Less, better and circular use – how to get rid of surplus nitrogen without endangering food security

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Key messages

1. The **excessive use of nitrogen-based fertilizers has severe environmental consequences**, including biodiversity loss, soil and freshwater degradation, and substantial greenhouse gas emissions.

2. The supply chain of mineral fertilizers results in **significant greenhouse gas emissions**, accounting for about 10% of agricultural and 2% of global emissions. Approximately 1-2% of the world's energy is allocated to fertilizer production, with about 95% of that energy being used for nitrogen-based fertilizers.

3. **85 to 95% of nitrogen applied to soil is lost** and does not make it to us as food. The current annual nitrogen surplus is double the amount compatible with the planetary boundaries for a safe operating space for humanity, and overall nitrogen use efficiency in food systems is only 5 to 15%, indicating huge losses.

4. High-income countries with intensive agriculture show huge regional nitrogen surpluses and losses. In contrast, in many lower-income countries, particularly in Africa, lack of access to nitrogen leads to soil degradation.

5. **Solutions are known.** Use nitrogen better, use it circularly, and use less. Increase use efficiency by decreasing food waste, and focusing on producing human food versus animal feed. Recycle nitrogen. Reduce, where too much is used.

6. **Food security is possible with less nitrogen**: with huge overuse and low use efficiency, much nitrogen can be spared without reducing yields. With nitrogen scarcity and soil mining, recycling should be increased before and besides adding new external nitrogen.

7. **Using "green" mineral fertilizers with fewer production impacts will not solve the problem.** The huge nitrogen surplus has the same adverse impacts in waterbodies, landscapes and ecosystems, irrespective of how the nitrogen has been produced.

8. The **existing intergovernmental, national and industry-led initiatives to tackle the nitrogen problem are ineffective**: those with ambitious goals lack power for implementation, and those with implementation power lack ambition.

9. For solutions, **we need credible industry business plans for a future with 50% less nitrogen**; we need credible commitment from governments to full cost accounting; we need credible signals from agriculture, the food sector and society for mutual support. **And we need this *now*!**

Summary

The problem is huge and there is no one-size-fits-all solution. The global nitrogen (N) surplus of about 120 Tg N annually contrasts with the limit for a safe planetary operation space for humanity of between 40 to 60 Tg N per year. Thus, a reduction of at least 50% globally needs to be achieved over the next decade. Many high-income regions report huge nitrogen surpluses, losses and very low nitrogen use efficiency, illustrating the need for drastic reductions in N inputs. In many low-income countries, predominantly in Africa, a different situation prevails, with N undersupply resulting in N mining of soils and corresponding soil degradation. Thus, regional differentiation is key. Historic accounts further illustrate the urgency of the situation. Since the 1960ies, human-generated reactive nitrogen production increased more than twenty-fold, now equalling and thus doubling the reactive N production from natural processes.

Solutions are possible without endangering food security. Overall food system level nitrogen use efficiency, captured as the ratio between N applied and N contained in food consumed, is only between 5 to 15% globally. In high-input contexts, reductions of N use without reducing yields are possible, thus increasing cropland nitrogen use efficiency, allowing for less and better use of nitrogen. High-income countries are characterised by high levels of animal products in diets and high food waste quantities. Reducing those by reducing animal numbers fed from feed grown on cropland and by reducing food waste and losses along the whole value chain would increase system level nitrogen use efficiency without endangering food security. This again reflects the goal of less and better use of nitrogen. Furthermore, following agroecological practices for repeated use by closing nutrient cycles and recycling hitherto unused nitrogen further adds to solution strategies. One example are nutrients from human faeces and urine, duly accounting for potential health risks and sociocultural factors that act as barriers to its use. In contexts of soil mining, these latter strategies are to the fore. There, focusing on keeping losses low and recycling available biomass is key, thus focusing on better and repeated use and placing less emphasis on the absolute reduction of nitrogen inputs.

Current nitrogen production and use is strongly shaped by unsustainable incentive patterns and unequal power relations. External costs of nitrogen fertilizer use are not internalised, neither on the side of the farmers or big livestock operators, nor with food industry companies or the fertilizer industry. Abandonment of flawed subsidies and implementation of True Cost Accounting through the internalisation of external costs is thus needed to get the prices right and to reflect the adverse effects of nitrogen overuse in the business decisions of the various key actors. Achieving this is however difficult, not in the least due to the high market concentration in the fertilizer industry and the currently high profits generated with their business model. Furthermore, the often low fertilizer to crop price ratio allows producers to hedge against the risk of lower yields by using more fertilizers than agronomically warranted for achieving certain crop yield levels.

Changes are not possible as long as the business model of the powerful market players is so closely linked to large nitrogen production and throughput and high feed and food production quantities, fuelling systems with high animal numbers and animal-sourced food shares in diets together with high waste and loss levels.

There are a number of international, national and sector-wide initiatives to reduce nitrogen surplus. They do however not reach their goals. These initiatives are largely rooted in the intensification paradigm and the business-as-usual narrative of agriculture and food systems. They mainly focus on increasing cropland level nitrogen use efficiency, which is laudable, but which does not address the major leverage points that need to be used for truly sustainable changes and transformation. These leverage points are primarily improvements of food-system level nitrogen use efficiency, following circularity principles and reducing the overall size of the food system regarding new external nitrogen inputs and nutrient throughputs in the system.

Key strategies for this are a reduction in cropland-based livestock production and a reduction in food waste and losses. Such reduction in throughput is however at odds with the current business models of the key players in the sector. Furthermore, many initiatives may appear ambitious, but in reality lack any structure to enforce and monitor implementation, thus not achieving much.

Solutions are known, but they need to put food security at the centre, require much more than incremental changes, and depend on dominant narratives being changed. The narrative that less nitrogen use endangers yields and food security in every case and everywhere is wrong. The narrative that powerful key players in industry and business in general want to contribute to solving the problem is wrong. The narrative of technological fixes being the most effective solutions needs to be overcome. Central for solutions are, first, information provision, including, education and training in optimal nutrient use. These could be provided relatively easily. Second, getting the prices right is of paramount importance. This applies both to internalisation of external costs of nitrogen use and also to abandoning flawed subsidies for nitrogen inputs. Third, technological solutions have a role to play albeit not being a game changer. Key examples are technologies for optimising fertilizer applications to achieve a certain yield, and also technological solutions for reducing reactive nitrogen emissions from fuel combustion in large industry plants or in power generation. Importantly, however, the technical solution of just producing mineral fertilizers with renewable energy and thus less GHG emissions without reducing the quantity of reactive nitrogen produced would not solve the problem. Finally, regionally differentiated and adapted solutions are required. Inspiration can always be gained from the various existing attempts to address the nitrogen problem in various countries, sometimes executed with more success, and sometimes less. Most important, however, is a thorough change in business plans, such that powerful key actors credibly commit to a future with only half the current nitrogen input and throughput.

Abbreviations

BNF	Biological Nitrogen Fixation
CSA	Climate-Smart Agriculture
GHG	Greenhouse gas
Ha	Hectare
HBP	Haber-Bosch process
N	Nitrogen
N_r	reactive Nitrogen
NUE	Nitrogen use efficiency
TCA	True Cost Accounting
Tg	Teragram, equals Megaton, i.e. million tons
y, y^{-1}	year, per year

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1. Introduction

The number of individuals sustained per hectare of arable land witnessed a significant rise from about 2 to almost 4.5 people during the 20th century (Erisman et al., 2008). This remarkable increase was largely possible only due to the utilization of the Haber-Bosch process (HBP), which allows converting the ample available molecular nitrogen in the air (N_2) into reactive forms (N_r) such as ammonia, that are readily available for fertilizing crops. This process allowed industrialized large-scale production of so-called "mineral fertilizers", thus making the potentially scarce and limiting key nutrient for crop growth, nitrogen, widely available at relatively low economic costs. This resulted in about half of all food protein in 2019 being produced with mineral fertilizers, providing food for about 3.8 billion people (Rosa & Gabrielli, 2023).

The introduction of mineral fertilizers decoupled nitrogen availability for crop production from closed nutrient cycles with minimized losses and from biological nitrogen fixation (BNF). The latter takes place in mainly legume crops and soils and had until then been the only source for new nitrogen for agriculture. In current agriculture, forage legumes and grasslands are the largest sources for BNF, with food crops contributing a minor part only. Making more nitrogen available for crop production via BNF is thus often in some competition with direct food crop production. This land competition was greatly relaxed through the availability of mineral fertilizers.

However, this independence of nitrogen inputs from BNF on crop- and grassland areas and from closed nutrient cycles comes with a number of severe drawbacks. First, it is based on a new dependence, namely from energy, and energy from fossil fuels in particular. This is because the Haber-Bosch process is very energy intensive, with energy from fossil fuels being the cheapest energy source for decades. Approximately 1-2% of the world's energy is allocated to fertilizer production, with about 95% of that energy being used for nitrogen-based fertilizers (IFA, 2009). Furthermore, the process also requires natural gas as one input material. Related to this, the supply chain of mineral fertilizers results in significant greenhouse gas (GHG) emissions, accounting for about 10% of agricultural and 2% of global GHG emissions in 2019. Their production accounts for almost 40% of total emissions linked to mineral fertilizers and their use, while field emissions from their application account for almost 60%. A small part, about 3%, relate to fertilizer transportation (Gao & Cabrera Serrenho, 2023; Menegat et al., 2022).

