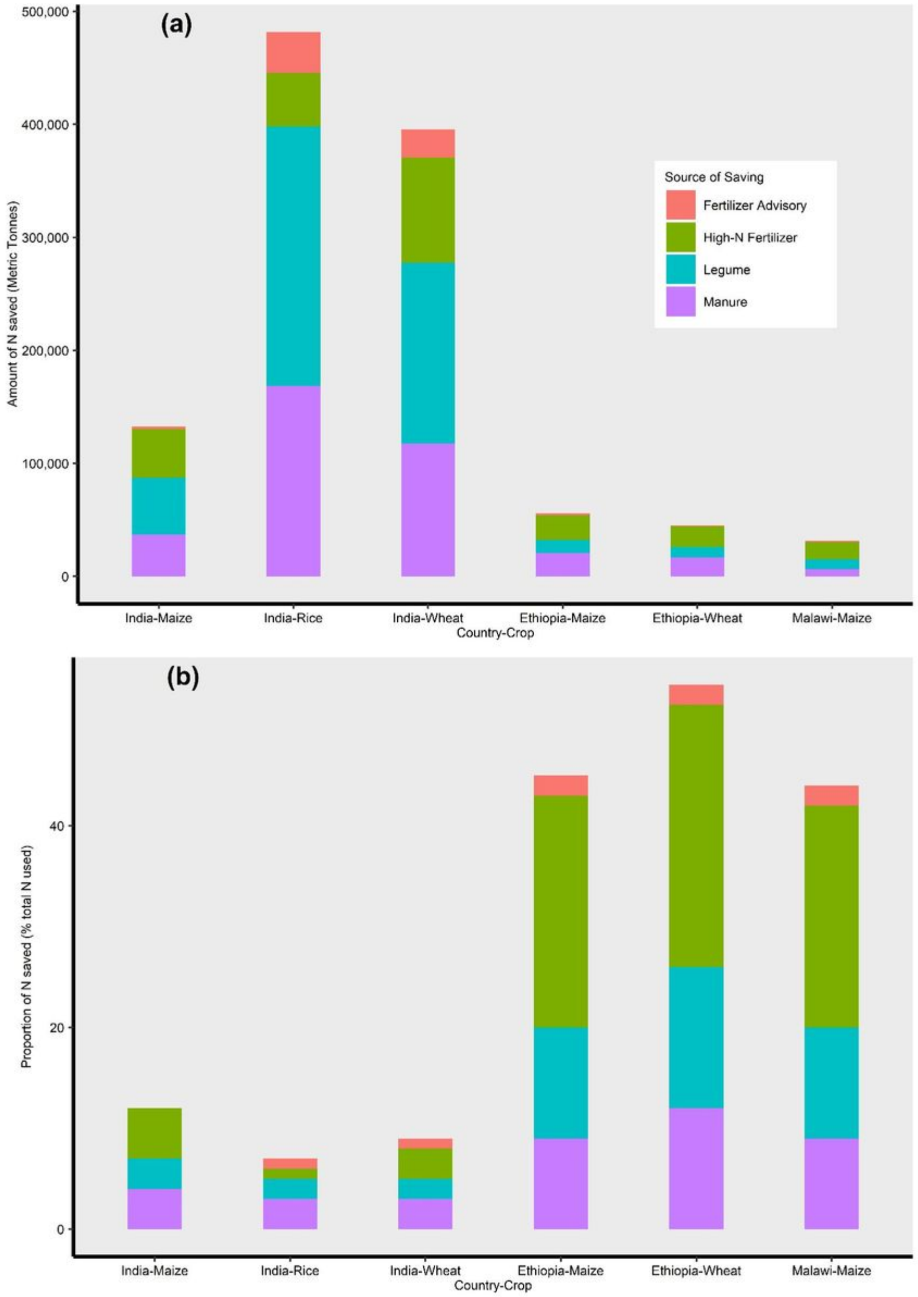

Figure 5

(a) Estimated total N-fertilizer saved in cereal production systems in India, Ethiopia, and Malawi through: (i) promotion of manure use (including compost) and legume production; (ii) subsidized access to increase use of high-N fertilizer types; (iii) 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.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SnappetalRebalancingglobalnitrogenSI1X2nov27.pdf