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RESEARCH BRIEF

A sustainability-oriented research and innovation agenda for nitrogen in the food system

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CONTENTS

Executive summary ... **1**

1. Introduction ... **4**
2. Objective and approach ... **7**
3. Principles for sustainability-oriented nitrogen research ... **8**

3.1 Adopt a food systems approach ... 8

3.2 Account for a broad range of sustainability outcomes ... 9

3.3 Promote inter-and transdisciplinary research ... 9

3.4 Require open science ... 10

3.5 Focus public research funding on public benefit ... 10

4. Research priorities ... **11**

4.1 Develop and evaluate solutions for nitrogen in the food system ... 11

4.2 Refine methods to assess impacts of nitrogen pollution ... 15

4.3 Expand and improve datasets on nitrogen in the food system ... 16

4.4 Develop future scenarios and assess policy options ... 19

5. Conclusion ... **23**
6. References ... **24**

EXECUTIVE SUMMARY

Nitrogen plays a dual role in food systems. On the one hand, nitrogen is an essential nutrient for all life forms and a key driver of productivity in agriculture. On the other, agriculture unavoidably emits nitrogen pollutants – ammonia (NH_3), nitrous oxide (N_2O), nitrogen oxides (NO_x), and nitrate (NO_3^-) – which are major contributors to negative environmental and health impacts, including climate change, toxic air pollution, and biodiversity-harming eutrophication of land and water ecosystems. Nitrogen is therefore central to many interconnected challenges in the food system, concerning also productivity and the economic viability of farms. Balancing the benefits and costs of nitrogen is therefore one of the most pressing sustainability challenges for the global food system.

Large reductions in nitrogen emissions from food systems are possible through a combination of agricultural efficiency improvements, waste reduction, and dietary shifts. Together, these approaches could potentially meet the ambitious reduction targets set globally and in the EU.

This brief presents a research agenda proposing a slight shift in focus, from the biological and physical solutions to the wider system implications of the solutions and barriers to systemic change. The main nitrogen problem is arguably not a lack of solutions but rather a failure to implement them at scale in ways that are both effective and socially acceptable.

Food systems science and policy are complex and impact everyone globally. To enable a wide range of stakeholders and decision-makers to engage meaningfully in these complex matters, researchers (agronomists, ecologists, economists, and political and behavioural scientists) must engage in interdisciplinary and transdisciplinary collaboration to produce policy-relevant information accessible to all. In this sense, research could play a larger role as an honest broker of policy alternatives, helping societies make informed decisions about difficult trade-offs under the scientific uncertainty that remains.

This brief presents 18 recommendations, five setting out overarching principles and the remaining 13 identifying research priorities grouped in four broad research areas. Given the strong connections to other issues in food system research, recommendations should be seen within the wider scope of food system sustainability. In short, the recommendations are as follows:

- **Adopt principles for sustainability-oriented nitrogen research.** Take a food systems approach, accounting for a broad range of sustainability outcomes and trade-offs and co-benefits between them. Promote inter-and transdisciplinary research that produces comprehensive yet accessible knowledge for public benefit.

- **Develop and evaluate solutions for nitrogen in the food system.** There is a continued need for both fundamental and applied research on options for nitrogen management in food systems. The largest potential for change is in agriculture. Key scientific challenges are to improve the understanding of how i) soil nitrogen inputs are used and transformed in soil-plant systems, ii) agro-ecological and ecological intensification practices quantitatively affect multiple costs and benefits, iii) coupled crop-livestock systems can be shaped at farm and landscape level for improved sustainability outcomes, and iv) interacting carbon and nitrogen cycles can be managed in carbon farming. Further, there is a need to improve economic cost estimates for all available solutions and to rigorously compare solutions and synthesize information about them in an open, accessible, and policy-relevant form.

- **Refine methods to assess impacts of nitrogen pollution.** The effects of nitrogen emissions on the environment are numerous and varied, due to the complex biogeochemistry of nitrogen, combined with variations in environmental conditions and population exposure. Although much is already known about the aggregate impacts of nitrogen emissions on the environment and human health, there is a continued need for research to improve the quantification of marginal nitrogen emissions, depending on place, time, and chemical form. In addition, it is essential to develop an improved understanding of environmental accumulation of nitrogen and so-called legacy effects that play out over time.