Second, the Haber-Bosch process triggered a change of scale in human impacts on the environment. Humans currently convert three- to fourfold more atmospheric nitrogen into reactive forms than the natural terrestrial biological fixation (Galloway et al., 2021). The cheap availability of reactive N due to the HBP resulted in a dramatic drop of nitrogen use efficiency (NUE). This applies to both NUE measured on a crop scale, through the quantity of nitrogen applied for producing a ton of wheat, for example, and on a more systemic scale, through the quantity of nitrogen inputs used to produce a ton of nitrogen in food, from a region or whole country, including animal and plant-based food. Currently, overall system-level NUE, defined as the relation of total global nitrogen inputs in agriculture to the total nitrogen in food being consumed, lies between only 5 to 15%, indicating a situation of massive and inefficient fertilizer overuse and huge potential for improvements (Erisman et al., 2008; UNEP, 2013). Food production and food security in today's food and agriculture are thus heavily dependent on mineral fertilizers, but the low NUE indicates a vast potential for improvement, as the same outcomes could be achieved with much less and more efficiently used mineral fertilizers than today (Gu et al., 2023). Importantly, regional differentiation is central, as in some regions, for example in several countries in Africa, opposite problems arise, with soil nitrogen mining taking place rather than nitrogen oversupply, due to lack of inputs.

Third, the low crop scale NUE results in large nitrogen losses to the environment, and the low systems-level NUE goes along with high levels of food waste of about a third of the production, as well as overconsumption and high production of animal-sourced food in many middle- and high-income countries. All this results in a number of adverse environmental impacts such as biodiversity losses, the degradation of soils and freshwater resources, and climate change. Because of this, agriculture ranks among the most significant factors that strain ecosystems, pushing them beyond their carrying capacities and contributing to the transgression of planetary boundaries (Galloway et al., 2021; Schulte-Uebbing et al., 2022; UNEP, 2013). Furthermore, the food systems of high- and middle-income countries are linked to dietary and other health consequences, as its polluting emissions adversely impact health, antimicrobial resistances is fostered and overconsumption is associated with various non-communicable diseases. The economic costs of all of these impacts from excessive nitrogen use are challenging to assess, but existing studies on damage costs and willingness to pay for mitigation indicate a global total cost ranging from US$200 billion to US$2 trillion annually (UNEP, 2013), including environmental and health impacts. A most recent study estimates global societal benefits from cost-effective mitigation of N overuse at about US$480 billion (Gu et al., 2023).

Any debate on how to address these drawbacks related to current nitrogen fertilizer use needs to account for a number of increasingly pressing challenges. Given the impacts of climate change on agriculture and a continuous increase in world population towards 10 billion people by 2050, pressure on food systems will further increase in the future. In many developing countries, economic growth is also expected to result in a shift towards consumption patterns with higher shares of animal protein sources and food waste levels. As a result, the total demand for food and for animal protein in particular, as well as for mineral fertilizers is anticipated to increase by 50% by 2050 (FAO, 2018). This substantial increase in demand in such business as usual scenarios would exert significant pressure on the food and agricultural sectors.

Thereby, it has to be emphasized that food security is not ensured even today. Food security, according to the FAO, means that "[…] all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food which meets their dietary needs and food preferences for an active and healthy life." (FAO, 2001). Agency and sustainability have been added as two important key aspects of food security, where in particular the latter allows hedging against arbitrariness that might come with allowing for any food preferences people may develop (Clapp et al., 2022). Food security is thus in particular not about keeping supermarket shelves full and meeting market demands only, but also focusing on assuring healthy, sustainable diets for all in an optimal way.

The FAO estimates that in 2022, between 690 and 780 million people faced hunger. Referring to a mid-range of 735 million people, this means that about 120 million people more face hunger than in 2019, before the COVID-19 pandemic (FAO, 2023b). The reason is not a lack of production volumes, given that global agriculture produces quantities that should allow for supply of around 3000 kcal per capita per day (FAO, 2023a). The challenge for food security is rather accessibility than availability of food (UNICEF, 2023). This is central for strategies aiming to tackle the challenges related to current nitrogen fertilizer use, as globally, production volumes are not the key limiting factor for achieving food security in a sustainable way. This is all the more the case in contexts of high volumes of food waste and losses and shares of animal-sourced products, as prevalent in many mid- and high-income countries. In addition, pressure on land for food production is expected to increase due to increasing demand for non-food uses for agricultural land, including the production of feedstock for bioenergy and biomaterials to replace fossil fuels and petroleum-based plastics.

Finally, the problem of excess nitrogen is not new. However, it gained increasing importance over the past decades, as mineral nitrogen inputs steadily grew with the related problems becoming all the more pressing (Sutton et al., 2021). Many of the detailed and more specialized assessments cited above are thus also not most recent but date from the first decade of the 21st century, while for more general numbers, such as total mineral fertilizer production etc. newer data exists. Generally, much of the data, for example on BNF, is also rather uncertain, and available numbers often cover larger ranges, thus providing gross estimates only, which however still suffice to draw a clear picture of today's situation regarding nitrogen use.

The bottom line of all of this is that agriculture uses very high quantities of new reactive nitrogen, mainly driven by massive inputs of mineral fertilizers, and that these quantities need to be drastically reduced. There is some general and increasing awareness of this, and since about 2014, global mineral fertilizer production stagnated on a high level, while BNF rather increased (Galloway et al., 2021). The situation of massive external N_r inputs thus largely remains unchanged despite some shift in sources away from fossil-fuel powered mineral fertilizers towards BNF, with corresponding benefits on some sustainability indicators, such as GHG emissions.

This report aims at discussing some solutions for these challenges. It starts by briefly addressing the current nitrogen use and use efficiency in agriculture and food systems and the costs of the various impacts related to nitrogen oversupply, and then focuses on potential solutions and related policies, including some assessment of the potential and gaps of already existing initiatives to tackle this problem. When talking about solutions, a regionally differentiated and context specific problem statement and solutions approach is needed to account for the specific characteristics and situations in different world regions and countries.

Finally, we point out that we adopt a systems level approach, meaning that we do not only focus on nitrogen use in the field and on farms, but centrally also on how nitrogen circles through the whole food system along value chains from agricultural production via processing and consumption to waste management. Thus, we neither do account for field or farm level impacts of nitrogen use only but also address its societal costs.

2. Current status of nitrogen fertilizer use and use efficiency

Four key concepts help to address the challenges that come from the current use of nitrogen. These are

- nitrogen use, captured as the total quantities of nitrogen applied in a certain context, and the resulting surplus or deficit when subtracting the nitrogen contained in the output produced;
- nitrogen throughput, captured as the quantity of N that cycles through the various ecosystems; and
- two notions of nitrogen use efficiency (NUE), the relation of nitrogen contained in the output to the nitrogen applied:
  - First, NUE in the agronomic sense, for single crops and on plot level, captures how much yield is produced with which nitrogen input.
  - Second, NUE in a systemic way on an aggregate food systems level, puts the total food produced (for example measured in quantity of nitrogen in human digestible protein) within a certain region and over a certain time in relation to the total nitrogen quantities applied within this system. We call this "full-chain NUE".

Furthermore, all this has to be seen in a

- context of trade and market dependencies, and
- with due regional differentiation.

2.1 Yields, nitrogen, and reactive nitrogen creation

The availability of nitrogen is often the second most limiting factor for plant growth, after water, thus significantly impacting yields (Ladha et al., 2022). The relationship between total applied nitrogen and yields - the N-Y-response curve - shows the key dynamics of nitrogen use for crop production (Figure 1). At low levels of nitrogen supply, additional units of nitrogen generate the greatest yield increments, but the yield gains gradually decrease for each additional unit of nitrogen until reaching maximum yield potential, beyond which yields do not further increase despite additional N inputs.

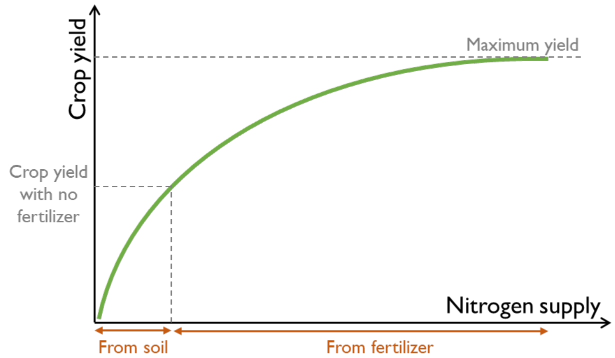

Figure 1: Yield-Response-Curve for N inputs (figure done by the authors)

Importantly, not only the total applied nitrogen quantity determines yields, but also the timing of application, as plant nitrogen demand is dependent on the growth stage of the crop, resulting in changing nutrient requirements over time. Furthermore, the form in which nitrogen is applied plays a role, as some forms are much more easily accessible to plants, for example mineral fertilizers, than others, such as nitrogen in woody biomass. In order to achieve maximum yields, it is thus necessary to have an adequate and balanced supply of plant-available nitrogen in terms of timing and quantity to avoid nitrogen limitation. This is also relevant for the losses related to nitrogen use. Some losses are unavoidable, due to the natural processes involved, such as denitrification in soils. Others, such as runoffs caused by precipitation, however, can be avoided and relate mainly to wrong timing and larger quantities than required being applied, as well as other management aspects not adequate for the specific location, for example tillage or crop choice and soil cover.

In various agricultural contexts, there is a large oversupply of nitrogen and reductions could be realised with minimal or no impact on yields (Cui et al., 2018; Gu et al., 2023; Wuepper et al., 2020).

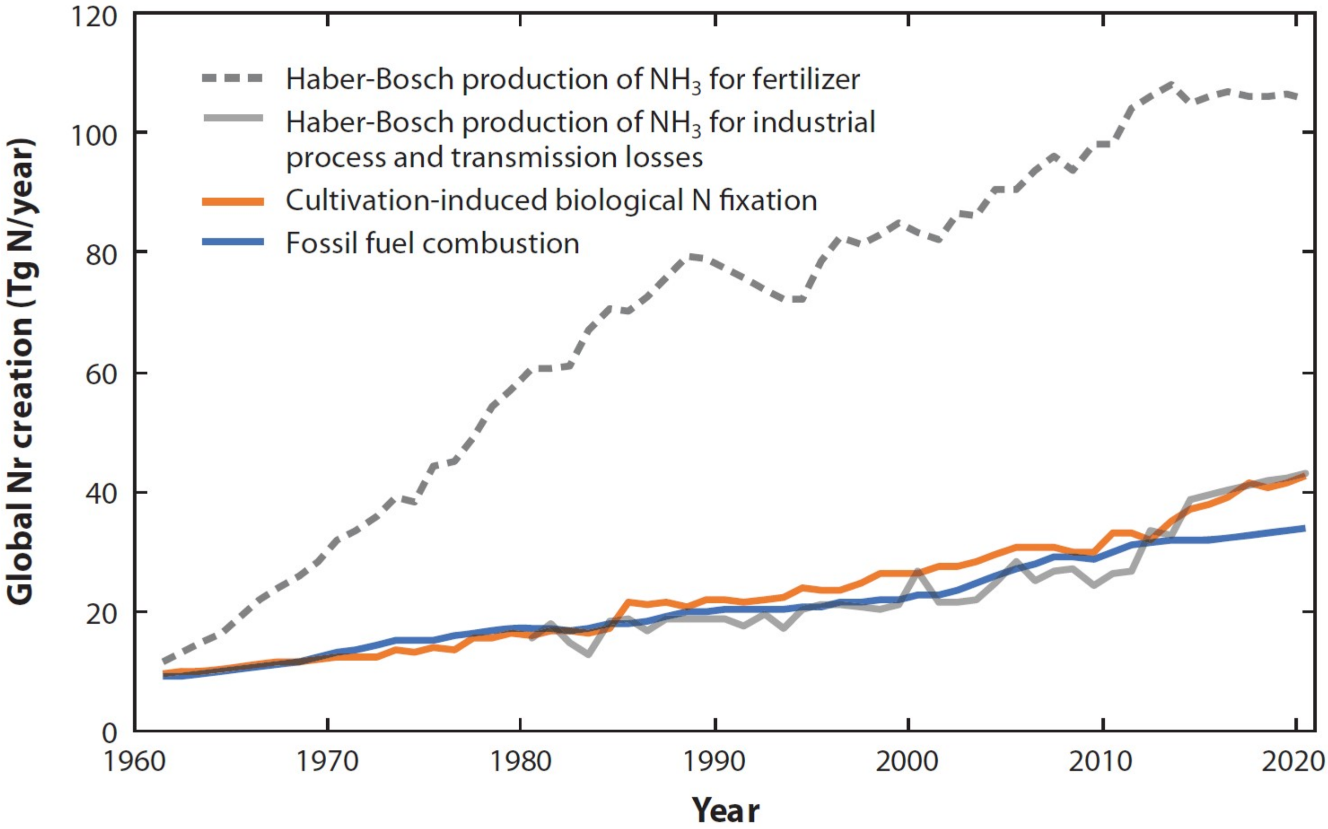

Figure 2: : Global N_r-Creation by HBP for agricultural and industrial use, by BNF and from fossil fuel combustion (in Teragrams (Tg) = Megatons N per year; from Galloway et al. 2021, Copyright © 2021 by Annual Reviews, licensed under a Creative Commons Attribution 4.0 International License).

Excessive fertilizer use by farmers can be attributed to several factors. Limited knowledge about proper nitrogen demand and about the environmental consequences of nitrogen overuse, lack of positive examples of successful fertilizer use reduction in their core peer groups, combined with economic pressures and risk-averse attitudes often lead to over-application of fertilizers, especially when they are easily accessible and affordable. The relatively low costs of mineral fertilizers, sometimes due to heavy subsidies like in India or Egypt, further encourage abundant fertilization to ensure constant N availability for maximum crop yields, even in the context of rising energy prices and other production costs (cf. Henderson & Lankoski, 2019; Houser, 2022; Kurdi et al., 2020; Zhang et al., 2015).

The current nitrogen oversupply is best assessed in historical perspective. Before industrialisation, natural nitrogen fixation summed to a total of about 200 Tg N_r/y, with 60 Tg from terrestrial and 140 Tg from marine ecosystems, and a small amount of about 5Tg from lightning. Today, human activities more than doubled this amount by adding another 220 Tg per year, with more than 40 Tg from BNF in agricultural lands, 110 Tg from the HBP for mineral fertilizer production and 40 Tg for industrial use, and 30 Tg from combustion of fuels in industrial plants, electricity generation and transport. Grain legumes are the most important part for BNF in agriculture, with about 35 Tg, and therein soybeans contribute more than two thirds. Since 1960, the HBP-based fertilizer production increased tenfold, BNF in agriculture fourfold, and N_r from combustion threefold (Figure 2). Some regional patterns can be discerned, as mineral fertilizer production showed the biggest increase in Asia and BNF in South America. By 2050, a further increase of 25 to 30% is projected for a business as usual scenario (Fowler et al., 2013; Galloway et al., 2021; Herridge et al., 2022).

This huge human-induced creation of N_r resulted in a massive disruption of the natural N-cycle by massively increasing flows of N_r through land and water ecosystems. Furthermore, only a fraction of the newly added N_r is converted back to molecular inert N_2 at some point in the cycle, thus resulting in overall increased flows of N_r through all compartments of the N cycle. Thus, this disruption of the N-cycle has two key aspects: First, it is less "closed" in the sense of continuously adding large quantities of new N_r from outside; second, it shows a massive increase of cyclic N_r-throughput through ecosystems that have adapted to much lower throughput over millions of years.

2.2 N use, surplus and deficit

Adding new reactive nitrogen N_r always disturbs the natural nitrogen cycle, but its assessment requires regional differentiation, as differences in regional contexts and utilization influence subsequent nitrogen losses and which and how environmental impacts may result.

For this, regionalised assessment of N_r inputs is important, but in particular also of N surplus and deficit. These correlate with how much N_r is lost to the environment, with corresponding adverse effects, or, for the deficit, how big a risk for soil nitrogen mining and related soil degradation may arise.

The planetary boundary for the global N surplus, that is the quantity of N still allowing for a safe operating space for humanity, is currently estimated to be at 40-60 Mt nitrogen per year. This is much lower than the current global nitrogen surplus of about 120 Mt nitrogen per year in 2010 (Rockström et al., 2023; Schulte-Uebbing et al., 2022), illustrating the size of the problem on a global scale. Ludemann et al. (2023) present a regionalized assessment, indicating surpluses in India and China, Europe, North and South America, and very low values in many African countries (Figure 3), and Chang et al. (2021) put this in relation to regional carrying capacities.

2.3 Cropland nitrogen use efficiency

As the surplus and deficit, cropland NUE addresses inputs in relation to outputs. The surplus and deficit build on the difference between inputs and outputs and report absolute values, which indicate a pressure to ecosystems or on soil degradation. NUE is built as the ratio of outputs and inputs and reports a percentage value. This is a measure for the efficiency of nitrogen use in the sense of the share of nitrogen applied ending up in the final product. Ideally, a NUE of 100% would be realised, meaning that all N applied ends up in the product,

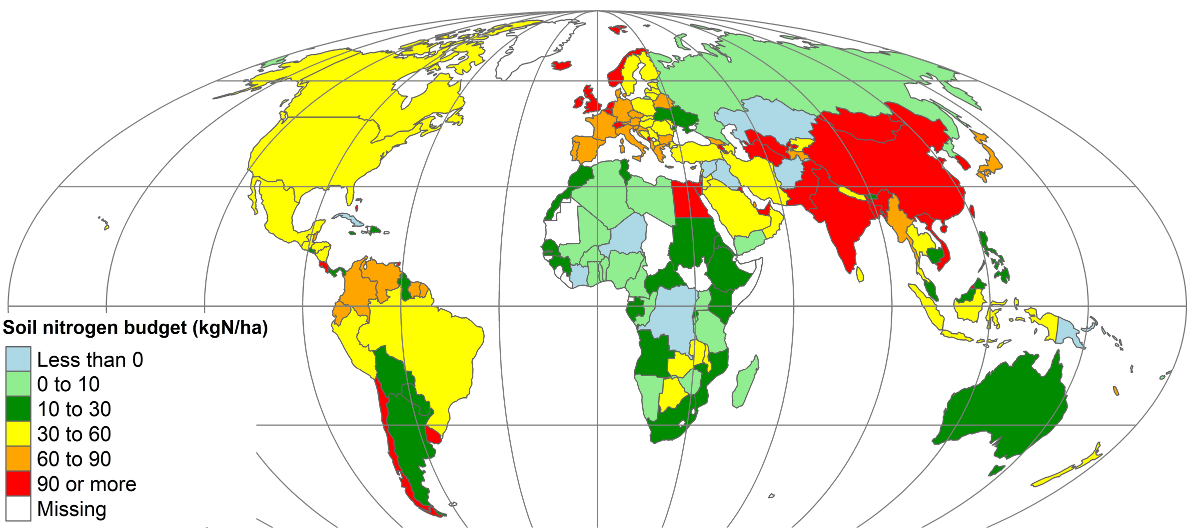

Figure 3: Nitrogen budgets (positive: surplus; negative: deficits) in croplands (in kilograms N per hectare and year: kg N/ha/y) for different countries (figure by the authors based on data from Ludemann et al. 2023).

avoiding any losses to the environment and not resulting in the mining of the nitrogen soil pool. However, given that the natural processes involved in nitrogen use on croplands, gaseous losses through biological processes and losses through leaching are unavoidable, a more realistic target area for optimal NUE is about 70-90%, which has to be realised in a balance between increasing efficiency and avoiding soil degradation, as well as intensification vs. extensification (cf. Figure 4).

For pure cropping systems, NUE between 70-90% indicate balanced N fertilization. This forms the basis for healthy soil and optimal plant growth. Values above 90% indicate that more nitrogen is being extracted from the soil than can be replenished. Such a situation leads to soil degradation. NUE values above 90% thus represent a risk of soil mining, because N requirements for plant growth and unavoidable losses are not met by N inputs. Values below 70% NUE indicate excessive fertilization, and values below 50% indicate high risk of N losses (Brentrup & Palliere, 2010). Looking at mixed systems including livestock, the target values shift downwards to 30-60% for a balanced system, due to additional unavoidable losses from manure management and the livestock system as a whole.