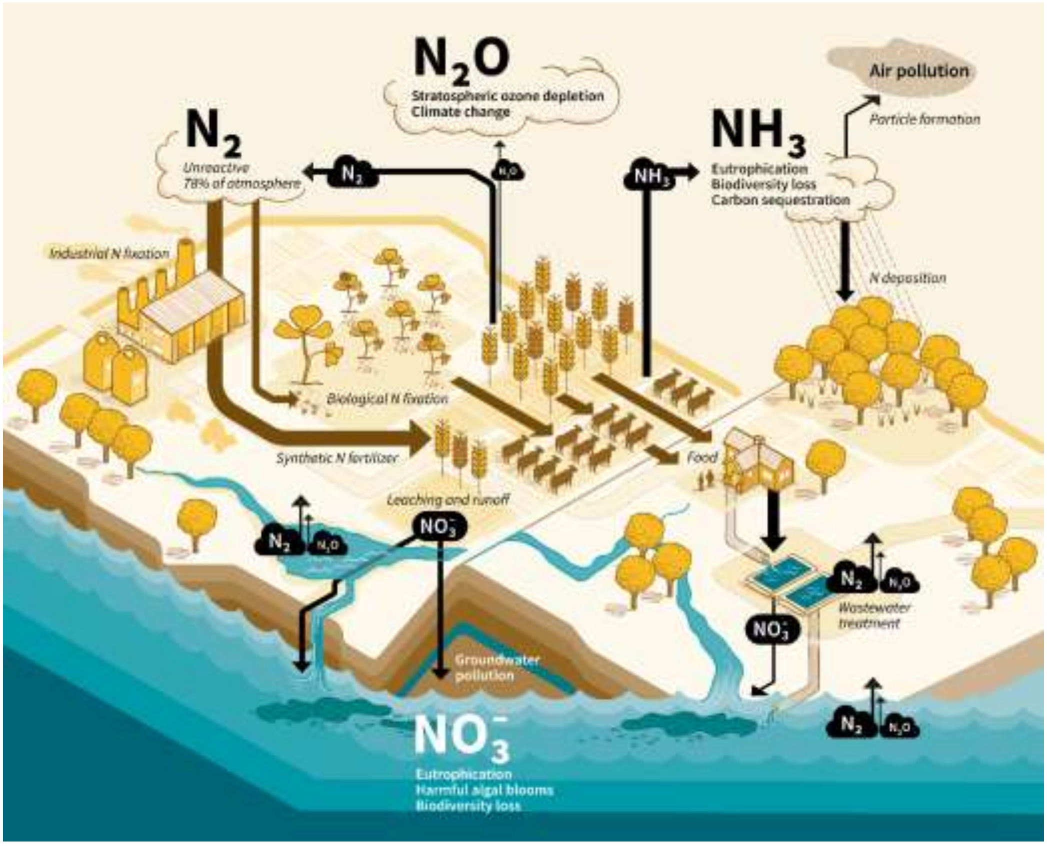
- **Expand and improve datasets on nitrogen in the food system.** Quantitative models of food systems are widely used for many purposes including quantification of production, resource use, and emissions, scenario analysis, and policy assessment. There is a lack of reliable primary data on many key variables of interest in food systems, including feed use, fertilizer use, agricultural management practices, and waste. Collaborative efforts are needed to collate existing data, collect additional primary data, and gap-fill and consolidate datasets through modelling.

- **Develop future scenarios and assess policy options.** To support rich and nuanced debates about how major change can come about, there is a need to develop scenarios and policy assessments adapted to the reality of stakeholder priorities and specific policies that also respond appropriately to the urgent sustainability challenges ahead. Researchers can help to provide timely, impartial, transparent, and rigorous policy-relevant information and analysis of policy options in relation to nitrogen and food systems more broadly. This will enable more actors to engage meaningfully in policy-relevant conversation at a time in which evidence is needed more than ever to inform policy impact assessment and decision-making.

1. INTRODUCTION

Nitrogen plays a dual role in food systems. On the one hand, nitrogen is an essential nutrient for all life forms and a key driver of productivity in agriculture. On the other, agriculture unavoidably emits nitrogen pollutants – including ammonia (NH_3), nitrous oxide (N_2O), nitrogen oxides (NO_x), and nitrate (NO_3^-) – which are major contributors to environmental and health impacts, including climate change, toxic air pollution, and biodiversity-harming eutrophication of land and water ecosystems (Sutton et al., 2011) (see Figure 1 for an illustration of nitrogen flows and impacts). Therefore, **nitrogen cuts to the core of many interconnected issues in the food system, concerning productivity, economic viability of farms, and environmental and health impacts.** Nitrogen's environmental and human health impacts are widely agreed to be priority issues both within the EU and globally.

Figure 1: Illustration of nitrogen (N) flows in the food system, pollution streams, and resulting environmental and health impacts. Illustration by Susanne Flodin from TABLE Explainer Nitrogen in the Food System (Einarsson, 2024), reproduced with permission.



There is no consensus on how much nitrogen pollution is “too much” (Einarsson, 2024). Ambitions to reduce emissions by about 50% have appeared in several high-level contexts: as a global target adopted by the UN Convention on Biodiversity (CBD, 2022), as an aim of the 2019-2024 European Commission’s Farm to Fork Strategy (European Commission, 2020), and as a “planetary boundary” estimated by researchers as an environmentally safe level (Schulte-Uebbing, Beusen, et al., 2022; Rockström et al., 2023). But when it comes to the fine print of actual policy, emission reduction targets are typically much more modest. Even from a scientific perspective, emission limits like the nitrogen planetary boundary are not simple empirical facts but rather estimates of how much pollution is tolerable before gradual impacts on ecosystems and human health reach unacceptable levels (Einarsson, 2024). The boundary could be lower or higher depending on how severe impacts are tolerated.

Nitrogen emissions to the environment are unavoidable side effects of agricultural production. The emission intensity per unit product can be reduced through technical and management changes, but emissions will never reach zero. Research suggests that a very ambitious package of coordinated measures to increase efficiency and reduce waste throughout food systems could reduce emissions by perhaps 30–50 percent globally compared to business-as-usual scenarios (Chatzimpiros & Harchaoui, 2023; Einarsson, 2024; Leip et al., 2022; Schulte-Uebbing, Beusen, et al., 2022), but it should be noted that these values are rather uncertain and that they are estimates of technical possibilities, not likely implementation results.

Human dietary change is a major opportunity to reduce nitrogen pollution (Billen et al., 2015; Chatzimpiros & Harchaoui, 2023; Leip et al., 2023; Westhoek et al., 2015). Animal-source foods account for a very large share of total nitrogen emissions, both because manure causes large emissions and because the majority of nitrogen harvested on global cropland is dedicated to livestock feed. If affluent populations shift away from the most feed-intensive animal source foods, nitrogen emissions could be substantially reduced. Scenario analyses show that a global 10–40 percent decrease in global nitrogen emissions could plausibly be reached through dietary shifts, especially in the more affluent populations (Einarsson, 2024). In summary, **an ambitious combination of dietary shifts and efficiency improvements could reduce global nitrogen emissions from food systems by 50 percent or more**, in line with the most ambitious high-level targets.