As with N inputs and surplus or deficits, NUE needs to be assessed with due regional differentiation (cf. Figure 5, next page). NUE differs widely between regions and countries and also locally, due to diversity of crops, soils and climate, policy context, and also management and farmer's access to fertilizers technology and knowledge (Govindasamy et al., 2023; Norton et al., 2015).

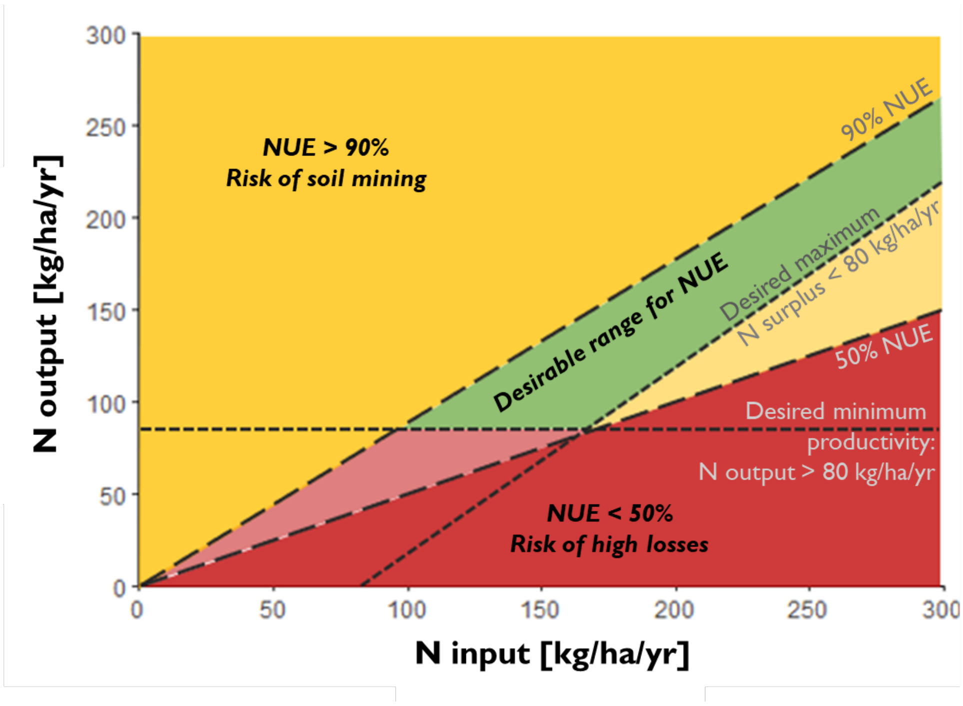

Figure 4: Conceptual framework for NUE, its optimal range and critical areas (figure by the authors, adapted from the EU Nitrogen Expert Panel, 2015)

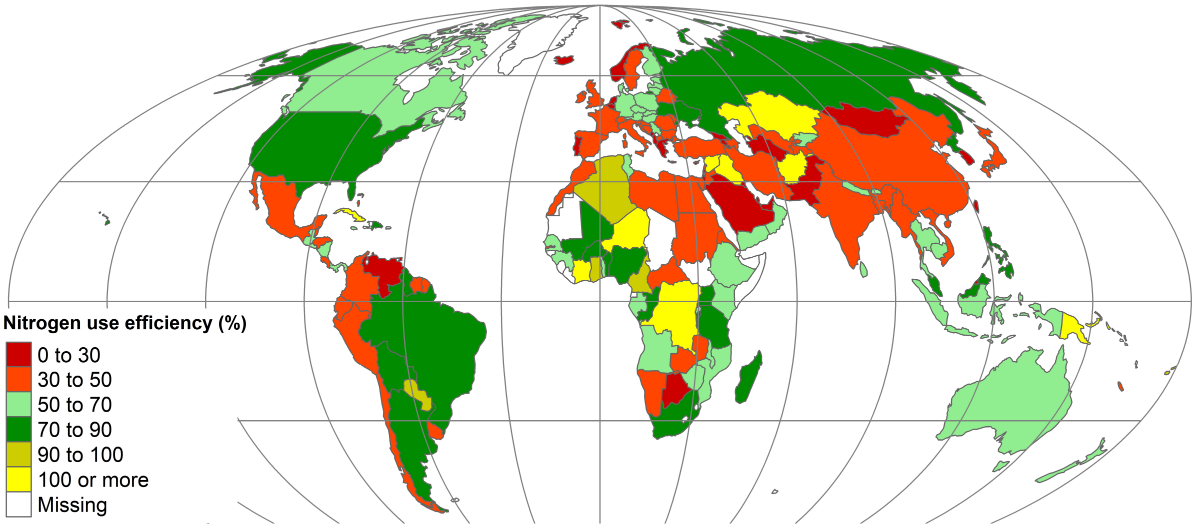

Figure 5: Cropland nitrogen use efficiency (in percent) for different countries (figure by the authors, based on data from Ludemann et al. 2023).

While many countries show low to very low NUE values, for example China, India, and many European countries, a number of countries especially in Africa show NUE values close to and higher than 100%. This means, that crops are taking up N from soils indicating soil mining (cf. Figure 5). There, a lack of efficiently using available biomass, avoiding nitrogen losses and closing nutrient cycles results in underexploiting the available potential. Additionally, the lack of purchasing power and infrastructure complicate access to fertilizers, which is further aggravated by the current tense situation on the international fertilizer market.

Improved use of available sources, in particular reducing losses and recycling waste nitrogen streams back to agriculture are the first measures to be taken, combined with a potential redesign of the production system to better fit the local production potential and characteristics. If mineral fertilizer is used in deficit situations, this should only be for an intermediate time and embedded in a long-term soil-fertility and nitrogen use strategy, to avoid lock in and dependencies from continuous mineral fertilizer use.

With increased N application, yield rises as well, as long as the plateau in the N-Y-response curve has not yet been reached (cf. Figure 1). However, keeping NUE on an efficient high level without soil depletion or soil N mining would mean that additional N needs to be administered properly according to fertilizer type, rate, time and place. Historical data has shown that countries in earlier stages of economic development tend to increase N application to achieve higher yields without paying due attention to also keeping NUE high. Thus, yields increase less than proportional to the fertilizer application rates. India and China are exemplary countries for this (Figure 6, next page).

Further economic development then often goes along with some "sustainable intensification", meaning that NUE starts to rise again in parallel with yields due to the adoption of improved fertilizer application and crop management practices, including the use of optimized plant protection and breeds. In some cases, higher yields are then even realized with lower N inputs. This is the situation for many developed countries, for example France or The Netherlands (Figure 6, next page).

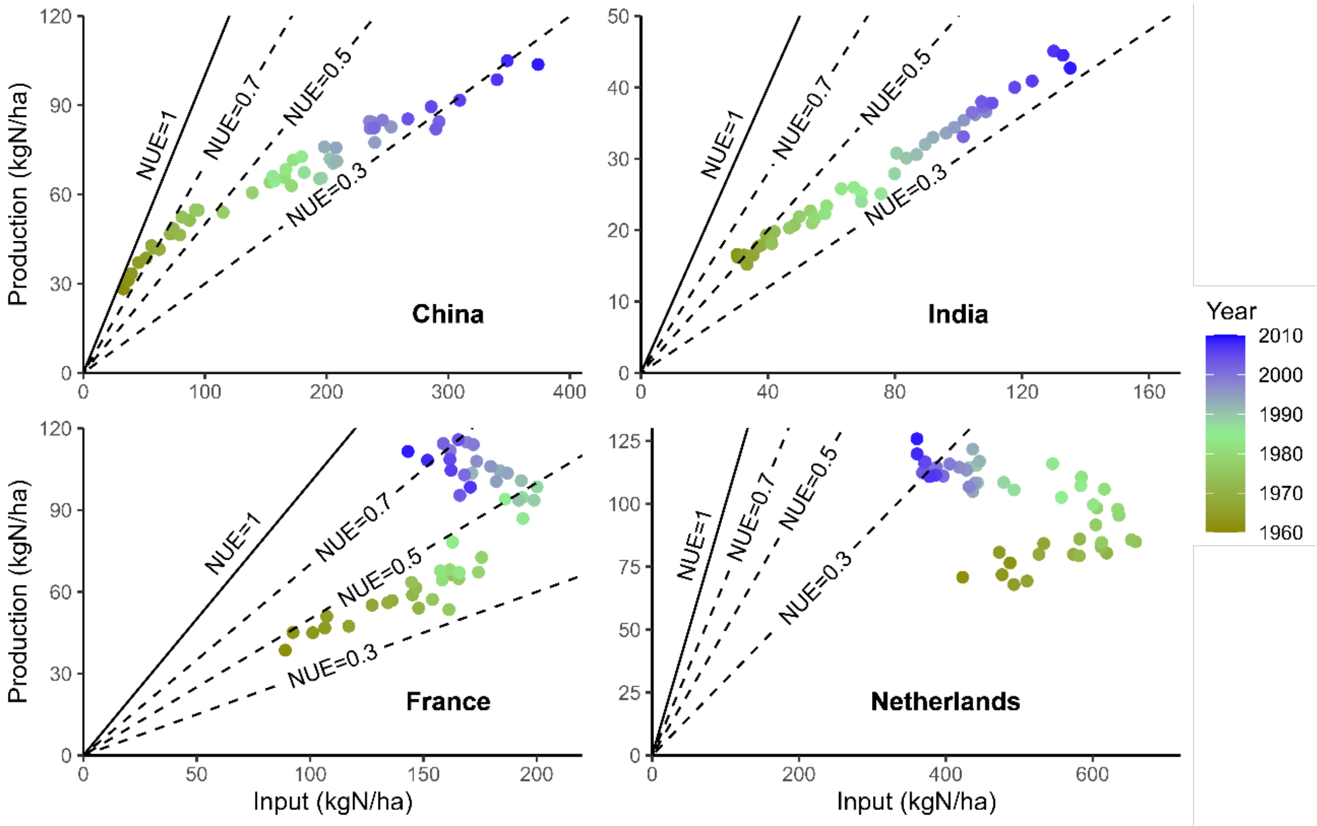

Figure 6: N-input-yield relation and NUE for the exemplary countries China, India, France and The Netherlands (in kilograms N per hectare; figure by the authors, based on data from Lassaletta et al. 2014)

When analyzing cropland NUE, it is important to emphasize that these are relative values only that do not allow for a statement on how much nitrogen may be lost to the environment in absolute terms. Low NUE tends to correlate with higher relative losses, but the absolute levels in total and per hectare may draw a different picture. The United States, for example, despite having an NUE of about 70%, due to the large total agricultural area and its intensive use rank third in terms of the global share of nitrogen losses (11%), behind China (33%) and India (18%) (West et al., 2014).

2.4 Full chain nitrogen use efficiency

A key indicator to capture the effectiveness of nitrogen use on a whole food systems level is the full chain NUE. It allows a holistic view of nutrient utilization throughout the entire value chain, considering inputs, outputs and losses at each stage. It measures the ratio of nitrogen in the final products for human consumption in relation to the nitrogen that entered the system. This goes beyond an assessment of how efficient N use is for a specific crop, as in the cropland NUE that accounts for the unavoidable gaseous losses and leaching. It also allows an assessment of how efficiently this N is used to produce food, thus accounting for losses from food waste and due to feed production for the livestock sector, which can actually happen with high crop-specific NUE.

This full chain NUE globally lies between only 5 to 15% (Erisman et al., 2008; UNEP, 2013). Key drivers of this very low overall efficiency are food waste and losses, the huge intensive cropland-based livestock sector, and untapped nutrient recycling potentials.

First, the quantities wasted and lost amount to about a third of the production globally (FAO, 2023c). The prime strategy is to avoid these losses as much as possible, and to recycle the nutrients contained in unavoidable losses to the highest extent possible. Second, livestock is very good at converting biomass, which humans cannot eat, such as byproducts, residues and waste, into valuable food. Livestock however becomes very inefficient in converting nitrogen inputs into nitrogen in food if animals are fed with human-edible biomass, such as grains or soy, or with biomass that is cropped on arable land, such as fodder maize, where crops for direct human consumption could be produced. The main reason is that the nutrient flow through the animal including manure extraction and management adds a huge source of nitrogen losses to the losses already present in crop production for feed or food. Finally, there are additional losses in the food system that arise due to lack of recycling certain nutrient flows back to the system, primarily the nitrogen contained in human faeces and urine (Harder et al., 2019; Theregowda et al., 2019). Potential health risks and sociocultural factors however pose considerable barriers to the use of these sources (Gwara et al., 2021). Avoiding these direct losses of nutrients at the end of the value chain would also help to improve the full chain NUE thus reducing the need to add new N_r for keeping a certain nutrient use level.

2.5 Mineral fertilizer markets and trade

The mineral fertilizer production industry operates under significant oligopoly, with four major companies covering two-thirds of market capitalization (CompaniesMarketCap, 2023). The current energy and climate crisis, compounded by factors such as the Russia-Ukraine war has led to record-high prices. In combination with the oligopolistic structure of the fertilizer industry, profits for the world's nine largest fertilizer companies increased more than threefold from 2020 to 2022, with the profit margin increasing from under 20% to 36% (IATP, 2023; NFU, 2022). Inequalities and unfair profits however also prevail in times of lower prices, as these companies are building their business on private profits from excessive mineral fertilizer production and trade, while the consequences of this, namely the costs of their overuse, are borne by society as a whole. Even more compelling, in many countries this business model is partly fuelled by governmental subsidies directly or indirectly reducing fertilizer input costs for producers – which again results in societies paying for the costs of these private profits.

Generally, fair pricing for mineral fertilizers and a corresponding reduction in demand and use would have beneficial effects for the environment in contexts of overuse and low NUE. However, it is crucial to consider the vulnerability of developing countries, particularly those in Sub-Saharan Africa, which rather face a scarce nutrient supply situation and are already prone to soil nitrogen mining. These countries often rely heavily on imported fertilizers, making them susceptible to transport cost increases, price fluctuations and supply disruptions in the global market. Reduced fertilizer supply can then result in yield decrease and drops in farm income and food production, and the situation of soil mining can be exacerbated if mineral fertilizers become unaffordable.

Finally, when talking about fertilizer markets, we also need to address the massive nitrogen flows through nitrogen embodied in feed and food commodities traded. These trade-flows also result in considerable transfers of reactive nitrogen between regions. In particular, the huge feed quantities imported to intensive livestock production regions such as many areas in the EU result in large nitrogen inputs, both in the form of BNF-based nitrogen in legumes such as soybeans and in mineral fertilizer-based cereals (Leip et al., 2022).

3. The costs of fertilizer use

The damages and societal costs of excessive nitrogen use arise in many places in our societies. There are the environmental damages and the related economic costs. But there are also health costs, and less tangible but not less relevant costs such as those related to losses in livelihoods and quality of life or to adverse effects of unequal market relations.

3.1 Damages and economic costs

Many of the negative impacts resulting from excessive fertilizer use are not immediately visible as costs to the producers, leading to externalization of damages and the lack of effective corrective measures for reducing fertilizer applications. Framed differently, the potential costs of lower yields due to applying too little N are much larger for the farmer than the potential costs of applying inefficiently high fertilizer quantities.

The damages from the massive fertilizer over-use and related losses to the environment are many and everywhere. Damages partly arise directly from fertilizer application or production, for example GHG-emissions, or from the current high throughput food system driven by mineral fertilizers, such as NH_3 emissions from the livestock sector with its adverse effects on air quality and ecosystems.

Impacts arise everywhere in the air, on the land and in soils, and in water bodies, and affect ecosystems and human health. In addition to GHG emissions, where N_2O not only contributes to climate change but also to stratospheric ozone depletion, nitrogen fertilizer (mineral fertilizers, but also manure) production, management and use also leads to the release of nitrogen oxides (NO_x) and ammonia (NH_3), with adverse effects on human health, including respiratory problems and increased mortality rates. These compounds can also contribute to the formation of fine particulate matter (PM) and photochemical smog, which can further harm human health (Paulot & Jacob, 2014). Deposition of N_r resulting from these emissions also has negative impacts on ecosystems, be it natural forests, grasslands, wetlands or even remote mountain regions, basically fertilizing ecosystems that have been adapted to much lower N_r availability with resulting changes in species composition, biodiversity and food webs (Simkin et al., 2016). Today, N_r deposition occurs almost everywhere and can show significant levels of N_r inputs also in remote areas (Tian et al., 2022). NO_x compounds also react with light and convert to ozone in the troposphere. This can decrease the photosynthetic ability of plants with corresponding adverse effect on their growth.

The overuse of N_r on soils can result in soil acidification with adverse effects on crop production. In addition, high N_r applications affect the soil microbiome and soil organisms in general, via toxic effects on some organism, and more systemic impacts on species composition and diversity, negatively affecting soil fertility. Generally, the oversupply of N_r in ecosystems results in losses of those species that are particularly adapted to lower availability levels. Finally, much of the excess nitrogen ends up in the groundwater and water bodies, impacting drinking water quality and resulting in eutrophication with related negative impacts on biodiversity in these ecosystems. Algae blooms and the formation of dead zones are frequent consequences when too many nutrients accumulate from larger watersheds, as for example in the Baltic Sea or in the Gulf of Mexico downstream from the Mississippi, and the rate of their occurrence increases (Altieri & Diaz, 2019, cf. Figure 7, next page).

All of these damages are accompanied by huge economic costs. The global costs associated with all forms of nitrogen pollution are estimated to range from \$200 to \$2 trillion USD annually. An important factor is always pollution-related health costs, be it from water or air pollution. In Europe, the costs of N_r-related air pollution account for over 50% of estimated social costs of total N_r pollution, equaling about one to four percent of GDP (Sutton 2013). These costs reflect the damage caused by poor management practices and inefficient application of nitrogen fertilizers. In developed nations, several hundred billion USD of financial losses can thus be attributed to the excessive use of nitrogen, which hampers economic growth and sustainability.

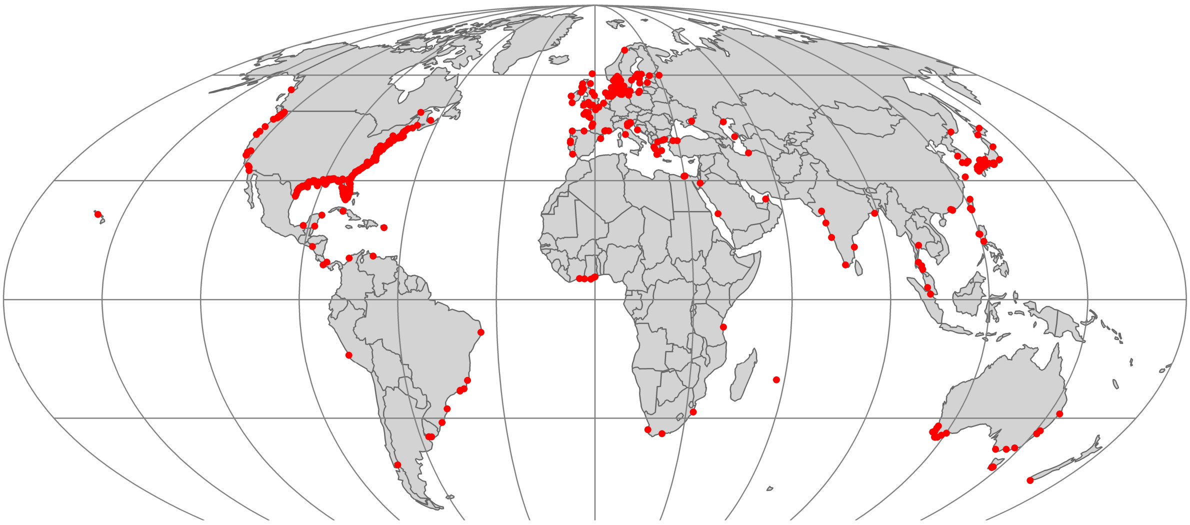

Figure 7: Global distribution of dead zones (red dots/areas; figure by the authors, based on data from Altieri et al., 2017 and Diaz et al., 2011). Antarctica is not displayed, as there are no dead zones reported for this region.