To get anywhere near such ambitious targets, there is an urgent need to accelerate implementation of known solutions, and to develop additional ones. This requires a major development of effective and socially acceptable policies to create incentives for innovation and structural change in agriculture, food and feed industries, and consumer behaviour.

At the same time, a similar scale of **change is urgently needed in food systems more broadly to deal with the interconnected issues of climate change, biodiversity loss, freshwater use, and human health and nutrition.** Solutions to these challenges offer some major co-benefits, since the drivers of problems are largely the same, but there may also be some trade-offs having to do with spatial structure and biogeochemical complexities of food systems (Sutton et al., 2022). These challenges therefore need to be addressed jointly to capture co-benefits and manage trade-offs.

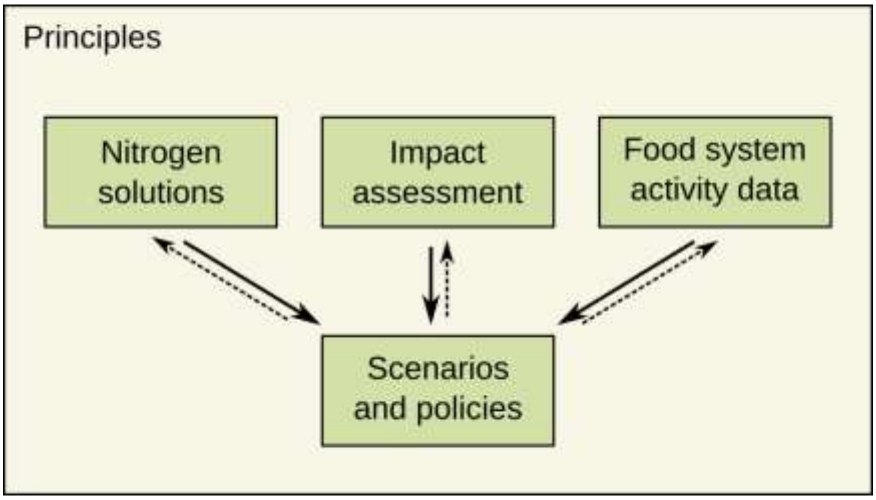
In summary, nitrogen is a key component of several sustainability issues in agriculture and food systems. **The main societal challenge is arguably not a lack of available solutions, but a lack of realistic, effective, and socially acceptable policies to create incentives for known solutions that provide multiple benefits and manage trade-offs for the environment and human well-being** (Kanter, Chodos, et al., 2020; Kugelberg et al., 2021; Sutton et al., 2022).

2. OBJECTIVE AND APPROACH

The objective of this brief is to present a research agenda describing priorities for research and innovation for EU research funding for agriculture and food systems, focusing on the sustainable use and management of nitrogen in the food system. The recommendations are based on a close reading of scientific literature as summarized in a recent research publication on nitrogen in the food system (Einarsson, 2024)[1].

The agenda presents 18 recommendations. Five recommendations are overarching principles (Section 3) and the remaining 13 recommendations are specific research priorities grouped in four broad research areas (Figure 2). All the research areas are interconnected and cross-fertilize, so boundaries between them are not easily drawn. Moreover, given the strong connections to other issues in food system research, the recommendations given here should be considered in the wider scope of food system sustainability.

Figure 2: Illustration of how the recommendations are connected. Five overarching principles for sustainability-oriented nitrogen research are proposed (Section 3). Research on solutions for nitrogen in the food system (Section 4.1), impact assessment (Section 4.2) and data on nitrogen in the food system (Section 4.3) are all crucial inputs to scenario building and policy assessment (Section 4.4). There is also a need to prioritize and contextualize the first three research areas (Sections 4.1 to 4.3) based on the wider systems and policy perspective (Section 4.4).



[1] Throughout this document, references are made to key scientific publications. Additional context and further references can be found in the overview publication (Einarsson, 2024).

3. PRINCIPLES FOR SUSTAINABILITY-ORIENTED NITROGEN RESEARCH

3.1 Adopt a food systems approach

Research on nitrogen in the food system needs to take a systems approach in several ways:

- **Consider the wider food systems context.** Nitrogen-related sustainability issues share drivers and effects with many other challenges. For example, production and consumption of animal-source food is an overarching theme connected to a myriad sustainability concerns related to land use, farm structure and economics, greenhouse gas emissions and human nutrition and health (Bodirsky et al., 2020; Gerten et al., 2020; Mitter et al., 2020; Willett et al., 2019). While not all of these issues are directly related to nitrogen, they should be considered alongside to build a comprehensive view of the available options for change.
- **Consider knock-on effects and interactions.** Changes to one food-system component almost always interact with other system components. As a specific example, emissions of ammonia from agriculture are co-determined by crop production practices, climate and soil conditions, livestock feeding efficiency, and systems for manure management, treatment, and application. Therefore, optimal outcomes in the whole system are generally not reached by optimizing one component in isolation. Specialists in different areas (e.g., livestock feeding or crop production) need to collaborate to understand these implications.
- **Consider trade-offs and co-benefits.** Many options to mitigate nitrogen-related problems can have positive or negative side effects on other issues. An example of a trade-off is that agricultural extensification tends to decrease nitrogen emissions and increase resource use efficiency, but it increases land use per unit product (van Grinsven et al., 2015). An example of a co-benefit is that more efficient livestock production tends to reduce not only nitrogen emissions most environmental impacts related to feed production and livestock metabolism (Herrero et al., 2015; Leip et al., 2015). Information about these trade-offs and co-benefits is crucial for informed decision-making about these inherently multidimensional outcomes.