Further costs of current lifestyles can also ultimately be attributed to excessive nitrogen use, namely those related to food waste and high animal-sourced product consumption. Current food systems with high shares in both waste and animal products are only possible because of mineral fertilizers. Food waste is estimated to cost 2.6 trillion USD globally, including costs of waste disposal and landfills, water pollution, GHG emissions and also social costs (FAO, 2014). The high consumption of animal-sourced products in industrialised countries correlates with a number of adverse health effects, such as many noncommunicable diseases, and their related health costs.

Lastly, the material losses in nutrients applied ineffectively amount to huge numbers. Assuming a nominal fertilizer price of 1 US dollar per kilogram of N (Sutton et al., 2019), the total global N surplus of 120 million tonnes N corresponds to losses of 120 billion US dollars. Depending on the development of fertilizer prices, this amount can correspondingly be much higher.

3.2 Societal burdens of excessive nitrogen use and pollution

The previous section illustrates the huge damages and economic costs that arise due to excessive nitrogen use. Not included but equally relevant are much less tangible costs such as reduced quality of life due to polluted drinking water that may lead to diseases or increases the effort to reach clean sources. Similarly, such less tangible costs can accrue due to losses in traditional livelihood bases or recreational value and the like, which, albeit rarely monetized, should never be neglected when listing the impacts of our current fertilizer overuse.

The domination of global food production using mineral fertilizer imposes unnecessary social burdens. Moreover, this dominance results in limited crop variety, dictated by breeds capable of efficiently utilizing high N inputs like wheat, maize, and rice, thereby reducing both crop diversity and nutrient uptake options.

The current mineral fertilizer and fossil fuel-based agricultural production and related globalised agricultural commodity markets also result in many strong dependencies. Producers, in particular smallholders in the global south, but also whole countries, are dependent on a few companies and countries for mineral fertilizers and whole packages of fertilizer, seed and plant protection for producers, and also for food and feed commodities.

These dependencies from external inputs increase the production risk for many producers and the risk for food insecurity for whole countries. Price increases, such as observed in the current times of the Russia-Ukraine-war, can quickly result in lack of financial resources to buy sufficient amount of inputs, viz. fertilizers, or food commodities, with corresponding consequences for the producers' livelihoods and the food security of the populations.

4. Current initiatives

Much action is currently being taken to address the nitrogen surplus and many international and also national initiatives claim to contribute to this. Below, we shortly refer a few of these. Regrettably, they do not deliver what they promise, largely being rooted in the intensification paradigm and business-as-usual narrative of agriculture and food systems, thus working on increasing efficiency, which is laudable, but not addressing the big leverage points that need to be used for truly achieve sustainable changes and transformation.

Agriculture Innovation Mission for Climate (AIM for Climate)

The launch of the Agriculture Innovation Mission for Climate AIM4C (AIM4C, 2023) took place in 2021 during the COP26 conference, led by the United States and the United Arab Emirates. AIM4C's primary goal is to promote and expedite agricultural innovation, specifically in the field of Climate-Smart Agriculture (CSA), through increased investment in this area. Currently, the initiative has already amassed over $13 billion in funding. CSA serves as an agricultural approach that seeks to address the challenges presented by climate change while simultaneously ensuring food security, enhancing resilience, and reducing greenhouse gas (GHG) emissions. It involves the integration of climate change adaptation, mitigation, and sustainable agricultural practices.

Critics argue that the Innovation Sprints, which are self-funded investments, are predominantly a form of greenwashing disguised as Climate-Smart Agriculture. Specifically, they claim that these initiatives neglect promising agroecological approaches and basically cement business as usual agriculture with its productivity and intensification narrative (IATP, 2022).

Global Fertilizer Challenge

The vulnerabilities of the global food system have become evident due to various factors, including events like the Russia-Ukraine war, climate-related impacts, and the increasing costs of food and fertilizers. In response, President Biden launched the Global Fertilizer Challenge initiative (USDA, 2023), aiming to secure $100 million in new funding by COP 27 to enhance the system's resilience against such shocks. This initiative focuses on supporting innovative research, demonstrations, and training programs to assist countries with high fertilizer usage and losses in adopting efficient nutrient management practices, alternative fertilizers, and cropping systems. By achieving higher Nutrient Use Efficiency (NUE), there will be a reduction in inputs such as natural gas and fertilizers, leading to decreased dependencies and improved food security. Remarkably, the initiative has surpassed its initial goal, raising $135 million for fertilizer efficiency and soil health programs to address fertilizer shortages and combat food insecurity. Triggered by this success, philanthropy and investors committed to fund additional $20 million for improving fertilizer production and use (Climateworks, 2022). How it performs in the field and which practices and agricultural systems it supports in the end are yet to be seen. However, critics point out that the initiative is also largely focusing on efficiency increases and a narrative of sustainable intensification, thus not contributing to the thorough transformation of the food system needed (Drugmand, 2022).

African Union Fertilizer and Soil Health Action Plan and the African Soil Initiative (AFSH/ASI)

Agriculture in Africa is confronted with various obstacles that hinder its progress and impede regional food security. Recent armed conflicts, such as the Russia-Ukraine war, have had a profound impact on fertilizer and food prices (Glauber & Laborde Debucquet, 2023). This has particularly affected smallholder farms, which are prevalent in Africa and tend to be most vulnerable to price fluctuations. Consequently, when prices rise, there is a decrease in demand for fertilizers, leading to nutrient depletion and soil degradation, ultimately resulting in diminished crop yields. Furthermore, the volatility of food prices, coupled with inadequate affordability and accessibility, further weakens Africa's food security in view of a rising population.

To address these challenges and enhance food security, the AFSH/ASI initiatives (FARA, 2023) focus on promoting locally-led food systems and improving access to agricultural inputs, such as fertilizers and seeds, as well as focusing on building up and conserving soil fertility. Additionally, investments will be made to boost continental fertilizer production capacity, thereby reducing reliance on external sources and enhancing self-sufficiency. An important aspect of ensuring optimal nutrient utilization and minimizing losses involves educating and exchanging knowledge about agricultural management practices that improve soil health and enhance agricultural productivity.

These initiatives have a clear production focus, but given the context of often scarce N supply resulting in soil mining and degradation rather than N surplus in Africa, such an approach is warranted. Reduction of N use is not a primary goal in many regions, nevertheless such initiatives should aim to avoid following the same route as industrialised agriculture by depending on mineral fertilizer supply, and focus instead on optimising NUE and closing nutrient cycles as much as possible, as well as sourcing new N_r via legumes in crop rotations.

Colombo Declaration

The "Sustainable Nitrogen Management Resolution" (adopted at UN Environment Assembly UNEA 4 in 2019 and supplemented at UNEA 5 in 2021) recognizes the multiple environmental impacts caused by anthropogenic N_r creation and pollution and calls for better coordination of national policies across the global nitrogen cycle. The UNEP established the Nitrogen Working Group (NWG) to facilitate the implementation of the resolutions (cf. Interconvention Nitrogen Coordination Mechanism INCOM) and assigned the International Nitrogen Management System INMS to draw an International Nitrogen Assessment. The results will be published prior to the UNEA-6 in 2024 (UNEP, 2022).

In 2019, UN member states launched the campaign on Sustainable Nitrogen Management 'Nitrogen for Life' and endorsed a proposed roadmap for action on nitrogen challenges called the Colombo Declaration. The goal is to halve nitrogen waste by 2030 and promote innovation for a circular nitrogen economy (INMS, 2019).

Whereas the prior resolutions lack any quantitative and binding goals, the Colombo Declaration has such a clear quantitative goal, although it is also not binding. It is thus rather a declaration of intent. Currently, it has only been signed by 15 countries. However, the new global goal has already led to adoptions such as the European Commission adding the goal to "reduce nutrient pollution by 50% by 2030" to the Green Deal (Sutton, 2021). The UNEA-6 in 2024 will be a crucial moment for putting more pressure on the implementation of a global Sustainable Nitrogen Management strategy, however, nothing binding is expected from this.

China

China has implemented several policy initiatives aimed at reducing nitrogen fertilizer use and improving nitrogen use efficiency in agriculture. One key initiative is the Zero-Growth Fertilizer Use Policy (van Wesenbeeck et al., 2021), which seeks to control the overuse of fertilizers and achieve a balance between nutrient supply and crop demand. This policy set a target of zero-growth in fertilizer use by 2020, encouraging farmers to adopt more precise and efficient fertilizer application practices. According to China's Ministry of Agriculture the use of chemical fertilizers has witnessed negative growth, and the goal of zero growth by 2020 has been achieved three years ahead of schedule. As next step, China will continue to reduce fertilizer use and increase efficiency, in accordance with the green agriculture initiative of General Secretary Xi Jinping. However, even significant reduction of nutrient surpluses due to increased use of organic manure and promotion of the recycling of crop residues will not lead to a major breakthrough in curbing the negative environmental trend, for which more drastic changes are necessary (van Wesenbeeck et al., 2021).