3.2 Account for a broad range of sustainability outcomes

Sustainability research should align with the UN Sustainable Development Goals (SDGs). Issues of particular relevance in the nitrogen context are, in alphabetical order:

- animal welfare,
- biodiversity and ecosystem health,
- climate change,
- economic costs for food production,
- economic distributional effects in society,
- economic viability of farms,
- human health,
- pesticide use and pesticide-resistant weeds,
- production of food and agricultural bioenergy and materials,
- resource use efficiency (e.g., nutrients, water, and land),
- soil health, including soil carbon stocks, biodiversity, and soil functions,
- system resilience in the face of crises, conflicts, and environmental shocks.

3.3 Promote inter-and transdisciplinary research

Sustainability challenges require diverse perspectives and expertise from academic disciplines including agronomy, environmental science, public policy, economics, sociology, and psychology. There is also a need to interact with policymakers and stakeholders in the design and assessment of agricultural solutions and policies to ensure relevance of the research.

In practice, however, there is a tendency for food-system sustainability research to silo into specific disciplines. When disciplinary gaps are bridged, e.g., biophysical and policy dimensions researched together, the research teams are rarely at the research front of both disciplines. Interaction with stakeholders does occur frequently, but there is room for taking this further, for example by basing research questions more directly on the concerns and knowledge of stakeholders. Moreover, although many researchers agree that the nitrogen research field would benefit from more social science approaches and more qualitative research, the field is currently dominated by natural science and quantitative research (Fischer et al., 2025; Gupta et al., 2021; Kanter, Del Grosso, et al., 2020; Thompson & Scoones, 2009; UNEP & FAO, 2024).

Food-system sustainability research would therefore benefit from

- deeper integration with state-of-the-art methods across disciplines,

- more frequent combination of quantitative and qualitative approaches to better address multifaceted issues,
- more interaction with policymakers and stakeholders in the food system.

3.4 Require open science

Research methods, datasets, and results should be transparent and publicly accessible to all (Peng, 2011; Stodden et al., 2016). Key benefits of making methods and datasets available include:

- Reuse: possibility for a wide range of researchers and analysts to reuse and repurpose research methods and results.
- Transparency: possibility for researchers and others to scrutinize methods.

Open science practices facilitate the reuse of data and methods, promote transparency, and enable broader scrutiny, which can accelerate scientific progress and innovation in nitrogen management. By mandating open science practices, research funders can make research more efficient, inclusive, transparent, and credible.

3.5 Focus public research funding on public benefit

Public research funding should prioritize projects that offer substantial societal value. Both goal-oriented and exploratory research should be supported, ensuring a balanced approach to addressing immediate challenges and long-term sustainability goals.

In particular for short-term and goal-oriented research, funding should be prioritized to projects that focus on major societal opportunities and risks. Assessment of research proposals should consider arguments, quantitative and/or qualitative, for why the proposed research is likely to give societal value-for-money and how they aligned with long-term societal goals.

There is also a continued need for long-term, explorative, and open-minded research projects for which the potential value-for-money is not straightforward to prove in advance. For example, strategic investment in research infrastructure, such as long-term field experiments and advanced analytical facilities, can provide a foundation for other research and innovation. Here, the requirement should rather be that research proposals demonstrate a major societal importance and a plausible way to success.

Public funding should avoid duplicating private-sector investments but can co-fund efforts to independently validate technologies and practices developed by private R&D.

4. RESEARCH PRIORITIES

4.1 Develop and evaluate solutions for nitrogen in the food system

Management practices and technologies throughout the food system can mitigate nitrogen-related impacts on the environment and human health. Such solutions often affect multiple sustainability dimensions (Section 3.2) and therefore promising solutions should be comprehensively evaluated to identify co-benefits and trade-offs.

There is a continued need to develop new solutions and to refine and evaluate established ones. Research must address the whole range of technology readiness levels, from concepts and early modelling and testing to practical implementation with farmers and other stakeholders. Priority should be given to practices and technologies that are widely used and/or that have the potential to provide major societal net benefits (Section 3.5).

Research in this category may include tentative systems analysis, e.g., using life-cycle assessment or food-system models to draw preliminary conclusions about potential societal impact if solutions are scaled up.

One function of research in this category is to provide data and model components for use in contexts of food-system modelling (Springmann et al., 2018; van Zanten et al., 2022), Life Cycle Assessment (Poore & Nemecek, 2018), and policy development.

Research in this category should therefore:

- quantify biophysical facts (e.g., effect on nitrogen flows and emissions, GHG emissions, energy use, etc.),
- quantify implementation costs, and
- describe barriers to implementation, including aspects that require qualitative research.

4.1.1 Quantify multiple effects of agro-ecological and ecological intensification practices

High-diversity agricultural practices promoted under various names and premises, including ecological intensification, agroecology, and crop diversification (Bernard & Lux, 2017; Fischer et al., 2025), have potential benefits including higher nutrient use efficiency (including nitrogen) but also higher water use efficiency, natural control of crop pests and diseases, higher productivity, higher yield stability, higher biodiversity in the agricultural landscape, reduced dependence on external inputs, and/or enhanced soil organic matter (Bommarco et al., 2013; Bowles et al., 2020; Kleijn et al., 2019; Wezel et al., 2009).

While the potential benefits of these practices are generally well understood, the quantitative effects and potential for upscaling in different pedoclimatic and economic contexts are less well known (Kleijn et al., 2019)**.** There is a need to better quantify the effects of such practices in multiple sustainability dimensions (Section 3.2) to comprehensively assess their costs and benefits.

Research studies at different scales are crucial to better understand and quantify such practices. Pot experiments, field experiments, and farm-system experiments (including crop-livestock interactions) can be combined to cost-efficiently build knowledge. Systems studies including food-system modelling and life cycle assessment can be used to understand the wider system implications of crop-livestock interactions (Billen et al., 2015; Van Zanten et al., 2019; van Zanten et al., 2022).

Long-term experiments spanning decades or more are particularly important since the ecosystem services often play out over time (e.g., throughout crop rotations) and also may accumulate over time (e.g., benefits of accumulating soil organic matter) (Johnston & Poulton, 2018; MacLaren et al., 2022; Rasmussen et al., 1998; Shah et al., 2017).

Finally, it is crucial that experimental studies have **rigorous statistical designs** with sufficient power to discern hypothesized effects, full and transparent documentation of experimental designs, and open data commitment from the start (Section 3.4). Pre-registration of experimental designs is preferable to ensure quality and avoid publication bias. Ideally, experiments should be comparable to other experiments to facilitate meta-analysis.

4.1.2 Improve fundamental understanding of nitrogen sources and soil nitrogen dynamics

The two main inputs of new reactive nitrogen in agricultural systems are synthetic nitrogen fertilizer and biological nitrogen fixation (Sutton et al., 2011; Ludemann et al., 2024). There is also a substantial recirculation of nitrogen to crops in the form of manure and crop residues (Bouwman et al., 2009; Lassaletta et al., 2016).

It is challenging to assess the effect of these different forms of crop nitrogen inputs on crop productivity and nitrogen pollution. The uptake and metabolism of nitrogen in plants is highly complex and depends on many interacting factors (Farzadfar et al., 2021; Hachiya & Sakakibara, 2017; Krapp, 2015; Schimel &

Bennett, 2004; Yan et al., 2020). Crop cultivation experiments typically use mineral nitrogen fertilizer as the only or main nitrogen input. Organic nitrogen inputs including livestock manure, green manure, and compost are commonly compared to mineral fertilizer in terms of equivalence during one crop year, although it is well known that mineralization and immobilization processes play out over several years. In fact, experimental evidence shows that **even in cereal crops fertilized with mineral fertilizer, the majority of plant nitrogen uptake often does not originate in fertilizer applied in the same crop year**, a fact likely having to do with complex soil nitrogen transformations (Yan et al., 2020). Moreover, the value of biologically fixed nitrogen depends on how the nitrogen-fixing (legume) crops are used (Billen et al., 2024; Peoples et al., 2019). For practical reasons, manure nitrogen needs to be used in close proximity to livestock production, which can create additional constraints.

Therefore, to improve nitrogen use and recycling in the food system, there is a need to further investigate and compare nitrogen sources, both from a scientific perspective focusing on biogeochemical mechanisms, and from a pragmatic perspective focusing on the pros and cons of different nitrogen inputs.

Key remaining research questions revolve around the contributions of different nitrogen sources to nitrogen emissions under different management practices and pedoclimatic conditions, their economic value in a systems perspective, and their short- and long-term effects on crop productivity.

4.1.3 Quantify nitrogen greenhouse gas flows in carbon farming

Carbon farming refers to agricultural practices that build soil organic matter and thereby sequester carbon in soil. The net climate benefit of carbon farming, however, depends also on other greenhouse gas emissions in the system, including methane emissions from related livestock (Section 4.1.3) and nitrous oxide emissions from crop cultivation. For example, cover crops can sequester substantial amounts of soil carbon (Poeplau & Don, 2015) but risk increasing nitrous oxide emissions (Abdalla et al., 2019; Basche et al., 2014; Davies et al., 2021; Guenet et al., 2021; Olofsson & Ernfors, 2022).

Carbon sequestration in soil also entails nitrogen sequestration since the carbon-to-nitrogen ratio of soil organic matter is stoichiometrically constrained to ca 1 kg of nitrogen per 10 kg of carbon (Batjes, 1996; Xu et al., 2013). **Carbon farming thus has a "nitrogen cost" which needs to be paid in some way**, either through increased inputs or decreased nitrogen available to crops (Abdalla et al., 2019; van Groenigen et al., 2017). **Therefore, carbon farming options need to be carefully evaluated in terms of nitrogen supply, long-term crop productivity, and implications for overall environmental impacts.**

There is a need for expanded design and evaluation of carbon farming options, including comprehensive greenhouse gas budgets and nitrogen budgets, to accurately know the constraints and overall climate effect of carbon farming.

4.1.4 Investigate economic costs for implementation

Knowing the economic cost of technology and management solutions is a prerequisite for designing societally cost-efficient policy (Bittman et al., 2014; Gu et al., 2023; Sutton et al., 2022; van Grinsven et al., 2013). Given the limited financing and large need for mitigation of nitrogen-related impacts, there is a requirement for **comprehensive and robust economic cost estimates** for the various options available, to help decision-makers prioritize efforts.

Comprehensive, open, well-documented, and up-to-date information on costs for nitrogen-related solutions needs to be developed for different contexts (e.g., depending on climatic conditions and scale of implementation). Since economic conditions constantly change, and technical innovations continue, the information should ideally be kept up to date through periodic data collection and/or models to update cost estimates.