In 2021 the Chinese government revealed its 14th Five-Year National Agricultural Green Development Plant issued by different departments and defined key goals to be achieved by 2025. Namely, reduction of chemical fertilizer use, increased application efficiency and improved utilization of agricultural waste, and curbing agricultural pollution. Furthermore, the implementation of soil improvement and fertility programs meant to counteract the acidification of arable land (USDA, 2021).

5. Solutions

Before focusing on solutions to the challenges related to N_r production and use, some general statements have to be made. First, the problem is long-known, and while research results related to it and measures to act towards solutions are available, implementation is lacking (GNA, 2012; NFU, 2022). The goal on global level is clear, namely to at least halve the global nitrogen surplus to stay within planetary boundaries (Schulte-Uebbing et al., 2022). This also means that incremental improvements will not suffice and a thorough transformation of agriculture and the food system is needed to tackle the nitrogen problem. The path to achieve implementation of the needed solutions, however, is complex and still not clearly defined (NFU, 2022).

Second, in this context of known problems and solutions but unknown concrete routes for action, the policy recommendations often remain rather general, partly building on the good will of key actors, such as fertilizer companies, seed and feed traders, chemical companies, big retailers, farmers unions, policy makers, etc., to work towards solutions (Dobermann et al., 2022; Galloway et al., 2021; Houlton et al., 2019; Kanter et al., 2020). Given this historic and current deadlock, we may assume that this good will is lacking. Thus, before we can have any hope for at least small steps towards solutions, we need to see that key players are truly willing to contribute to solutions. Given that the most promising solutions are all related to a reduction of the production, the inputs and the throughput of nutrients in the food system (cf. below), we need commitments from the key actors to work towards reduction of the quantities that are at the core of their current business models: fertilizer, feed, and livestock product quantities. Unless key players offer credible strategies for such reductions, the problems related to nitrogen use will not be resolved.

Third, regionally differentiated solutions are key. The global issue of massive nitrogen oversupply plays out very differently in different regions. In Sub-Saharan Africa, there is a lack of access to nitrogen, leading to nitrogen mining. In India, rising prosperity coupled with population growth has resulted in wasteful nitrogen usage. Meanwhile, in affluent regions like Europe, the USA, and soon China and other emerging nations, the increasing demand for animal products has led to inefficient utilization of valuable agricultural resources (Galloway et al., 2021). The nitrogen problem has evolved into a global challenge with regional ramifications of very different kinds. Under a global requirement of massive reductions of total nitrogen use, partly, what is too much in some regions must be redistributed to where it is rather lacking.

To present inputs for solutions in this context, we first try to establish some common ground on which all actors may be able to agree to, and then we address some general characteristics of solutions.

5.1 A common ground for solutions

The first requirement for any solution to the nitrogen problem is its contribution to food security. It has to be clear that food security is not endangered by any such action. Given the low cropland and value chain NUE values and large surpluses in many countries, there is ample room in current food systems for reducing N use while not endangering food security. In other contexts, where soil mining may instead be the challenge, optimized nutrient recycling and closing nutrient cycles, partly even increased use of optimal nutrient sources, rather than use reduction are the priority. In any case, the narrative to which all players may agree is one of sustainable food security, as this is the main goal for stakeholders. Sometimes, the discourse on N use reduction may not enough take into account the fear that food security could be endangered and critics of mineral fertilizer use reduction have an easy task in presenting themselves as the only players truly interested in food security.

Similarly, there are the livelihoods of farmers, which also need to take center stage in the debates. Often, these debates have an environmental focus and lack sensitivity to what a reduction in N use may mean for farmers. As with food security, there is ample room for improvements regarding NUE and N surplus without endangering decent livelihoods, but how this is achieved has to be a central part of any solution strategy. Solutions that increase circularity by reducing waste and cropland-based animal numbers, for example, are only possible with huge changes, including that certain production operations such as pig fattening are possible only at a much lower scale in the future. Thus, paying attention to farmers' livelihoods means that it is attempted to take all stakeholders along, that their reservations are taken seriously and alternatives are credibly developed and offered, all without compromising on the environmental goals that need to be achieved.

Thirdly, such stakeholder-focus also applies to potential effects of nitrogen reduction policies on food prices, which may particularly negatively affect the poor. Any proposal has to credibly show how this may be avoided.

Reducing N use will hardly become a common goal among all stakeholders, but ensuring food security in a sustainable way may well be so for most stakeholders besides some hard-nosed business players, for example. On the ground of such a common narrative, commonly acceptable solutions may then be developed more easily.

Fourth, it is clear that N use leads to huge private profits among few players and large external costs borne by societies. Because of this discrepancy, it can clearly be argued for policies to internalize these external costs, as otherwise, the true costs of nitrogen fertilizer production and use are not adequately considered in decision-making processes. Furthermore, the fact that only a few companies dominate the fertilizer market in an oligopolistic structure should be addressed.

The currently relative low price of fertilizers has in particular to be seen in relation to the crop price. In many countries, the fertilizer to crop price ratio is very low. This results in large opportunity costs of using less fertilizer with the risk of lower yields, while using excessive fertilizer quantities to ensure higher yields comes with relatively low private costs, thus setting incentives for overuse. In consequence, there is then also some positive correlation between higher fertilizer to crop price ratios and higher cropland NUE, as wasting mineral fertilizers via overuse becomes more costly the higher its price is in relation to the price gained from the final agricultural product produced with it (Zhang et al. 2015).

5.2 Central characteristics of solutions

When talking about the characteristics of solutions, we can clearly state that many are realistic. Despite the lack of progress in N surplus regulation and the worsening environmental situation, there are technical and institutional solutions for the nitrogen problem. Several studies have shown that it is possible to maintain or even improve yield levels with reduced N application or lower losses due to improved NUE (see for example Anas et al., 2020; Cui et al., 2018; Mueller et al., 2012). Cost-effective agronomic mitigation measures of N pollution from global croplands can increase overall crop yield by 10-30% and NUE by 10-80% while at the same time reducing nitrogen pollution in the environment by 30-70%. Implementing these measures has the potential to generate substantial global societal benefits, estimated at approximately 480 billion US dollars, spanning crucial areas such as food supply, human health, ecosystems, and climate (Gu et al., 2023). Numerous national governments possess a remarkable potential to significantly curtail global nitrogen pollution without needing to compromise substantial agricultural production. On a broader scale, countries which manage to produce 35% less nitrogen pollution than their neighbouring nations only exhibit a mere 1% greater yield gap, indicating the minimal impact of N use on achievable vs. actual yields in these cases (Wuepper et al., 2020).

There are also many promising case study countries that show some beneficial development, albeit not yet to the extent needed. Nevertheless, such cases can serve as beacons of hope for other countries that commit to tackle the nitrogen problem. Much literature exists concerning the performance of countries regarding NUE, N surplus, fertilizer-crop-price ration, etc. (Galloway et al., 2021; Zhang et al., 2015), which all can serve as a basis for other countries to identify similar cases and to mutually learn about what may work and what may not. The Netherlands is an example of considerable improvements since 1990, when they reported huge surplus levels of almost 330 kgN/ha that have since been reduced to still too high levels of almost 200 kgN/ha in recent years (Galloway et al., 2021; OECD, 2023). Progress has stopped, however, with increasing opposition towards any further N reduction (Boztas, 2023). Sikkim and Andhra Pradesh in India may be promising examples of natural farming with lower N use (Dorin, 2022). Other cases, such as Sri Lanka, who failed in converting to organic agriculture due to a very badly designed process without due support and training of farmers and adequate conversion period (Torrella, 2021), or Switzerland, where a vote for a basically organic production system did not pass (swissinfo, 2021), provide ample real world experience on how and how not to approach the nitrogen problem.

A second characteristic of solutions is that there is no one-size-fits-all approach. Country-specific and regionally differentiated solutions are required, accounting for the respective pedo-climatic, agronomic, economic, cultural and policy contexts. A key differentiation is between situations of nitrogen overuse and deficit or very high and low cropland NUE. Furthermore, full chain NUE also differentiates countries with high and low values. Depending on these characteristics, solutions may look very different.

5.3 Guidelines for solutions

There are many suggestions and compilations for solutions to address the nitrogen challenge we are facing (see for example Sutton et al., 2022; Kanter et al. 2020, Table 1; Galloway et al. 2021, section 6.3; Houlton et al. 2019, Table 1; Dobermann et al. 2022). We do not want to repeat those, and given the need for locally adapted solutions, any country or region seriously attempting to develop solutions should anyway first refer to this and other more specific literature in detail and in direct relation to the case at hand to learn what may be used as a basis for practicable solutions. Thus, we rather focus on a number of guiding principles that capture the big leverage points of solutions and allow them to be grouped.

First, the farmers need to know what happens on their fields (Galloway et al., 2021; Zhang et al., 2015). The farmers' decisions most directly influence how much N_r may be lost to the environment and which economic and societal costs this may entail. Thus, assuring their best knowledge of the situation in the field, regarding N requirements and availability is a central step towards increased cropland NUE and thus reduced losses. The Netherlands can serve as a case study for such monitoring that evidently has been successful in reducing use, albeit from very high to high levels only, and not yet reaching anything compatible with ecosystem boundaries (Galloway et al., 2021). Farmers often have access to relatively cheap fertilizers but only limited nitrogen management knowledge. Being rather risk-averse towards yield losses this easily results in fertilizer over-use in order to be on the safe side and hedge against production losses. This can be improved by adequate training and advisory services on optimal fertilizer application and minimizing nitrogen losses, but also on precision farming and agroecological techniques. The former aims at reducing mineral fertilizer quantities by optimising their use, the latter aims at replacing mineral with organic fertilizers that are based on recycling organic waste as a nutrient input rather than producing new N_r. Important also are the encouragement of soil health improvement measures, such as optimised tillage, organic fertilizers and amendments, cover cropping, improved crop rotations, and the use of nitrogen-fixing crops. These strategies enhance the capacity of soils to retain and utilize nitrogen effectively, which is key particularly in contexts of nitrogen scarcity with the danger of soil mining.