4.1.5 Synthesize knowledge on food system solutions

There are many known management practices and technologies that could be used more widely to mitigate the impacts of agricultural nitrogen, and to some extent, these have been catalogued and compared (Bittman et al., 2014; Hafner et al., 2018; Sutton et al., 2022). But to fully inform policies for food system sustainability, there is a need for more comprehensive information on multiple sustainability aspects (Section 3.2). Given that solutions with different pros and cons must be prioritized and combined into packages, taking a systems approach to assess their compatibility and combined effects is crucial (Section 3.1).

Knowledge can be synthesized in different ways, using qualitative and/or quantitative methods, including but not limited to statistical meta-analysis. In some cases, life cycle assessment and similar approaches are useful to clarify the system-wide effects of different solutions. Interdisciplinary research collaborations may be necessary for some synthesis tasks (Section 3.3). Collated datasets arising through such work should be documented and disseminated freely (Section 3.4). Ideally, **synthesized information should be purposefully prepared to facilitate reuse in food system models and policy contexts** (Section 4.4).

4.2 Refine methods to assess impacts of nitrogen pollution

Understanding the impacts of nitrogen emissions requires consideration of time- and place-dependent factors, such as ecosystem sensitivity, environmental transport, and population exposure.

Given the complexity of the nitrogen cycle and its interconnection with other biogeochemical cycles, **both fundamental and applied research** must be carried out to understand, characterize, and quantify effects of nitrogen in the environment. From a pragmatic policy perspective, quantifying marginal impacts is most useful to design efficient policies, but the accuracy and long-term improvement of knowledge also depends on fundamental research.

4.2.1 Improve quantification of marginal impacts of nitrogen emissions

Nitrogen pollution causes a range of different impacts, including global warming, algal blooms, biodiversity loss, cancer, and respiratory diseases (Sutton et al., 2011; van Grinsven et al., 2013). The type and severity of these impacts depend on where, when, and in what chemical form nitrogen is released to the environment (Gu et al., 2023; Schulte-Uebbing, Beusen, et al., 2022). To **target mitigation efforts where they make the most difference**, requires robust quantification of marginal impacts of different nitrogen emissions.

More specifically, further research is needed to explore and quantify to what extent nitrogen in the environment causes gradual degradation versus strongly nonlinear impacts or even tipping-point impacts. Such information can be used to motivate and refine environmental quality standards, “planetary boundaries”, and other limits.

Examples of marginal impacts that would be particularly relevant to better quantify:

- **Climate change.** Nitrogen emissions make both warming and cooling contributions to climate change. The balance between warming and cooling contributions due to marginal emissions is determined by the chemical form, location, and timing of emissions in ways that are yet incompletely understood (de Vries et al., 2014; Erisman et al., 2011; Pinder et al., 2013; Schulte-Uebbing, Ros, et al., 2022).
- **Air pollution.** In the many regions where atmospheric emissions of ammonia (NH_3) are roughly constant over time, while emissions of nitrogen and sulphur oxides (NO_x and SO_x) fall, there is a growing atmospheric imbalance between these pollutants, with implications for

atmospheric chemistry and transport and related environmental and human health impacts (Gu et al., 2021; Sutton et al., 2020).

- **Eutrophication.** In both terrestrial and aquatic ecosystems, there is a large spatial and temporal variation in co-limitation of multiple nutrients for eutrophication status, with the result that marginal eutrophication impact of nitrogen emissions varies considerably (Du & de Vries, 2018; Garnier et al., 2010; Wurtsbaugh et al., 2019).

4.2.2 Investigate environmental accumulation, time lags, and legacy effects

Despite decades of research, there is yet a rather incomplete understanding of the pathways that agricultural nitrogen emissions take in the environment. Large quantities of nitrogen can accumulate in soil, groundwater, and surface water, but it is still difficult to predict the magnitudes, retention times and ultimate fates of these accumulating pollutants (Galloway, 1998; Puckett et al., 2011; Liu et al., 2024; Van Meter et al., 2016).

4.3 Expand and improve datasets on nitrogen in the food system

Quantitative food-system models are widely used to estimate environmental emissions and impacts, to assess the potential to scale up various solutions, to explore policy options, and much more (Amann et al., 2011; Bodirsky et al., 2014; Chatzimpiros & Harchaoui, 2023; Lassaletta et al., 2016; Oenema et al., 2009; Schulte-Uebbing, Beusen, et al., 2022). All of these applications require data on material flows and activities in food systems.

There is a **surprising lack of basic data on material flows and activities in food systems**. For example, most countries have no comprehensive collection of primary data on livestock feed use, manure flows, processing of food and feed, food loss and waste, crop rotations, fertilizer use by crop, or consumption of food and non-food agricultural products (Bodirsky et al., 2014; Bruckner et al., 2019; Einarsson et al., 2021; Lassaletta et al., 2016; Ludemann et al., 2022). International databases contain long time series of primary data on a few key variables at country level, most importantly production of commodity crops and livestock, international trade in commodities, and aggregate use of some inputs, including mineral fertilizers (FAO, 2024; Ludemann et al., 2024). Certain regions and countries have additional data collection, for example, on farm structure and economics, but these are not straightforward to compare internationally. Most other data on activities and material flows in food systems are estimated using models that combine agricultural statistics, experimental results, remote sensing data, and expert estimates (e.g., Bodirsky et al., 2014; Britz & Witzke, 2014; Havlík et al., 2014; Lassaletta et al., 2016; Ludemann et al., 2024; Monfreda et al., 2008; Robinson et al., 2014; Stehfest et al., 2014).

The lack of comprehensive primary data leads to large uncertainties about resource use, environmental impacts, and potential for improvement of food system sustainability. The quantitative models widely used to understand current food systems and design options for change typically have a rather rough representation of key issues such as cropping systems, feed use, food and feed processing, and food loss and waste. Progress on fundamental scientific questions, such as global carbon and nitrogen flows, is constrained by a lack of data.

Current datasets should be expanded and refined to support a deeper understanding of food systems and the development of effective policies. There is a particular need for datasets to reflect different environments and agricultural systems, avoiding bias to certain regions and/or dominating agricultural systems.

Pragmatically, **efforts need to be opportunistic, drawing on existing databases and initiatives, and allowing for a mix of data sources** including statistical surveys, remote sensing data, and other opportunistically available evidence. Efforts should ideally be coordinated with other uses in food system research and policy, such as the EU Farm Sustainability Data Network (FSDN) and national inventory reporting to the Air Convention (CLRTAP) and Climate Convention (UNFCCC).

In this area, it is imperative to require open science, where both data and models are freely shared, to enable scrutiny, reuse, and collaboration by a wide range of researchers and analysts.

Variables of particular interest for nitrogen management include:

- crop production, including
    - areas and productivity of meadows and pastures and arable forage crops,
    - crop rotations and tillage,
    - irrigation, and
    - fertiliser use by crop, including mineral fertilisers, manure, and other fertilisers;
- livestock production, including
    - feed use,
    - grazing practices and grazing feed intake,
    - excretion of nutrients, and

    - manure management;
- processing of primary agricultural products into food, feed, fuel, and other products; and
- food loss and waste from farm to fork.

4.3.1 Collate existing data

Cost-effective improvement of data supply should begin by taking stock of existing data that is not yet collated. Possible data sources to start from include:

- published statistical surveys on national or subnational level, which are not yet consolidated into international databases,
- unpublished microdata from statistical surveys, which could be further processed to fill data gaps, and
- observational non-survey data from, e.g., farm advisory programs or industry initiatives.

Work in this area needs to pay close attention to differences in nomenclature, measurement methods, etc., that may limit the comparability across data sources.

4.3.2 Collect additional primary data

Where severe data gaps on important variables are identified, additional efforts are needed to collect additional primary data. Statistical surveys must have rigorous statistical designs (e.g., considering representativeness, suitable stratification, and power analysis) to ensure data quality and fitness for purpose. Ideally, data collection should be recurring over time, e.g., through constant remote sensing or recurring statistical surveys.

Major efforts in primary data collection should be coordinated internationally between relevant government authorities and research institutions to ensure efficiency and usefulness. Existing initiatives for data collection (e.g., national agricultural statistics and in the EU the FSDN and LUCAS surveys) should be leveraged to simultaneously fill data gaps in research, sustainability monitoring, emission reporting, and other uses.

4.3.3 Gap-fill and consolidate datasets through modelling

Realistically, there will always be remaining data gaps even after existing data is collated (Section 4.3.1) and additional data is gathered (Section 4.3.2). Mathematical models of different kinds (e.g., biophysical, econometric, or machine-learning models) can be used to gap-fill and consolidate various datasets.

During the last decade, there has been a proliferation of new food-system datasets that estimate various quantities such as land use, crop production, and fertiliser use with an increasing level of detail. Although potentially very useful, the accuracy of these new datasets is sometimes difficult to ascertain because of the many assumptions and approximations built into the analysis.

Further development of such derived and partly modelled datasets should be encouraged, but to **quantify and manage remaining uncertainties**, researchers should mainstream the use of:

- uncertainty quantification, e.g., using Monte Carlo simulation,
- open-source code and data,
- tracing of data provenance, i.e., whether data stem directly from measurement or from an estimation procedure.

4.4 Develop future scenarios and assess policy options

Broadly speaking, **the major knowledge gap on sustainable food systems is not what could be done but rather how change could come about**. Previous research has extensively explored biophysically possible scenarios for future food systems, including technical and management changes as well as dietary change (Billen et al., 2015, 2024; Bodirsky et al., 2014; Gu et al., 2023; Leip et al., 2022; Springmann et al., 2018; Willett et al., 2019). But there is a relative scarcity of analyses adapted to the reality of stakeholder priorities and specific policies, that also respond appropriately to the huge and urgent sustainability challenges of food systems.

Realistic scenarios and policy options are needed to support societal debate on nitrogen and food system sustainability more broadly (Section 3.2). Research should support the creation of policy-relevant tools and assessments that help to clarify political and legal feasibility and potential impacts of different options. Interdisciplinary research (Section 3.3) is crucial in this context.

Scenario analysis, especially quantitative scenario analysis based on mathematical models, plays an important role as a way to reason transparently and stringently around the effects of different courses of action. The interactions between food system components (Section 3.1) make it almost impossible to reach accurate estimates without food system models. Further development of quantitative food-system models is therefore necessary to keep models up to date with emerging solutions and concerns. Multiple models should be maintained to address different needs and to avoid overreliance on specific assumptions built into models.

Policy-relevant research needs to engage with the specific policies that address nitrogen in the food system. In the EU, there is a complex patchwork of EU policies touching directly or indirectly on nitrogen, including the Common Agricultural Policy, the Nitrates Directive, the National Emission Ceilings Directive, the Habitats Directive, the Water Framework Directive, the Wastewater Treatment Directive, and the Effort Sharing Regulation. In addition, there are national policies and global or regional conventions including the Air Convention's Gothenburg Protocol and its Annex IX, the Convention on Biodiversity (Kunming-Montreal Target 7), and the Helsinki Convention. Substantial involvement of policymakers, stakeholders, and political scientists is needed to make rigorous analyses of this policy landscape.