Such changes always involve a certain risk and uncertainty. Risk aversion due to limited resources often leads to a conservative attitude. With collective cooperation among farmers, their market power is strengthened and the focus lies on economic margin maximization rather than yield maximization. This can create more freedom and less aversion towards the adaption of new practices (NFU, 2022). Good information provision, training and advisory services can help to proceed quite far in this direction.

Second, it is central to get the prices right and to work towards full or true cost accounting (TCA). On the one hand, this means internalizing external costs through appropriate policies, such as an environmental tax on the creation of new reactive nitrogen to account for its negative externalities. On the other hand, this means abandoning flawed subsidies, such as for mineral fertilizers in contexts of oversupply, which are in place in many countries. Currently, a significant portion of public financial support for fertilizer use flows into a few hands of the private sector, such as mineral fertilizer producers, or is used to cover the social and environmental costs resulting from excessive N use. Instead, these financial investments should be directed towards improving cropland NUE. India for instance, spent about 7 billion US$ in 2016 for fertilizer subsidies, causing N losses of 10 billion US$ and an estimated 75 billion US dollars in costs to health, ecosystems and in climate change (Sutton et al., 2017). With estimated full chain NUE of just about 20%, the government should at first use public funds to increase NUE.

Thus, a promising approach involves providing farmers with alternative and long-term support through capital securities and investments, enabling a successful and safe transition towards sustainable nitrogen use. The concept of cross-compliances, which combines mandatory regulations and voluntary incentives, offers promising possibilities in achieving these goals (Kanter et al., 2020).

Particularly in regions where low wages and aversion to yield-reducing risk prevail, financial incentives play a pivotal role in promoting sustainable nitrogen use on farms. By offering financial security and support for the adoption of circular nitrogen practices and by rewarding improved NUE and soil health, positive changes can be triggered with the potential to spill over into various aspects of agricultural sustainability. Optimally designed insurances for compensation payments in case yields drop below a certain level can also support farmers' efforts to reduce nitrogen use, as such insurances would help to replace excessive nitrogen use as a strategy to hedge against possible yield losses.

A caveat with "getting the prices right" is the potential danger to the poor in the form of increasing food prices. Clearly, measures to hedge against this need to be in place. In richer countries, however, this is a minor share of the population and it is legitimate to demand from the majority to pay for the external costs of their consumption. Finally, it is far from clear how exactly nitrogen reduction policies and internalization of external costs of mineral fertilizer use affect food prices. If implemented via NUE increases, higher fertilizer prices may be compensated by lower use, without affecting yields and food prices.

Third, circularity needs to increase on all levels. Food losses and waste need to be reduced, nutrient cycles need to be closed as much as possible and providing animals with feed that could be eaten by humans directly or is sourced from croplands, where food for direct human consumption could be grown must be reduced (Dobermann et al., 2022). In intensive production contexts, this means making the food system smaller in nutrient inputs, outputs and throughput. This leads to improvements, as it reduces new reactive nitrogen input use and thus losses, and increases cropland NUE as well as full chain NUE. For the latter, the only viable approach to achieve optimal full-chain NUE in animal production is to have a system based on feed that is not competing with human food such as grass and by-products that are unsuitable for human nutrition. Such livestock production would produce much less animal-sourced food than it does currently, thus necessitating drastic dietary changes in high-income countries with high shares of animal protein in diets, but it would be far more resource-efficient and free huge feed crop areas and the related fertilizers and other inputs for direct human food production (Schader et al., 2015). Furthermore, it would require striking changes in the business models of several key players, as the basis for their business, namely fertilizer, feed and livestock product quantities, would need to be highly reduced. Framed differently, this also means that certain value chains need to disappear or be drastically reduced in volumes.

Furthermore, increasing full chain NUE encompasses reusing hitherto largely untapped sources of N_r, such as human faeces and urine. Currently, these are treated in sewage plants, with the goal to release as few N_r to the environment as possible, which partly means recovery of N_r for reuse as fertilizers. Mainly, however, it rather means conversion to non-reactive forms. This is beneficial to the environment, but very inefficient from a nutrient use point of view as the original generation of this N_r already consumed high amounts of energy and natural gas. Hence, a focus should be on increasing N_r recovery rates in sewage plants, thereby clearly duly accounting for the barriers that this faces due to potential health risks and sociocultural factors.

Closing nutrient cycles and reducing losses is in particular relevant also in contexts of soil mining, to avoid ever-increasing dependence on mineral fertilizers as the only nutrient sources. Optimized crop rotations with legumes that focus on building soil fertility contribute importantly to this – which again links back to the importance of a good knowledge basis for the nitrogen problem as relevant for their fields among the farmers.

Importantly, for supporting and triggering these changes, a political space for transformation needs to be created. This again strongly links to citizens' actions' and clear signals from civil society calling for intervention in markets. The responsibility to implement solutions does not only rest on farmers, business players and policy, but citizens also have to actively contribute.

One promising solution to address part of the reactive nitrogen surplus lies outside agriculture, namely in reducing NO_x from fuel combustion in industry installations, power plants and transport. This is a waste product, where no players have stakes regarding having built a business on its use. However, reducing it is costly, thus triggering opposition. An inspiring example on how to deal with this is Sweden, which managed to introduce a tax-refund-scheme for reducing these emissions (thereby, all emitters pay a tax on NO_x and get it refunded in relation to their relative efficiency of NO_x per kWh power or heat generated in comparison to all other plants), with considerable success (Bonilla et al., 2015).

Finally, we close with highlighting an approach that is often promoted but that does not help to resolve the nitrogen surplus: that is any approach that proposes to add new N_r with fewer production impacts ("green fertilizers", produced with renewable energy). These strategies are often promoted as sustainable solutions by the fertilizer industry, but will not solve the problem of nitrogen surplus. As long as the quantities applied remain the same, they will have the same adverse impacts on waterbodies, landscapes and ecosystems, irrespective of how they have been produced. As good as it may be for climate change mitigation, it will be ineffective in tackling the N surplus. Thus, any strategies of decarbonisation, clearly important for GHG emission reductions, do not contribute to addressing the N problem. In this view, the "American-Made Fertilizer Production" (USDA, 2022) for example, providing US$ 500 Million towards innovations in US fertilizer production will not be relevant for reducing N overuse.

6. Conclusions

For conclusion, we start with three narratives that need to change.

First, the narrative that less nitrogen use generally endangers yields and food security is wrong. Globally, in a context of a wasteful use of valuable nutrients with low nutrient use efficiency, high nutrient surplus, large shares of animal-sourced products in diets and huge amounts of food waste and losses, we can still go a long way in nitrogen use reduction without endangering food security. Clearly, this is different in regions of high NUE prone to soil mining, where reductions are not the primary focus but rather recycling and avoiding losses, but it applies to the regions where actions are most required. Besides increasing NUE, this also encompasses the system level changes of reduced cropland use for animal production with corresponding much lower animal numbers and animal-sourced products in diets, as well as the reduction of food waste and losses.

Second, the narrative that industry and business in general want to contribute to solve the problem is wrong. The key players related to the nitrogen challenge need to develop business models that work with much less nitrogen production, throughput, trade and consumption. This is central for the required food system level changes that largely coincide with much smaller food systems regarding nitrogen requirements and throughput. This primarily affects the generation of new reactive nitrogen for mineral fertilizers, but also the new reactive nitrogen from biological nitrogen fixation in soybeans for feed. Without business models for such drastically reduced nitrogen use, solutions will never be implemented. This is the situation today, where the problem and the solutions have been known for decades, but their implementation and the whole political debate around nitrogen makes little and insufficient progress only. Thus, as long as no credible signals from key business players are visible to seriously address the nitrogen challenge, for example credible business plans for halving nitrogen use by 2030, many efforts to achieve some improvements will be a waste of time.

Third, the narrative of technological fixes being central for solutions needs to be overcome. To a certain extent, technological solutions contribute to solving the problem. They can, for example, help to increase NUE when optimising fertilization applications, as done in precision farming. However, the leverage of such technical solutions will never reach the level required to solve the problem. This leverage will also remain far below of what is possible with full system level changes such as reductions of cropland-based feed and animal numbers, as well as food waste and losses. In particular, technology will not contribute to solutions in the context of decarbonisation of the economy, for example via producing mineral fertilizers from renewable energy sources. This contributes to reduce GHG emissions, but it does not reduce new N_r inputs and it thus does not contribute to address the general nitrogen oversupply. Nevertheless, due credit has to be given to the potential of digital technologies for crop diagnostic, climate prediction and the like within farmer education, advisory services and capacity building.

We are somewhat more optimistic when talking about some strategies that can be pursued in any case, already now.

First, information provision, education and training in optimal nutrient use are still needed in many contexts and could be provided relatively easily. In many contexts, NUE can be significantly increased and nitrogen surplus reduced without yield losses.

Second, getting the prices right is of paramount importance. This applies both to internalisation of external costs of nitrogen use and also to abandoning flawed subsidies for nitrogen inputs. Implementing this will, however, be much harder and depends on the political will to do so and the cooperation of key business players and stakeholders.

Third, as mentioned above, technological solutions have a role to play albeit not a game-changing one. They are, for example, important for closing nutrient cycles via reducing losses, such as recycling human faeces and urine for use in agriculture. There, in particular, however, sociocultural factors that may pose barriers to its use are also central. Furthermore, technology is also key in reducing N_r-emissions from fuel combustion in power plants, industry energy operations and transport, although this affects a minor part of new N_r only.

The challenge is huge, but the scientific basis of knowledge is large and robust and solutions are known. We now need to get down to action. Good plans as formulated in many international initiatives are not enough – we need to see concrete results. So, who of those who have the power to change something will make the first step?

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