Note that this call for increased realism and direct policy relevance does not imply that research should be limited to minor changes to food systems. History shows that major food system transformations are possible, and there is a need to reflect these historical insights in the exploration of possible futures (Gingrich et al., 2015; González De Molina & Toledo, 2014). There is a continuous need to challenge established narratives and to develop new narratives that correspond to the scale of the food system's sustainability challenges.

Policy for dietary shifts seems highly relevant not only considering health effects and climate change (Funke et al., 2022; Ivanovich et al., 2023; Klenert et al., 2023) but also considering that high-level political ambitions for reduced nitrogen pollution exceed what can be achieved merely through technical optimization (Einarsson, 2024). It is worth investigating the long-term effects of focusing policy on technical efficiency, given that an excessive focus on resource use efficiency may lead to additional lock-ins and normalization of fundamentally unsustainable practices (Herzon et al., 2024).

4.4.1 Develop interdisciplinary scenario analysis and policy assessment

To ensure societal relevance, the methodology for scenario analysis and policy assessment needs to become more interdisciplinary. Research teams should combine state-of-the-art elements from biophysical sciences (agronomy, biogeochemistry, environmental science, etc) and social sciences (political science, economics, sociology, economic and environmental history, behavioural psychology, etc) (Kanter, Del Grosso, et al., 2020; Kugelberg et al., 2021; UNEP & FAO, 2024).

In particular, there is a need to build capacity and mutual understanding in interdisciplinary collaborations grappling with, for example,

- institutional, legal, and economic frameworks and policies,

- economic costs, economic efficiency, and distributional effects of policy options,
- societal acceptance of policies,
- social and psychological enablers and barriers to changing human behaviour,
- drivers of supply and demand in food systems,
- practical applicability of agricultural technologies and management practices, and
- biogeochemical intricacies of nitrogen cycling and impacts of nitrogen.

The insights generated in such research should be presented in a form that can be used in food system modelling, scenario analysis, and policy assessment.

4.4.2 Enable more actors to engage in scenario analysis and policy assessment

The science and policy of food systems are intricate matters that require substantial resources to engage with. At the same time, food system policy affects literally everyone in the world and therefore it should be a priority to make the field accessible also to stakeholders and decision-makers with limited resources.

There is a need to set up systems that continuously provide timely, impartial, transparent, and rigorous policy-relevant information and analysis of policy options in relation to nitrogen and food systems more broadly. This will enable more actors to engage meaningfully in policy-relevant conversation. In this time of misinformation and unrestrained political spin, finding common ground for evidence and policy impact assessments is greater than ever.

The construction of such systems should consider the following components:

- A knowledge base of basic evidence. This could include, for example, information on food-system processes, pollution, efficacy and costs of mitigation options, and relevant policies and legal frameworks.
- Timely and transparent analyses. With reference to the above-mentioned knowledge base, experts could provide rigorous but accessible analyses of policy options, outlining key implications and points of political disagreement.
- Accessible tools for independent assessment. Also based on the above-mentioned knowledge base, researchers could develop accessible, user-friendly tools to enable independent assessment of scenarios and policies. Such tools could include, for example, quantitative models for scenario analysis and qualitative frameworks for policy assessment.

All these resources should be peer-reviewed with the explicit aim of providing a transparent and even-handed common platform of evidence and tools on which meaningful discussions can be built. The researchers providing these resources should represent different disciplines and viewpoints (Section 4.4.1). Ideally, the people involved in these activities can collectively play an important role as an honest broker of policy alternatives (Pielke, 2007).

4.4.3 Enable more actors to engage in scenario analysis and policy assessment

In addition to providing accessible resources for independent analysis (Section 4.4.2) research funding should enable researchers to engage with policy-relevant scenario building and policy assessment in direct collaboration with stakeholders and decision-makers. This is an opportunity for mutual learning between all actors, where researchers should be incentivised to bring the latest scientific findings and rigorous methods (Section 4.4.1) into these collaborations, while remaining open to the priorities and concerns of stakeholders.

5. CONCLUSION

This research agenda calls for an integrated, interdisciplinary, and policy-oriented approach to nitrogen management among other issues in food systems.

Although much is already known about nitrogen cycling in agroecosystems and in the environment, there are still fundamental scientific problems of major practical relevance. For example, research is needed on nitrogen cycling in soil-plant systems with particular attention to how plants obtain nitrogen from soils via mineral nitrogen fertiliser, biologically fixed nitrogen, and recycled nitrogen sources, and to assess sustainability implications for plant nutrition, agricultural production, and carbon farming approaches. Ambitious and rigorous experiments, in particular long-term experiments, are required to generate robust knowledge. Moreover, to prioritise and target pollution mitigation, there is a need for improved quantification of marginal environmental and health impacts of nitrogen pollution depending on time, place, and chemical form.

By providing timely, impartial, transparent, and rigorous policy-relevant information and analysis of policy options and barriers to change, researchers can enable more actors to engage meaningfully in policy-relevant conversation on nitrogen and other complex food-system issues. Here, inter- and transdisciplinary research teams have an important role to play in development and maintenance of databases, models and other assessment tools, and state-of-the-art analyses adapted to the needs and interests of stakeholders and decision-makers. To ensure relevance in the EU, this research must connect to current and emerging policies such as the Air Convention, Climate Convention, and EU policies including the Common Agricultural Policy and directives and regulations relating to air quality, biodiversity protection, and climate change. This way, research can play a large and important role as an honest broker of policy alternatives by providing a common ground of evidence and rigorous policy impact assessments.

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